Thesis: Air Transport and Operations

Stochastic simulation of delay propagation

Improving schedule stability at Kenya Airways

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Kenya Airways The Pride of Africa

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Executive Summary

The main challenge for passenger airlines is the design of a profitable flight schedule. A hub-and-spoke network gains from collecting and re-distributing large amounts of passengers through their hub. The Network Planning conundrum is that revenue and costs are made and incurred sequentially. The revenue is collected prior to the day of operations. However, it is only then that costs are made and the profitability of the schedule can be measured. To maximize profitability, operational robustness has to be gauged during the network planning phase.

Kenya Airway operates a highly connected hub and spoke network. Its strategy pivots around intra-Africa traffic and African traders to and from the Middle East and Asia, for which it's hub in Nairobi forms a geographical competitive advantage. It's current challenges lies in increasing it's fleet of 32 aircraft and expanding it's schedule in a sustainable and punctual way. The tightness of it's schedule translates in an instability where delays can cascade through the network like the toppling of dominoes. Of all delays at Kenya Airways, 51%[1] are reactionary delays[2]. This is higher than the 46% as experienced in the mature European airline industry (EuroControl, 2010). In line with Kenya Airways' growth strategy, a pressing problem is how they can adapt their flight schedule to increase potential punctuality. It needs to be studied how delays occur in a hub-and-spoke network.

During the last decade, more academic work has focused on planning for uncertain operations making schedules more stable or robust, which means that schedules are less sensitive to delays (Clausen et al., 2010). It is in this field where a tension has build up between a static and deterministic robust planning mentality and the real world being dynamic and stochastic[3] (Cohn and Lapp, 2010).

Central to the thesis is the development of a stochastic simulation to model the propagation of delays through the flight network. The analogy that can be made is the toppling of dominoes, where the fall of the first domino illustrates the primary delay caused. What this research sets out to do is find out how many dominoes will be toppled over, i.e. subsequent flights are delayed due to that first flight being delayed. Furthermore, a relationship is sought and found where the force of the first domino falling, i.e. duration of the delay, is related to the number of dominoes it will topple over, i.e. the severity of the delay.

Research Framework

Before the project setup is discussed, the research is placed in an industry framework to describe how the robustness of a flight schedule will lead to a higher airline punctuality and profitability.

Airline profitability is driven by a maximization of revenue and minimization of cost. Expanding this equation and understanding the drivers behind airline profitability shows that a further broadening of focus towards punctuality is needed.

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[1] The period of study is set between September 2010 and September 2011 due to the data integrity of Sabre Movement Control Flight Following System as explained in Appendix B.

[2] Reactionary delays are knock-on delays that occurs due to a primary disruption on a preceding flight.

[3] Stochastic refers to systems behaving in a pattern that may be analyzed statistically but may not be predicted in a precisely or deterministically.

An analysis on daily On-Time departure Performance at Kenya Airways shows a high historical variability which indicates that there is no consistent on-time performance and, hence, that this is the area where profitability can be increased.

Considering the impact of reactionary delays[4] on the punctuality of Kenya Airways, a pro-active flight schedule design could reduce the impact of disruptions. To achieve this the focus of the department of Network Planning should be expanded towards the stability of their flight schedule. This could be realized by a pro-active plan towards decreasing the network effect of nuisance delays[5], since these form the majority of the delays.

Project Setup

The aim is to analyze schedule stability in a schedule design phase as this allows to improve potential punctuality pro-actively. To formulate a feasible objective, a choice is made to narrow the scope of the research down to simulating the absorption robustness[6] in terms of aircraft and passenger connectivity for a proposed schedule. Focus is placed on studying short single delays and their impact on passenger connectivity which allows to simplify the disruption response strategy of the IOCC[7].

After scoping the problem area and within the freedom of the the project problem, a clear research question can be formulated:

> *How can the absorption robustness be simulated for a proposed seasonal flight schedule in terms of aircraft and passengers, and how can this be used to aid Kenya Airways in increasing schedule stability?*

Conceptual Model

The general framework for the conceptual model is an activity-on-node flight schedule representation where a delay can propagate through either the lines of flight or via a passenger connection. The next flight is delayed if the previous arrival delay exceeds the resource slack for the aircraft and all critical passenger connections. Early departures are permitted if all resources are ready for flights departing from smaller and non-slot restricted airports.

The model allows to stochastically model the Block-time, Minimum Turnaround-time and Minimum Passenger connecting-time using Log-Normal distributions that are fitted to historical data flight performance data.

The flow of transfer passengers through the schedule is obtained from historical data after translating Origin and Destination demand to flight leg connections. Delaying a subsequent flight to protect the flight itinerary plans of the transfer passengers is a deterministic function of the number of passengers and the subsequent downward flight frequency.

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[4] From a delay analysis at Kenya Airways, it is found that the 51% of delays are due to reactionary effects. A statistical correlation analysis shows that at Kenya Airways the daily On-Time Departure performance is more affected by the number of reactionary delays than the number of primary delays.

[5] At Kenya Airways, nuisance delays are considered to have a duration of 20 minutes or less.

[6] This is the objective that aims to schedule with enough margin to absorb the anticipated nuisance delays.

[7] The Integrated Operations Control Center (IOCC) of Kenya Airways coordinates network wide the operations on the day of operations

Stochastic simulation

The purpose of the simulation is to visualize per flight a simulated relation between the duration of the primary delay and the delay severity[8]. Furthermore, a robustness metric is proposed to compare the robustness of flights and the stability of flight schedules.

The basis for the stochastic Monte-Carlo delay scenario simulation is the delay propagation model. The previous introduced analogy to the toppling of dominoes can be extended to the Monte-Carlo simulation where the scenario of toppling that first domino is repeated until a clear picture can be made as to which dominoes are affected. A formal description of this process is a self-iterative shortest path algorithm that runs acyclic from the source delay node downstream till all delay is absorbed.

Three data sources are used to run the simulation. First, the schedule information and the possible flight connections are extracted from Netline, a Lufthansa schedule management system. Second, historical flight performance data is extracted from Sabre Movement Control Flight Following System and describes the stochastic nature of the Block-time, Turnaround-time and Passenger Connection-times. Third, the expected transfer passenger load on Origin and Destination level is from Delorean, a passenger booking analysis tool from KLM. After pre-processing the input data for a schedule, the schedule sensitivity simulation can be run.

The flight delay severity simulation visualizes per flight the relation between the duration of the primary delay and the delay severity. The range of primary delays is taken between -20 minutes and 30 minutes. 32% of the flights depart early, and as such the scenario of an early departure is analyzed. The flight robustness metric proposed to compare flights is the Expected Delay Severity where the delay severity curve is weighed against the probability of a primary delay.

The schedule sensitivity experiment simulates the delay severity curve for each flight in the schedule. From this, a robustness metric for the flight schedule is found. To compare flight schedules, the total of the expected delay severity can be taken. This is defined as the Aggregated Expected Delay Severity. Changes in the schedule stability between flight schedules can be compared.

Improving schedule stability

A pro-active methodology is created that uses the stochastic simulation of delay propagation to identify factors that can improve schedule stability during the design of a seasonal schedule. Furthermore, the application of the methodology is illustrated by describing how an alternative timing of the Lagos (LOS) flights is made.

The starting point of the methodology is analyzing the baseline schedule. Then the critical flights are analyzed on a flight level to maximize effectiveness.

Analyzing the critical flights on a flight level begins with the flight delay severity simulation, after which an alternative flight timing is created based on confident timings for the Block, Turnaround, and Passenger Connections. Then, an impact analysis of the alternative flight timing on the robustness of the flight; aircraft fleet availability; and the commercial impact on the possible passenger connections is done.

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[8] Delay severity is defined as the number of flights the primary delay affects downstream.

The result of the impact analysis can lead to retiming the critical flight to make a concession towards the flight robustness. Subsequent flights or preceding flights can also be re-timed to protect passenger connectivity where possible.

The final step of the methodology is a comparative study done to assess the improvements of the alternative flight schedule over the baseline schedule.

Then it will be explained how this methodology was applied and which results where achieved. The analysis of the baseline schedule showed an imbalance in the contribution of the flights to the aggregated expected delay severity. A further fundamental analysis finds a positive relationship between the expected delay severity and the Block-time confidence; Turnaround-time confidence; and the Passenger Connection-time confidence[9]. All three are correlated to the expected delay severity as is intuitively expected.

The flight to Lagos (LOS) is found the most critical due to the challenges of a low Block-time confidence and an interconnected passenger connectivity with Dubai (DXB) which causes a large cascading delay propagation. Lengthening the Lagos (LOS) rotation to increase the Scheduled Block-time is not possible without breaking the connection into or from the Dubai (DXB) flight. To solve this conundrum, a daily alternating connection from Lagos to accommodate connections to and from Dubai is proposed. An impact study on the alternative timing to Lagos (LOS) shows the improvement on the delay severity curve is realized throughout the range of delay durations. However, integration of the schedule into Netline shows that the current number of 767-300's cannot handle the required set of flights whenever there was large maintenance planned. As such, the alternative flight plan is set to be implemented per February 2012 when the fleet will be strengthened with an extra Boeing 767.

In conclusion, an alternative flight schedule including all retiming solutions is made and simulated to show that the aggregated expected delay severity computed has decreased from 192 to 157. From the top 30 most critical flights, 15 have a decreased expected delay severity.

Verification and Validation

The purpose of the verification and validation process is to ensure that the simulation fully comprehends the problem; credible and accurate simulation results are made; and sufficient confidence is created by Kenya Airways as to accept the recommendations.

The first possible error, occurs if the wrong problem is solved, or if the simulation does not fully comprehend the problem. This has been overcome by a proper feasibility study towards the drivers of on-time departure performance prior to the start of the research project Schellekens (2011). Furthermore, the model's assumptions have been made in agreement with key decision makers at Kenya Airways.

The second error, occurs when invalid simulation results are accepted as if they are sufficiently valid. To ensure valid simulation results involvement of the department of Network Planning has been intense throughout the development of the simulation. Furthermore, the flight severity simulation has been validated with empirical data. Five examples are discussed in this chapter to validate several aspects of the simulation. The conclusion is that the simulation is sufficiently valid as the historical delay severity points coincide with the simulation of historical flight schedules.

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[9] Confidence is defined as the historical probability the the Actual process will be completed within the Scheduled Time.

The third error might be that the simulation results are rejected, while it is found that they are sufficiently credible. This has been overcome by sufficient involvement with the key decision maker's in this academic project. The presentation in the Operational Leadership Team meeting, chaired by Bram Steller (Chief Operational Officer), ensured that an implementation time line for the alternative flight timing to Lagos (LOS) could be decided upon.

In conclusion, it can be said that there is sufficient confidence in the quality of the model within the range of the intended use.

Conclusions

The nature of this research project allows to discuss the main conclusions for Kenya Airways and academia separately.

Two deliverables have been presented to Kenya Airways, being the Block-time analysis module and the stochastic simulation of delay propagation.

- The first deliverable is a Block-time analysis module which has been developed to support the proposed methodology to improve schedule stability by giving insight into Block-time confidence. Per august 2011 it has been implemented as a separate tool that enables the department of Network Planning to advice on changes and allow to monitor variances in Actual Block-times. Using this Block-time analysis tool the department of Network Planning have already advised on Scheduled Block-times improvement for 27 flights which have been implemented per September 2011.
- The second deliverable to Kenya Airways and the final product of this thesis is the stochastic simulation of delay propagation which is currently in a phase of conceptual design. As such, it served a fundamental purpose as to deepening the understanding of the stochastic nature of delay propagation. Being an accurate and validated tool, implementation into a schedule design tool is advised and requires further development in connecting actual passenger booking (Delorean) and flight performance (Sabre Flight Movement Control).

  The current research on stochastic simulation of delay propagation has been shown to work and able to create simulations of scenarios to assess schedule stability prior to the day of operations. An alternative flight timing has been created for the critical rotation to Lagos (LOS) using a methodology that uses the stochastic simulation of delay propagation to improve schedule stability. The implementation time line set is per February 2012 due to previously discussed restrictions on aircraft.

There are four main contributions for the academia. A comparative metric for flight and schedule robustness has been made that can be simulated using a stochastic simulation that integrates passenger connectivity. The accuracy of the simulation results has been proven through a validation with empirical data.

- It is shown to be feasible to simulate delay propagation in a delay propagation model. This research showed that incorporating passenger connectivity results in a more accurate representation of the true delay propagation in the hub-and-spoke passenger network of Kenya Airways.

- The simulation has been extended to include stochastic parameters for the Block-time, Turnaround-time and Passenger Connecting-Time to deliver more accurate insight into the behavior of delay propagation.
- The stochastic simulation of delay propagation is validated using empirical data. The flight oriented model has been validated with empirical data showing the relevance of simulation delay propagation through aircraft and passengers.
- The research has been done proposing a comparative metric for flight robustness and schedule stability. This academic research simulated the expected delay severity for alternative flight timings and concludes that this is a useful and validated metric to quantify the impact on a schedule re-timing decision.

In conclusion, a pro-active approach using the stochastic simulation of delay propagation proposed can control system impact of unavoidable disruptions and improve overall punctuality. The strength of the proposed methodology is that it works alongside the Netline Schedules System and, hence, allows for the incorporation of soft issues into the schedule design whilst considering schedule stability. The strength of the solution is that it can determine the impact of retiming decisions on schedule robustness if you deviate from the 'ideal' plan. An environment can be created where less ad hoc delay mitigation management is needed, and more focus can be placed on operational excellence.

Preface

This research project has been a steep learning curve for myself. I therefore wish to thank all who helped me in the process for their support. At Kenya Airways I was warmly welcomed in the Network Planning department. I would like to thank my daily supervisors Beatrice, Sammy, Doreen, Maxine, and all others who helped throughout the research.

Writing the thesis itself has been a great challenge. My thanks go out to all who were willing to read through: they pushed me to continuously challenge my own writing and structure.

A special thanks goes for the graduation committee of this thesis, for their inspiration to push my research to a next level. Furthermore I wish to dedicate a special credit to Paul Roling who has been willing to strengthen the graduation committee as an external auditor.

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Graduation committee

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Glossary

Absorption robustness The robust planning objective that aims to schedule flights with enough margin to absorb the anticipated nuisance delays.

ABT Actual Block Time, difference between the ATA$_i$ and ATD$_i$.

ACARS Aircraft Communications Addressing and Reporting System. A message transmission system between aircraft and ground stations.

ACT Actual Connection Time, the connection time for transfer passengers realized between two flights as the difference between the ATD$_k$ - ATA$_i$.

Aircraft type Division of the aricraft in sub fleets where flights can be interchanged.

ATA Actual Time of Arrival, aircraft arrival into the bay (chocks on).

ATD Actual Time of Departure, aircraft departure out of the bay (chocks off).

ATT Actual Turnaround Time, between the ATA and the ATD.

Avoidable delay Delay caused by internal activities, which could have been avoided by specific actions or organizational influences.

Block-Time The time between departure of the aircraft from the bay (chocks off) and arrival into the bay (chocks on).

Circular Flight A flight sharing a flight number with two non-hub destionations. For example, flight 886 to Guanghzou (CAN) with a lay-over stop in Bangkok (BKK).

Citypair The origin and destination of a flight leg.

Commercially accepted delay Delay that is inherent to the operational setup of Kenya Airways.

Crew Group of flight crew and cabin crew required to operate a scheduled passenger flight.

Degradable robustness The robust planning objective where a schedule is broken down into independent layers that isolate disruptions from being propagated throughout the network.

Delay Departure delay of the aircraft out of the bay, difference between the ATD and the STD.

Delay propagation tree The visualization of the delay propagation in a time line network representation.

Delay severity The number of delayed flights due to the primary delay.

Delay severity curve The graph that plots the duration of the primary delay versus the delay severity.

Delorean A KLM passenger booking analysis tool used by Kenya Airways.

Disruption An operational conflict that could result in a flight delay if there is insufficient slack planned.

Flexibility robustness A method to create flight rotation patterns with sufficient overlap in a point-to-point based network. On points of overlap, tails can switch flight rotations to minimize delay propagation.

Flight A flight consists of a flight number and one or more flight legs.

Flight leg The event between departure out of the bay and arrival into the bay.

Flight number Flight Number in an IATA format starts with the Airline Code followed by a four digit numeric code.

Flight robustness Scheduling a flight with the objective to decrease additional operations costs, ease the recovery or isolate delays from moving downstream to subsequent flights.

Flight rotation The combination of flights flown by one aircraft to depart from the hub (Nairobi) and return back. Example is the flight KQ0532 to Lagos (LOS), and back on KQ0533. Circular flights are also considered flight rotations.

Flight schedule A set of planned flights.

IATA International Air Transport Association.

IOCC The Integrated Operations Control Center of Kenya Airways, coordinating network wide the operations on the day of operations.

JKIA Jomo Kenyatta International Airport. The hub airport of Kenya Airways in Nairobi (NBO).

KLM Koninklijke Luchtvaart Maatschappij, Royal Dutch Airlines.

KQ The IATA airline code of Kenya Airways, used as an acronym for Kenya Airways throughout the paper.

MCT Minimum Connecting Time, the minimum required time to connect the passengers and their bags between flights.

MTT Minimum Turnaround-Time, the minimum amount of time required to perform all turnaround processes.

Netline Netline Sched, a Lufthansa schedule management system used by Kenya Airways for optimizing flight schedules on tail rotations and utlization.

Network Planning department The department responsible for the airline strategy, network design and flight schedule.

Nuisance delays Kenya Airways' defined term to describe departure delays that are less then 20 minutes.

O & D Origin and Destination. Refers to the flight plan of the passenger booking as the initial origin and the final destination.

OTP On-time Departure Performance, percentage of flights that departed within a set time margin from their Scheduled Departure Time (STD).

PCT Programmed Connecting Time, the planned passenger transfer time between two flights. Formalized as STD$_k$ - STA$_i$.

Primary delay Delay that directly occurred because of an operational disruption.

Reactionary delay A knock-on delay that occurs due to a primary delay.

Revenue Management department The department responsible for the capacity planning and pricing strategy to maximize revenue.

Robustness See flight robustness.

Sabre Sabre Movement Control Flight Following System containing historic flight performance data.

SBT Scheduled Block Time, difference between the STA$_i$ and STD$_i$.

Schedule stability The goal of robust flight schedule planning. To create a flight schedule with high probability of operating as planned.

Simulation cycle One cycle of a simulation resulting in one outcome.

Simulation run One set of simulation cycles, a collection of outcomes.

STA Scheduled Time of Arrival, planned aircraft arrival into the bay (chocks on).

Stability See schedule stability.

STD Scheduled Time of Departure, planned aircraft departure out of the bay (chocks off).

STT Scheduled Turn Time, the planned ground time of the aircraft between flights as the STD$_{i+1}$ - STA$_i$.

Turnaround The ground processes of the aircraft between the arrival into the bay and the departure from the bay.

UML Unified Modeling Langage.

Unavoidable delay Delay caused by external factors. As such these are more difficult to control by internal measures.

UTC Universal Coordinated Time (UTC), IATA standard to indicate flight times.

1. Introduction

The main challenge for passenger airlines is the design of a profitable flight schedule. A hub-and-spoke network gains from collecting and re-distributing large amounts of passengers through it's hub. The size of airlines have steadily increased to benefit from economies of scale and so has the complexity (Wu, 2010). The Network Planning conundrum is that revenue and costs are made and incurred sequentially. The revenue is collected prior to the day of operations. However, it is only during the day of operations that costs are made and the profitability of the schedule can be measured. Costs associated to delays are subject to the execution of the operations. To decrease these variable costs, operational robustness has to be gauged during the network planning phase. Using operational performance data as a feedback to design schedules is becoming quintessential.

Kenya Airways operates a highly connected hub-and-spoke network. Its strategy pivots around intra-Africa traffic and connecting African traders to and from the Middle East and Asia, for which it's hub in Nairobi forms a geographical competitive advantage. For the financial year 2010-2011 they carried over 3 million passengers, of which 47% of the passengers are transferred in Nairobi. Kenya Airways, furthermore, is a fast growing African airline; On october 18, 2011, they launched it's 56th destination to Jeddah, up from 33 destinations in just 5 years time.

The current challenges for Kenya Airways lies increasing it's current fleet of 32 aircraft and expanding it's schedule in a sustainable and punctual way. With only 9 wide body aircraft and a delayed order of 787 Dreamliners, more pressure will come to feeding and de-feeding it's long-haul flights in an already congested hub airport. The tightness of Kenya Airways' schedule translates in a in-stable schedule where delays cascade through the network like the toppling of dominoes. Of all delays at Kenya Airways, 51%[1] are reactionary delays[2]. This is higher than the 46% as experienced in the mature European airline industry (EuroControl, 2010).

In line with Kenya Airways' growth strategy, the question arises how it's flight schedule can be adapted to increase potential punctuality by studying how reactionary delays occur in a hub-and-spoke network. This led to the research of robust scheduling, to investigate what can be done to improve the flight schedule as to make Kenya Airways more resilient against disruptions.

During the last decade, more academic work has been focused on planning for uncertain operations by making schedules more stable or robust, which means that schedules are less sensitive to delays (Clausen et al., 2010). It is in this field that a tension has build up between a static and deterministic planning mentality and the real world being dynamic and stochastic[3] (Cohn and Lapp, 2010). This has

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[1] The period of study is set between September 2010 and September 2011 due to the data integrity of Sabre Movement Control Flight Following System as explained in Appendix B.

[2] Reactionary delays are knock-on delays that occurs due to a primary disruption on a preceding flight.

[3] Stochastic refers to systems behaving in a pattern that may be analyzed statistically but may not be predicted deterministically.

influenced the current state of robust scheduling, and reveals the potentials.

First off, airline operations are stochastic, both when the delays occur (Arikan et al., 2010) and the variability of how these delays are absorbed by the network (Mueller and Chatterji, 2002). However, current research focuses on optimizing flight schedules (AhmadBeygi, 2008; Weide, 2009; Burke et al., 2010; Duck et al., 2011) by a deterministic analysis of how a delay could propagate through the network with delay propagation trees[4]. Mueller and Chatterji (2002) did an initial analysis on a stochastic approach to study delay propagation and discussed how deterministic approaches overestimate the amount of delays propagated through the network. Nevertheless, the model of Mueller and Chatterji (2002) uses publicly available data which only incorporates stochastic flight times. This thesis is done in collaboration with Kenya Airways for in depth airline operational data to also allow for a stochastic estimation of the Minimum Turnaround-times and the Passenger Connection-times. As such, more closely estimating the true propagation of a delay through a flight schedule.

The second aspect is that schedules are dynamic, as implemented flight schedules are often far from the optimized seasonal flight schedule[5]. This makes sense, as the requirements for each week are different due to for example large maintenance; charter flights; or additional ad-hoc flights due to demand[6]. As such, schedule planners can benefit from research on decision support tools that gauge effects of flight retiming decisions on schedule stability, an inevitable precedence to operational profitability, when deviating from the original optimized plan. Following this line of thought, this thesis sets out to develop a methodology that uses the more realistic stochastic delay propagation simulation to analyze and improve critical flights within the operated schedule. This, with the aim of being able to gauge the impact of an alternative flight timing on schedule stability and the commercial impact of passenger connectivity.

Central in this thesis is the development of a stochastic simulation to model the propagation of delays through the flight schedule. The analogy that can be made is the toppling of dominoes, where the fall of the first domino illustrates the primary delay caused. What this research sets out to do is find out how many dominoes will be toppled over, i.e. subsequent flights are delayed due to that flight being delayed. Furthermore, a relationship is sought and found where the force of the first domino falling, i.e. duration of the delay, is related to the number of dominoes it will topple over, i.e. the severity of the delay.

The paper is outlined in figure 1.1. First this academic research is placed into an industry and academic framework. Within the framework, a research goal and setup is discussed, chapter 3. Next, the development of a conceptual model of how delays propagate through the flight schedule of Kenya Airways. Chapter 5 describes the specification of the conceptual model into a computerized simulation that is subsequently ready for validation and experimentation. Finally, the application of the simulation on improving overall schedule stability is discussed.

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[4] Delay propagation trees are a method of visualization of delay propagation in a time line network representation.

[5] This conventional wisdom is found when working together with schedule planners, but is referred to quite limited in the literature. The only reference found is Cohn and Lapp (2010).

[6] As an example, on 9 July 2011 South Sudan became an independent state and Kenya Airways catered for the extra circumstantial demand in flight capacity by operating larger equipment and launching a double-daily frequency.

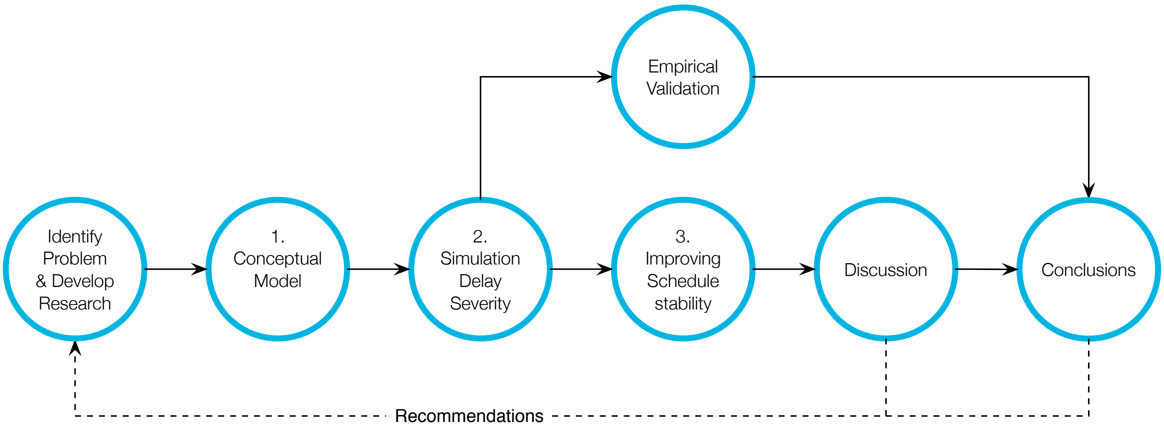

Figure 1.1. ***Paper outline.*** *The conceptualization of the research work flow.*

2. Research Framework

The purpose of this chapter is to place the research into an industry and academic framework. The relationship between this chapter and the thesis is shown in figure 2.1.

The first section introduces the perspective of Kenya Airways (KQ) towards stability of flight schedule. The second section discusses the academic framework in which the research is placed, and what academic niche it fulfills.

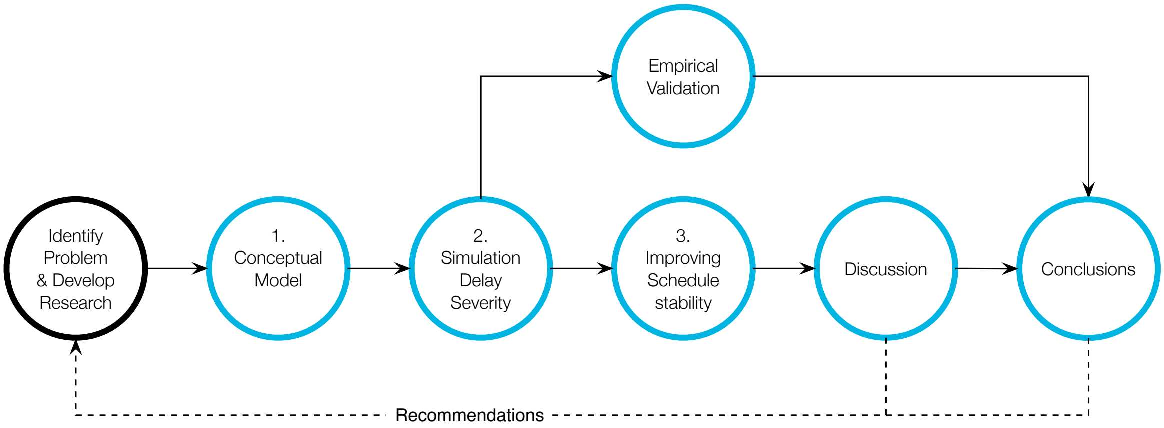

Figure 2.1. Placing the research problem into a framework. The first step of the research is to place the identified problem into an industry framework and an academic framework .

2.1 Kenya Airways' drive for Punctuality

This section describes the initial study on drivers towards On-Time departure Performance (OTP). This is defined as the percentage of flights that depart within a set margin, either 0 minutes or 15 minute (IATA, 2007). After that, the potential to focus on reducing impact of commercially accepted delays and unavoidable delays through robust scheduling is discussed. The conclusion is that there is a potential for research on how to broaden the focus of the Network Planning department, a focus on decreasing reactionary delays.

To start off, a brief description of the delay causes. Primary delays are due to disruptions occurring during the Turnaround or Block-time, a breakdown of causes is given in section 2.1.3. Reactionary delays are flights that depart later than scheduled due to a previous flight arriving late. The originating delayed flight delays either the aircraft, passenger or crew to be on-time for the next flight to depart.

2.1.1 Airline Profitability requires a focus on punctuality

Airline profitability is driven by maximization of revenue and minimization of cost. However, when expanding this equation it can be seen that a broadening of focus towards punctuality is needed to understand the drivers behind airline profitability.

The airport profitability equation of Belobaba et al. (2009, ch 3.1.1) can be expanded with the operations performance concept of Enk (2010) to the current concept that is shown in figure 2.2. Both revenue maximization and cost reduction will be further explained.

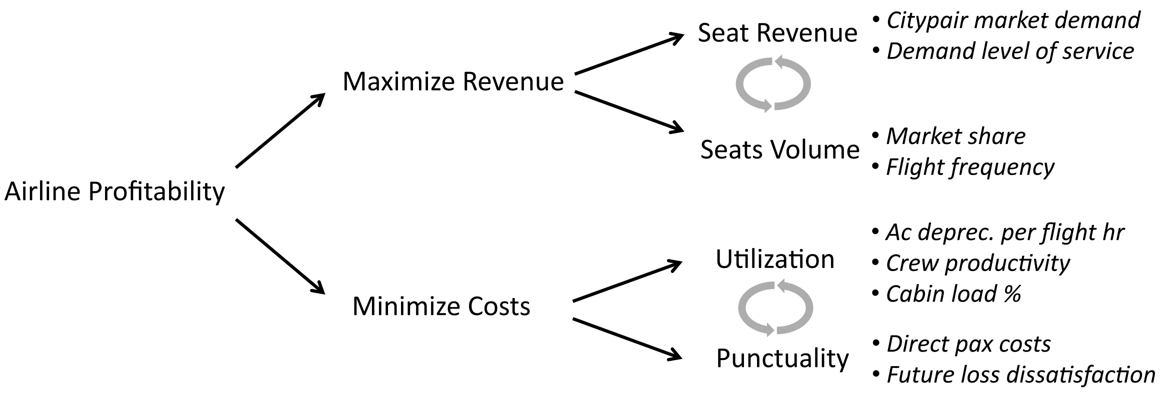

Figure 2.2. The airline profitability equation. Conceptualizing the key drivers of airline profitability as the maximization of revenue and minimization of costs. Each are a balancing act of own drivers. (Adapted and extended from Belobaba et al., 2009; Enk, 2010)

Maximizing revenue is balancing revenue per seat and number of sold seats. For the scope of this literature review this topic is not discussed in detail but for a more in depth understanding, refer to McGill and Van Ryzin (1999), Bertsimas and de Boer (2005) or Pak and Piersma (2010).

Revenue is driven by the market demand of an origin and destination pair and the market share of the airline. The frequency of flight and seat price on the origin and destination city pair drives the number of seats sold. This is considered a price competition on a route basis, described as a Cournot economy by Smit and Trigeorgis (2004). The implication of this is that the market share on competitive routes with comparable products is inversely related to the revenue per seat. Products are generally considered comparable if the total trip time is similar. For example, the trips by Ethiopian and Kenya Airways from Lagos to Dubai are similar as they both incur a stop at a hub. On this origin and destination pair, Emirates has a superior product as it offers a direct flight.

Operational costs are decreased by balancing utilization and punctuality.

Higher airline punctuality decreases passenger costs with respect to delay. As the research conducted by EuroControl (2011) describes, passengers delay costs come in hard and soft forms. Hard costs include passenger rebooking, compensation and care costs. In Europe these are regulated on a european level (EU, 2004). Soft costs include the passenger value of time and the dissatisfaction that can cause them not to return to the airline. Another soft costs that cannot be quantified is that passengers might not choose an airline for travel, even with no prior experience, due to the general unpunctual perception of that airline.

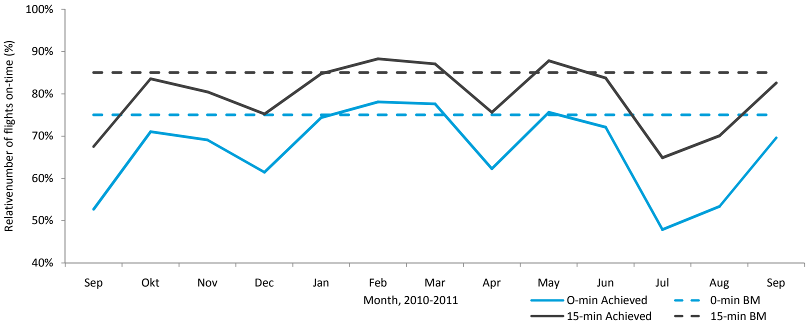

Figure 2.3. Monthly on-time Departure Performance. *Historical analysis of monthly on-time departure performance realization. (Source: Analysis of Flight Movement Control data of Kenya Airways between September 2010 and September 2011)*

Utilization is inversely related to the slack-time for the resources (aircraft, cabin- and cockpit-crew) between flights. Aircraft utilization is traditionally the main key performance benchmark for departments of Network Planning. Optimization for utilization is done in each step of the planning phase. The first optimization is during the fleet planning, where the Network Planning department optimizes for a minimum required number of aircraft. The second optimization is during the schedule roll out, where Revenue Management department focuses on the maximization of expected cabin load factors. (Bazargan, 2010).

2.1.2 Kenya Airway's focus on punctuality

The direct passenger delay costs [1] at Kenya Airways drive the operational focus to increase the on-time departure performance. Direct passenger delay costs in the financial year 2010-2011 amounted to 708 million KS (5.6 million €), or 13.1 % of the net profit. Passenger delay costs consists of passenger delay compensation, hotel accommodation, food and drinks.

KQ sets an operational target to reach 85% within 15-min on-time departure performance. To reach this, a 0-min benchmark of 75% is set for the financial year 2010-2011 out of the consideration that the 0-min departure performance drives the 15-min departure performance.

This statement is made and can be backed by a correlation analysis for the period September 2010 to September 2011[2]. The statistical correlation analysis shown in figure 2.4 found the correlation between the 0-min and 15-min departure performance to be high, 0.99. This indicates a strong relationship. As such it can be concluded that an operational focus on the 0-min will improve the 15-min on-time departure performance.

A further analysis on daily 0-min departure performance shows a high variability [3], thus indicating the potential to improve punctuality. Figure 2.4 provides an analysis between September 2010 and September 2011 with the number of days that a certain 0-min departure performance was met. The variability is high, with no days of a 0-min departure performance of over 95%. Furthermore, the yearly average is 61.1%, lower than the KQ's internal target of 75% 0-min benchmark.

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[1] Kenya Airways considers direct passenger delay costs, EuroControl (2011) shows total delay costs to be far higher

[2] This period is chosen due to the data validity, and is explained in more detail in Appendix B.1

[3] Variability indicates that there is no consistent performance, implicating that the OTP is often beneath benchmark.

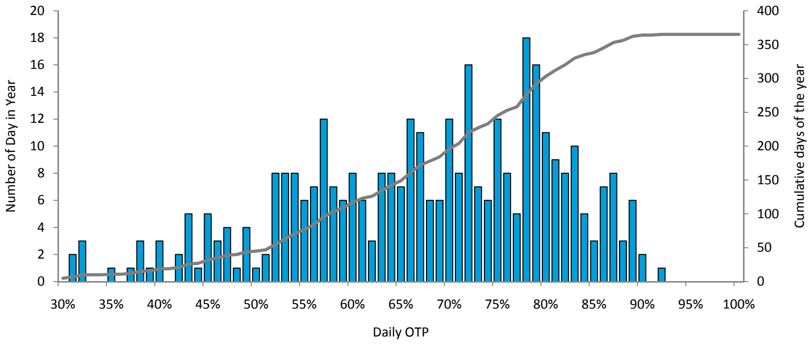

Figure 2.4. Realization of OTP. *The daily overall on-time departure performance is plotted on the x-axis versus the number of days that this was achieved. It is shown that the variability is high, which indicates a low schedule stability. (Source: Analysis of Flight Movement Control data of Kenya Airways between September 2010 till September 2011)*

2.1.3 Delay breakdown shows a high impact of reactionary delays

From a delay analysis at Kenya Airways, it was found the largest share of delays was reactionary. Furthermore, from a statistical correlation analysis it is seen that reactionary delays are a stronger driver behind on-time departure performance than the primary delays. As such it is concluded that there is a large potential to target and minimize reactionary delays to increase overall airline punctuality at Kenya Airways.

Delays are documented by the Integrated Operations Control Center (IOCC) into a flight movement control module from Sabre. Over thirty thousand delays have been analyzed for the period between September 2010 to september 2011. The import, processing of this data is explained in Appendix B.1. From this analysis it is found that 49% of the delays are considered primary and 51% reactionary delays.

A previous study towards the drivers behind on-time departure performance by Schellekens (2011) discussed the causes of primary delays and reactionary delays.

Primary delays are attributed to root disruptions. These mostly occur during the ground time of the aircraft. The main cause of primary delays are due to the turn-around process[4], around 28% of the delays. Further causes are due to the technical state of the aircraft, mostly attributed to equipment failure or overdue aircraft deferrable defects. Airport or air-traffic control delays are also considered when the airport movement is restricted or there is a lack of bays. A last primary disruption is weather related, mainly caused by intense rainfall in Nairobi or snowfall in Europe.

Reactionary delays are caused as a result of primary delays. There are three reasons for a reactionary delays:

Aircraft The main cause, in 40% of the delays, the aircraft does not arrive on time for the flight due to a previous delay.

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[4] All processes occurring on and around the aircraft between the arrival into the bay and the departure from the bay

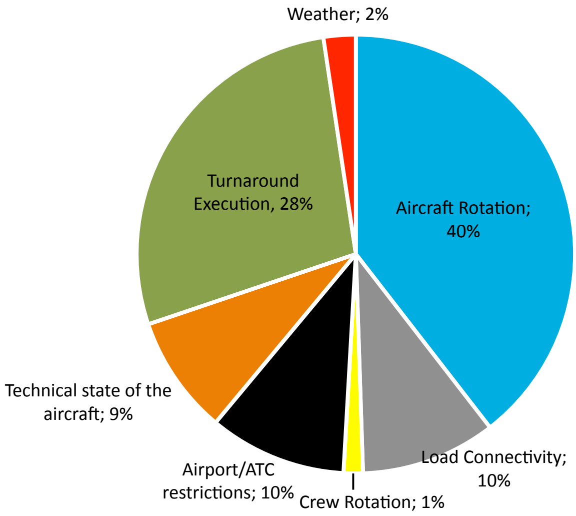

Figure 2.5. Delay Breakdown. *A breakdown of all disruptions. (Source: Analysis of Flight Movement Control data of Kenya Airways between September 2010 to September 2011)*

Passengers The nature of a hub and spoke network is the redistribution of passengers at the hub. As such, the second cause for reactionary delays is a deliberate wait for a flight to connect passengers from a delayed flight.

Crew At KQ, crew schedules are planned such to follow aircraft. However, on a minority of the domestic flights the crew can transfer between aircraft tails. If the previous flight has been delayed, this could cause a reactionary delay.

At KQ, 51% of the delays are reactionary. This is higher than the European benchmark discussed by EuroControl (2010). In Europe, the share of reactionary delays has continuously increased from 37% in 2003 to 46% in 2010. The main causes described is an increasing congested airspace that decreases the system's ability to absorb disruptions.

A statistical correlation analysis for the case of KQ shows that the daily on-time departure performance is more affected by the number of reactionary delays. Figure 2.6 plots the daily on-time departure performance and the number of delays per type for all days between September 2010 and June 2011. This results in a correlation of -0.77 between the number of primary delays and on-time departure performance. Reactionary delays were correlated stronger, -0.93. This indicates that reactionary delays are a stronger driver behind on-time departure performance than the primary delays.

2.1.4 Focus on schedule stability reduces reactionary delays

Operationally, there is a focus on on-time departure performance, but progress is hampered due to the large impact of reactionary delays after unavoidable disruptions occur. This phenomenon is conceptualized after a categorization of the disruptions.

Disruptions can be categorized along two measures, level of avoidance[5] and impact to operations(Wu, 2010). This categorization is required for the understanding of effectiveness of improvement

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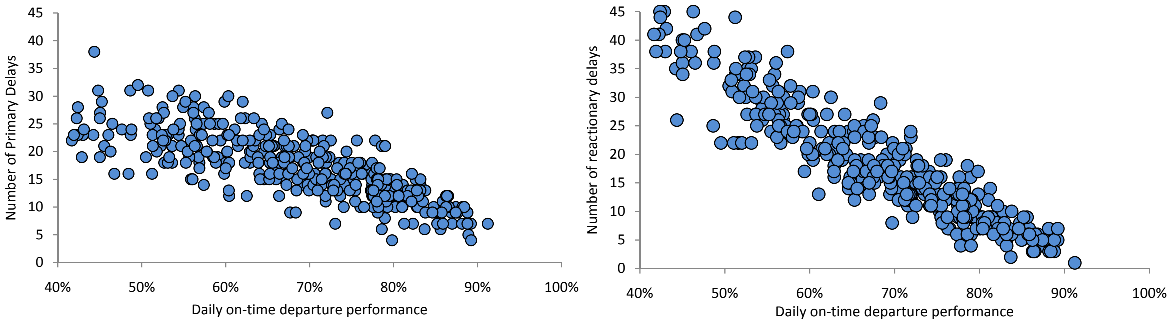
[5] The level of avoidance is determined according to internal KQ standards



(a) Primary Delays, $\rho = -0.77$

(b) Reactionary Delays, $\rho = -0.93$

Figure 2.6. Correlation OTP against delays. *Correlation scatter plots of daily on-time departure performance and Primary (2.6a) or Reactionary (2.6b) delays. Following this statistical correlation analysis it can be seen that reactionary delays correlate stronger with the daily on-time performance. (Source: Analysis of Flight Movement Control data of Kenya Airways between September 2010 and September 2011)*

measures. Examples of disruptions filed in this categorization is shown in figure 2.7a.

Disruptions are rated according to their level of avoidance in three categories. The first catagory is avoidable delays. These are caused by internal activities, which could have been avoided by specific actions or organizational influences. Examples could include the wrongful filing of flight plans.

The second category is the unavoidable delays which are caused by external factors. Which are more difficult to control by internal measures. One such example is a airport closure due to failure of airport backup generators for runway lights.

A third category falls between avoidable and unavoidable, considered as the commercially accepted disruptions. These disruptions fall into a separate category as they are inherent to the operational setup of Kenya Airways. For example, the delays caused by passengers[6] that could have been avoided through disallowing passengers on flights of Kenya Airways. However, the conscious decision has been made to pursue a passenger airline business model, and as such these disruptions occur.

The second measure considered in the categorization is the level of impact (Wu, 2010). Nuisance delays are considered to have a smaller impact, both in duration and severity. At Kenya Airways, nuisance delays are considered to have a duration of 20 minutes or less. Severity is defined by AhmadBeygi et al. (2008) as the number of affected flights due to the disruptions. For systemic disruptions the number of affected flights is high, both in delays as well as cancellations.

The understanding of categorizing disruptions according to the level of avoidance and impact allows for the allocation of improvement measures. Figure 2.7b shows the three main areas and the effectiveness towards types of disruption.

Avoidable delays are caused by internal activities, and require focusing on improvements in operations or organization to decrease the probability of occurrence.The author's initial research (Schellekens, 2011) concludes with a set of opportunities to increase operational integrity. Examples include measuring clearly defined Performance Indicators in a operational dashboard; a translation to departmental reliability benchmarks; and a research towards tail assignment to aim for operational stability.

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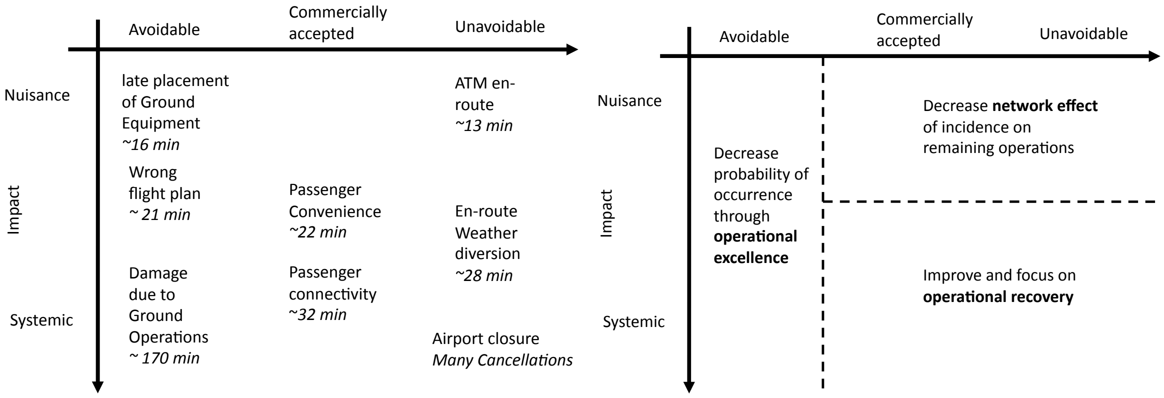
[6] To illustrate, these delays are caused by irregular passenger behavior such as sickness or drunkenness.



(a) Examples **(b)** Improvement target areas

Figure 2.7. Concepts to reduce the impact disruptions. Disruptions can be categorized according to level of impact and avoid-ability. Left indicates examples as to how these can be categorized. Right shows the target that is specific to each proposed solution. (Model extended from Wu (2010))

Reducing the impact of commercially accepted or unavoidable disruptions is targeted by a focus on the schedule design and operational recovery, as can be read from figure 2.7b. The difference between a focus on operational recovery and improved robust schedule design lies in the level of impact. As Sodi (2011) describes, a pro-active attitude in the design of the schedule targets the impact of disruptions that occur frequently and with lower impact. This is achieved by focussing on the network effect[7] of an incident, considered as the schedule stability. This forms the basis for the focus of this thesis from an industry perspective.

Ensuring for inherent robustness against the less frequent and systemic disruptions is a waste of resources. This is because the required system slack or other robustness measures outweigh the cost of the resource. Instead, a focus on the recovery of the operations is seen to be more effective.

A further analysis on the duration of delays shows a high level of nuisance delays, which are delays of a duration of twenty minutes or less. Shown in figure 2.8, 58% of the primary delays are found to span 20 minutes or less. As supposed to primary delays, only 40% of the Reactionary delays span 20 minutes or less. This shows that the potential gains to reduce the schedule impact of primary delays are large.

In conclusion, it is seen that there is an opportunity to decrease the network effect of commercially accepted or unavoidable nuisance delays. From an industry perspective, this is where the focus of this thesis lies.

2.1.5 Schedule stability requires a broadening of focus of Network Planning

The airline schedule planning is a multi-tier process, explained in this section for Kenya airways.

For an overview of the airline schedule planning process refer to Bazargan (2010), Cohn and Lapp (2010), Wu (2010) and Barnhart et al. (2003). For a Kenya Airways specific description refer to Enk (2010).

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[7] The network effect is considered the possibility of a reactionary delay, as well as the number of reactionary delays following a disruption.

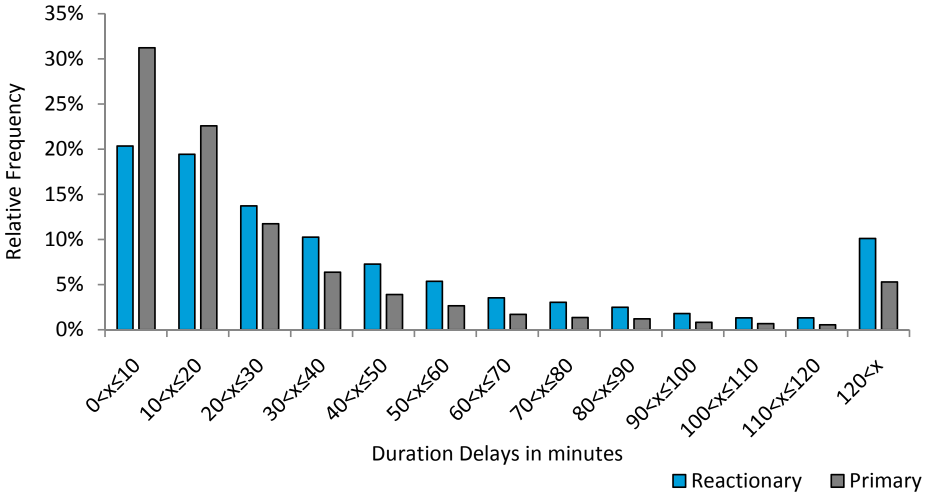

Figure 2.8. ***Historical delay duration.*** *Duration histogram of delays showing the duration impact of both primary and reactionary delays. (Source: Analysis of Flight Movement Control data of Kenya Airways between September 2010 and September 2011)*

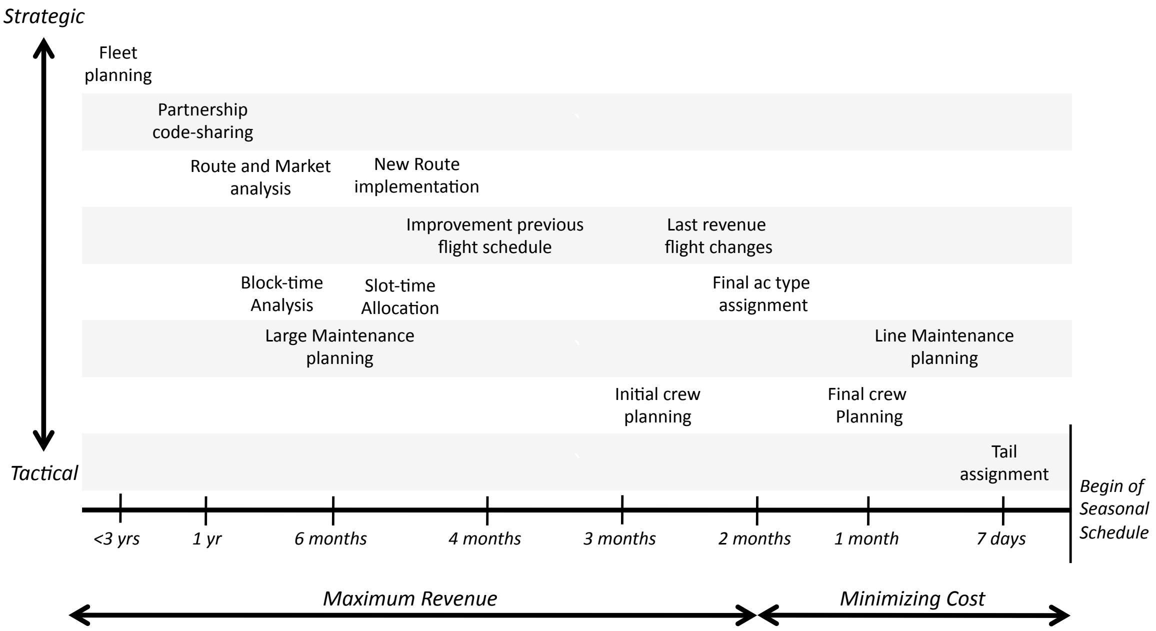

Figure 2.9. ***Schedule rollout timeline.*** *Gathered from interviews and from (Enk, 2010; Clausen et al., 2010; Wu, 2010), the optimization drivers of each Network Planning event can be related to the required time of execution.*

Adapted from interviews and Enk (2010); Clausen et al. (2010); Wu (2010), a generalized timeline of how the roll-out of a seasonal schedule at Kenya Airways should be is shown in figure 2.9. The main processes include fleet planning, strategic route selection, flight planning, crew planning, and ends with the maintenance planning and tail assignment.

Figure 2.9 shows if a sub process either pursues maximization of revenue or minimization of costs. The division is along the timeline. Long-term processes are driven by maximizing revenue, through a maximization of utilization. Short-term processes are generally driven by minimizing costs.

In conclusion to the previous discussion, there is an opportunity to consider punctuality and costs during earlier stages of the schedule roll-out. However, it is acknowledged that the design of the schedule does include soft drivers making it difficult for a clear optimization objective to be formulated. Soft drivers can include the qualitative value of a departure during the morning wave, the de-feeder flight connectivity and the value of the aircraft type flown (irrespective of demand driven).

As a final remark, a focus on costs during earlier phases of the schedule rollout will allow for greater flexibility in cost decisions on the day of operations. Stolz (2004) shows that the variability in options decrease towards the day of operations. This means that choices in the design of the schedule influence the choices that remain on the day of operations. For example, the choice to develop a large inbound bank decreases the number of reserve bays that one can use in case of irregular operations.

The result of this investigation shows that there is a potential for the Department of Network Planning to broaden the focus on schedule stability. This could be realized by a pro-active plan towards decreasing the network effect of nuisance delays, that form the majority of all the delays.

2.2 Literature review on robust scheduling

This section introduces relevant research on disruption management and the pro-active counterpart, robust schedule planning. The aim of this section is to place this research into an academic framework, and identify research possibilities. For an overview of airline operations and planning refer to Belobaba et al. (2009).

First the general concepts behind disruption management is discussed, followed by an overview of earlier work on robust schedule planning. Thereafter the main schedule simulation methods are described. This section concludes with the academic niche to research robust scheduling through the simulation of delay curves.

2.2.1 Disruption recovery

Even though the purpose of this academic work is not disruption recovery, the initial works on disruption recovery has led to robust planning. It is therefore necessary to briefly describe disruption recovery. For an overview of methods and industry outlooks refer to Yu and Qi (2004),Kohl et al. (2007),Artigues et al. (2010) or Clausen et al. (2010).

The importance of schedule optimization grew with the increased competition due to the United States airline Deregulation Act of 1978 (Kohl et al., 2007). With airlines more focused on increasing resource utilization, problems with flight disturbances increased. This led to a growing importance of punctuality. Early work on optimization techniques after disruptions has led from this period, for example Teodorovic and Guberinic (1984). A review of practices used in today's disruption recovery methods is described by Clarke (1998).

The creation of the Integrated Operations Control Center (IOCC) at KQ has led to sensitizing staff on on-time departure performance and stimulated an attitude towards avoiding delays. The IOCC coordinates network wide KQ operations on the day of operations, with the aim of minimizing the effects of disruptions on punctuality and operational costs.

2.2.2 Robust schedule planning

The emergence of disruption recovery management leads to the evolution towards its pro-active counterpart, Robust schedule planning to increase the stability of the schedule, called schedule stability. When aiming for flight specific robustness the term used is flight robustness. The general concept is explained by Lan (2003) as to decrease additional operations costs, ease the recovery and/or isolate delays from moving downstream to subsequent flights. This is achieved through planning for uncertain operations with dynamic network parameters.

Beatty et al. (1999) introduced the concept of propagating delays in a flight schedule. A delay multiplier was defined as the relative amount of propagated delay in the system due to a primary disruption. A relationship arose between the length of initial delay, the time of day of the delay occurrences and airline schedule connectivity for American Airlines considering crew and aircraft.

AhmadBeygi et al. (2008) studied delay propagation in a passenger airline flight schedules. He introduces the concept of delay severity as the number of flights affected downstream by a primary delay. This allowed for studying robustness on a schedule level. However, one of the limitations of his approach was to study a hub-and-spoke network without the consideration of passenger connections, which is an essential aspect of a hub-and-spoke network.

Robust stochastic optimization was first introduced in other fields such as the steel-plate industry (Watanabe and Ellis, 1993; Clausen et al., 2001; Duck et al., 2009). The main idea behind robust stochastic optimization is to recognize that different scenarios might occur. Historical performance data is used to create scenarios, finding an optimal solution for each scenario. The robust optimal solution that follows is the most suited solution over the range of probability weighted scenarios. This development has lead to the introduction of the concept of robust scheduling in the airline industry, albeit adapted.

The general concept of a robust flight schedule, as is described by Lan (2003), is to decrease additional operational costs; ease the recovery; and/or isolate delays from moving downstream. This allowed research allowed for the introduction of three specific objectives of robust airline schedules in the flight planning stage:

- **Flexibility robustness**: Proposed by Ageeva and Clarke (2000) as a method to create flight rotation patterns with sufficient overlap in a point-to-point based network. On points of overlap, tails can switch flight rotations to minimize delay propagation. The design proxy is to ensure that the number of spare resources (aircraft and crew) and number of points of switching is high. Bian et al. (2003) introduces Number of Aircraft on Ground parameter. Large networks can become more robust once there are more interchangeable aircraft planned on the ground.
- **Degradable robustness**: Suggested by Kang and Clarke (2002) as the idea of a degradable airline schedule. The essence is that the schedule is broken down into independent layers that isolate disruptions from being propagated throughout the network and, as such, minimizing the

impact of a disruption to one sub network only. Main design goal is to schedule no connectivity between sub networks for aircraft, crew and passengers.

- **Absorption robustness**: Introduced by Scholl (2001), this is the objective that aims to schedule with enough margin to absorb the anticipated nuisance delays. Wang et al. (2003) proposes a method to estimate the required slack of a flight rotation based on historic route block-arounds and aircraft turntimes. Main design parameters are that block and ground time are scheduled with sufficient slack. However, it is the airline's goal to schedule enough margin, but not so much as to allow for airline resources to be wasted.

2.2.3 Modeling airline schedules for operational simulation

This section introduces the simulation tools required for modeling airline schedules, and forms the basis for robust schedule planning.

To model the effects of a robust schedule Abdelghany et al. (2004) introduced a flight schedule representation model. This model primarily focused on crew operations in a point-to-point network where crew and aircraft follow different rotations. However, it has the potential to be expanded for passenger connectivity. It was the basis for the following simulations experiments.

The first research projects used this schedule representation to simulate and optimize system slack-time to increase the schedule absorption robustness. Lapp et al. (2008) introduced a recursion-based simulation to model the propagating delay due to disruptions of shared resources (crew and aircraft) between independent flights. Cohn et al. (2008) used this simulation as cost function in their linearized optimization model to re-allocate the existing slack time to increase the absorption robustness of the network. However optimizing lines of flight for the re-allocation is slack time is questionable for hub and spoke networks due to the protection of passenger flight itineraries.

AhmadBeygi et al. (2008) studied delay propagation on a aircraft and crew level using a recursion-based simulation. The research innovates as it attempts to study the flight schedule in a wide perspective, understanding the bottleneck flights. However, in assessing the delay propagation a deterministic model is used.

Duck (2010) continued in his research to understand schedule stability by a recursion-based simulation to assess the delay impact of a set of disruptions. The drawback of his approach is that his model deterministically determines the reactionary delay impact of a disruption.

A second stream of research focuses on the use of stochastic discrete simulation as a tool to understand the operations of a flight schedule during major disruptions. The basis of discrete event simulation is Shannon (1975) showing how a formalized simulation can be used to study phenomena. Development of such models are described by Banks (1998) and Leemis and Park (2006). The basic approach is to model flights as events which are queued in a heap based on departure time. If a flight is delayed, consequences on the resources can be found and their subsequent flights must also be delayed or swapped. This method can also take into account the whole schedule, and therefore can also incorporate resource swaps.

Lee et al. (2004) discusses SimAir, a discrete event simulation to model and optimize aircraft recovery after a major disruption. Kohl et al. (2007) simulated overall airline operations during large scale disruptions and has incorporated a passenger recovery mechanism.

Further work on stochastic discrete simulation was done by Jacobs et al. (2006). The research project used, a Java based, Discrete Simulation Open Source Library (DSOL) to simulate a model of the KLM network to understand their the schedule robustness. The simulation included aircraft robustness only, and considered flexibility robustness by penalizing tail swaps.

Stochastic modeling for schedule robustness has been researched by Arikan et al. (2010) who incorporated variables Block-times. The research focused on expected on-time performance of programmed lines of flight. The research is limited to only aircraft rotations and fixates required turn-around time. However, the research shows that incorporating operational variability can generate a more reliable measure of robustness.

2.2.4 Research opportunity for robust scheduling with delay curve

Concluding the review of relevant literature, it is found that there is an academic niche to study robust flight planning for hub and spoke networks using delay severity curves including passenger connectivity. A delay severity curve is defined the relationship between the duration of the primary delay and the number of flight affected downstream. The concept is based on the notion of delay multipliers (Beatty et al., 1999) and delay severity (AhmadBeygi et al., 2008).

This leaves the opportunity open to study passenger-centric robust flight planning, which requires two main aspects;

First, the concept of stochastic delay severity curves as a unit of measurement for robustness should be analyzed. This measure is appropriate as it connects to the operational focus on on-time departure performance and allows to focus on a flight level. However, most models determine delay severity deterministically. A stochastic model can take the variability of the operations into account to estimate the network's ability to recover from a disruption more accurately.

Second, it is necessary to quantify delay propagation in a hub and spoke network where one considers the flow of transfer passenger. Even though the field of robust schedule planning has become active over the last decade, the majority of the research focused on robust crew and aircraft planning. Considering that 47%[8] of the passengers at Kenya Airways transfer at the hub in Nairobi, passenger flows are important to account for during the design of the flight schedule. Furthermore, as Lapp et al. (2008) mentioned, there is the possibility of extending the concept of propagation trees with passenger connections.

Concluding the literature review, it is suggested that there is a void in the research towards robust schedule planning with passenger connectivity in a hub and spoke network.

This concludes how this thesis fits in an industry and academic point of view, as to why this research is undertaken. The next chapter describes the research setup, and builds upon the basis formed in this chapter.

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[8] Figure found from analysis of the passenger flow data from Delorean for the financial year 2010-2011.

3. Research Setup

This chapter discusses the research setup by describing the research objective statement and the research methodology. The aim is to analyze schedule stability through simulation in a schedule design phase as this allows to improve punctuality. The basis of how the robustness of a flight schedule will lead to a higher airline punctuality has been discussed in the previous chapter.

3.1 Summary of the planning problem

Aiming for profitability requires an accurate projection of all costs during the planning phase. However, currently at Kenya Airways costs involving punctuality are not quantified. The consequence is that Kenya Airways tend to create flight schedules focusing on maximizing the utilization of resources. Yet, as Enk (2010) concluded, this focus will lead to higher sensitivity towards reactionary delays and, as such, additional operating costs.

The main challenge for optimizing flight schedules towards profit would be to holistically model the airline's operations to estimate expected revenue and costs in terms of revenue per seat, seats sold, utilization and punctuality for proposed schedules. This requires an extension of the current academic research towards integrating the stochastic nature of airline operations in the holistic model.

3.2 Scoping the project

Holistically modeling the airline's operations would allow the planning department to gain insight into the expected profit for a proposed schedule. For the aim of this research project these ambitions are formulated into a feasible objective.

A choice is made to narrow the scope of the research down to simulate the absorption robustness in terms of aircraft and passenger connectivity for a proposed schedule.

1. The objective of the research is to study absorption robustness.
2. Focus is put towards studying short single delays and their impact on passenger connectivity. This allows to simplify the disruption response strategy of the IOCC.
3. Current Kenya Airways' crew rosters are designed to follow aircraft[1], thus it suffices to only study aircraft and passenger connectivity throughout the flight schedule.

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[1] Crew schedules at KQ are planned such that during a shift they stay on one aircraft tail.

Ad. 1)The objective of the research is to study absorption robustness.

Schedule stability can be achieved through three robustness objectives, as is described in section 2.2, however it has been chosen to research absorption robustness. This is the objective that aims to schedule with enough margin to absorb the anticipated nuisance delays.

Flexibility robustness is not optimal for Kenya Airways due to two reasons. First, in a two-wave hub and spoke system, as Kenya Airways, a natural overlap point already exists where tails can be switched of flight rotation patterns if necessary. In addition, a lack of fleet uniformity[2] of Kenya Airways makes tail switches only possible with harmful upgrade or downgrades of aircraft types.

A second possibility is to focus on a degradable fleet robustness, but this is not opted for due to the highly dependent flight schedule. Due to a large number of transfer passengers, no clear subsystem of feeder flights and trunk flights can be made.

In conclusion, this research project will be to simulate absorption robustness to increase schedule stability.

Ad. 2) Focus is put towards studying short single delays and their impact on passenger connectivity, allowing to simplify the disruption response strategy of the IOCC.

The disruption propagation of major disruptions, such as full airport closures, depend on the success of the recovery response by the IOCC. Furthermore, absorption robustness solutions for these scenarios may require unrealistic level of slack time, and that is presumed to be a waste of valuable resources.

The delay policy will state that the departure of subsequent flights will wait until: the scheduled departure time; the aircraft is ready and the required connecting passengers are on board[3].

This way delays that are taken into account are commercially acceptable or un-avoidable nuisance delays. The solution for these delays are to incorporate slack in the schedule design to minimize consequences. Avoidable delays should be solved with operational excellence. And longer delays cannot be absorbed by slack, and focus should be on schedule recovery.

A last research constraint is to simulate simulation where single disruptions occur. This is acceptable as the impact of disruptions is the object of study. Delays can then be assumed as single and the delay reason is irrelevant.

Ad. 3) Current Kenya Airways' crew rosters are designed to follow aircraft, thus it suffices to only study aircraft and passenger connectivity throughout the flight schedule.

Integration of crew into the schedule simulation will be done through the assumption that the crew follow one tail. This assumption is correct in that currently crew can only switch tails during one duty on domestic flights to Kisumu and Mombasa[4]. As is shown in the delay breakdown in chapter 2, crew rotation rarely cause delays.

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[2] Table A.1 in Appendix A shows the fleet of KQ per september 2011. The size of sub-fleets are about 5, however not each tail is interchangeable. For example, KQX (a Boeing 767-300) is not able to fly to Europe due requirements on navigational equipment. This illustrates that even tail swaps within sub-fleets is limited.

[3] Followed from interviews with Patrick Muisyo (Manager Flight Operations Control) and Thomas Omondi (Head of Operations Control)

[4] Followed from interviews with John Siaya (Manager Crew Scheduling)

3.3 Research question

After scoping the problem area and within the freedom of the the project problem, a clear research question can be formulated:

> *How can the absorption robustness be simulated for a proposed seasonal flight schedule in terms of aircraft and passengers, and how can this be used to aid Kenya Airways in increasing schedule stability?*

The main research question can be divided into 7 sub research questions. The research methodology per sub question will be explained further in the next section.

1. Considering all delays at Kenya Airways, which types of delays could be targeted through absorption robustness to increase schedule stability?
2. How could the level of robustness be measured for a flight schedule?
3. In the case of Kenya Airways, by what means can the model for the propagation of a delay through a flight schedule be conceptualized?
4. How do you incorporate the following building blocks for the conceptual model:
    (a) What is required to model an aircraft turnaround time?
    (b) How is the performance of the scheduled flight blocktime modeled?
    (c) By what means could the flow of transfer passengers through the schedule be modeled?
5. How will the propagation of a delay through a schedule be simulated, resulting in the following questions?
    (a) In what way could the simulation suitably be characterized and formalized?
    (b) By which methods could the model be constructed into a computerized simulation?
    (c) How could the model be verified?
    (d) How could the findings be validated?
6. How can this model be applied to improve Kenya Airways' schedule robustness?
    (a) By what means can flight schedules be interpreted and tested on robustness?
    (b) How could you increase the robustness of the proposed flight schedule?
7. How can the simulation experiment be implemented at the Network Planning department to aid Kenya Airways in increasing schedule stability?

3.4 Methodology

This section describes the methodology, where the research approach of each question is explained and justified.

1 - Considering all delays at Kenya Airways, which types of delays could be targeted through absorption robustness to increase schedule stability?

Delays are categorized and drivers for on-time departure performance can be found. The methods applied is a study based on a literature review, interviews with experts and statistical analysis of flight performance data.

Through literature review, the current state of disruption management is investigated. Experts delivered an insight into how the IOCC operates. Flight performance data generates an insight into quantifying delays of flights. This insight lead to the development of a categorization of delays along the level of impact and the level avoid-ability. The categorization remained mainly qualitative due to validity of disruption documentation data, however it sufficed to indicate the impact of increasing absorption robustness at Kenya Airways.

2 -How could the level of robustness be measured for a flight schedule?

The development of a unit of measurement for schedule robustness is an iterative process, combining knowledge from literature review and airline operational experts at Kenya Airways. The concept of the delay curve is an extension from the delay multiplier, introduced by Beatty et al. (1999). The applicability of the proxy is case tested in close cooperations with the department of Network Planning team of KQ for concept acceptance.

3 - In the case of Kenya Airways, by what means can the model for the propagation of a delay through a flight schedule be conceptualized?

The basis for the time-line flight schedule representation is the research by Abdelghany et al. (2004), and extended with the introduction of transfer passengers. The development of the conceptual model is done in close cooperation with the department of Network Planning team of KQ for structural validity. Following this it appears that flight crew are scheduled as such to follow aircraft. In conclusion, the study of delay propagation at KQ requires the analysis of the flow of aircraft and passengers, thereby neglecting flight crew.

4.a - What is required to model an aircraft turnaround time?

A stochastic model is created from historical data on the duration of the turnaround process on an aircraft type level. The advantage is that all available data has been collected and can be extracted from the flight movement control software. The possibility of an early departure is connected to the slot restrictive nature of the airport. This approach can be validated with a statistical correlation analysis and needs to correspond to the expert opinions of ground stations.

4.b - How is the performance of the scheduled flight block time modeled?

Average historical actual block times are used as the estimator of the block time performance. This is advantageous because flight performance is documented clearly, and as such available for analysis and sufficient influences on the block time can be taken into account. The downside is that there is no or limited historical data for new routes or existing routes flown by new aircraft types.

4.c - By what means could the flow of transfer passengers through the schedule be modeled?

First, the quantification of the transfer passengers flow between flights is done using reports from a bookings analysis tool used by KQ, Delorean. This system allows for an insight in historical number of bookings on origin and destination level. These can then be used when estimating the number of transfer passengers between flights for a proposed flight schedule under the assumption that the historical seasonal demand is similar.

The second step would be to understand how the flow of transfer passengers propagate disruptions through the schedule. It was found from interviews that the Operations Control Center maintain relative strict guidelines as to when flights must be delayed for passengers. These guidelines can be formalized and integrated into a conceptual model.

The reason why this is not done stochastically is that historical data on when to delay flight due passenger numbers is not well documented. As such, an incomplete simulation arises. Therefore, in discussion with Kenya Airways, this deterministic element is integrated.

5.a - In what way could the simulation suitably be characterized and formalized?

After a literature study and interviews with experts on this area a choice for simulation is made and explained. Two streams of research could be followed, of which one was chosen to develop a discrete recursive simulation model.

A possibility would be to conduct a discrete event simulation, with the ability to adapt levels of model granularity and complex business rules. However, the nature of the research is to understand the delay curves of flights which requires a large number of simulation runs. The possibility to integrate complexity into the simulation was therefore deemed unnecessary.

It was opted to choose for a simpler and quicker simulation model, that could simulate a delay propagation tree recursively by starting from the point of disruption. The model was based on the concept introduced by Lapp et al. (2008) and extended with transfer passenger flows. This approach allows for the possibility to incorporate Kenya Airways specific guidelines for propagating passenger connection delays. The choices are made in close cooperation with the Network Planning department.

5.b - By which methods could the model be constructed into a computerized simulation?

The main focus of this study is the creation of a flight schedule representation and a computation model to study flight schedule robustness. To keep this project within the scope of the thesis project it will be made in Matlab using an object oriented approach. The downside is that a direct implementation into the workflow of Kenya Airways is made more difficult.

5.c - How could the model be verified?

Model verification was done through a series of unit tests. Small samples of data can be run, of which the results can be manually verified.

Furthermore, the choice to develop in Matlab allowed for an agile software development cycle. This approach develops with multiple iterations where new features are added sequentially. This philosophy of this software development is used to increase moments of model verification, and increase the involvement at Kenya Airways.

5.d - How could the findings be validated?

Both structural and predictive validity of the simulation experiments are necessary. Structural validity will be achieved through close cooperation with the decision makers, the department of Network Planning, to ensure correct assumptions and appropriate model boundaries.

Predictive validity is achieved through comparing the expected robustness proxy with the current operation. The most suited method was determined to be comparisons with empirical delay curves. Even considering the limitations the quality of the delay documentation, it was opted the most suited method as replicability is ensured.

6.a - By what means can flight schedules be interpreted and tested on robustness?

The proposed simulation is to work alongside Netline Flight Schedules, a software package that manages and optimizes flight schedules for aircraft utilization. Existing and proposed schedules created in Netline can be tested. After integration with Netline, the robustness proxy to rate flight sensitivity is used to compare flights.

6.b - How could you increase the robustness of the proposed flight schedule?

After simulating the flight schedule on robustness, the most critical flights can be further investigated and improved. A methodology can be developed that utilizes the insights of the simulation to make an alternative flight timing to improve flight robustness. However, the impact on the schedule should be considered. First, that no Minimum Turnaround-time is breached. Second, that the Minimum passenger Connection-times are adhered to. If the Minimum passenger Connection-times is infringed, the impact on passenger demand should be studied. Through an iterative approach improvement measures can be studied on robustness via the delay severity simulation. Therefore, a good integration with Netline is required.

7 - How can the simulation experiment be implemented at the Network Planning department to aid Kenya Airways in increasing schedule stability?

In collaboration with the Network Planning department, ownership of the block time confidence module can been realized by ensuring for close collaboration during development.

Implementation of the delay severity simulation is beyond the scope of this study. Implementation of such tool requires large data integration to several database systems. However, as a proof of concept recommendations for multiple routes can be achieved to create an understanding of how such decision support tools can work. The recommendations are created alongside schedulers and the scheduling system Netline to allow to incorporate as much of the soft constraints as possible.

As an overview of where each research question is answered, figure 3.1 shows the breakdown of the chapters.

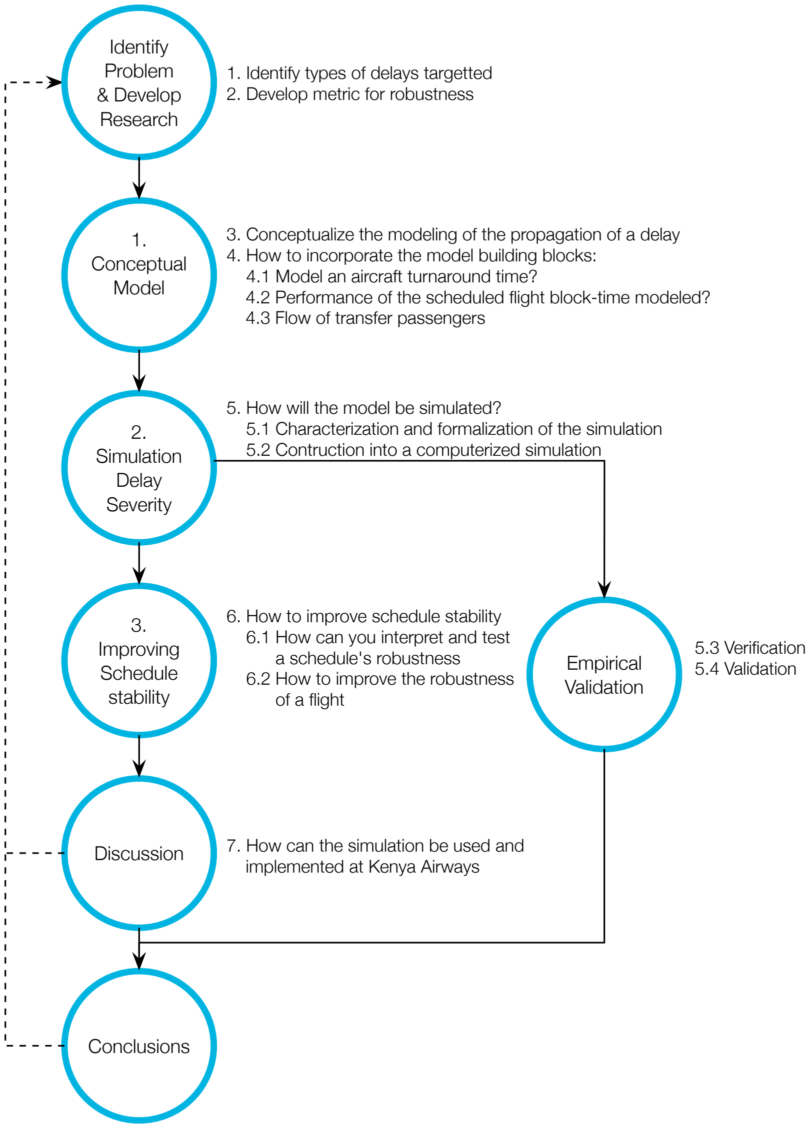

Figure 3.1. ***Research sub questions.*** *A workflow indicating the relationship between the sub questions and forms the basis for the setup of the thesis.*

4. Conceptual Model

This section introduces the basis of the conceptual model of how delays propagate[1] through the flight schedule, indicated as the first research step in figure 4.1. A conceptual model forms the input for the simulation, which is discussed in the next chapter.

The conceptual model starts with the representation of the flight schedule is treated. The model describes the interaction between four building block, these being the drivers behind schedule stability,

The four building blocks are (1) the Block-time; (2) the Turnaround time; (3) the Passenger Connecting time; and (4) the number of transfer passengers. Modeling these starts with a discussion on the historical dataset used to fit a probability distribution. The summary of probabilities found forms a direct input for the computational simulation.

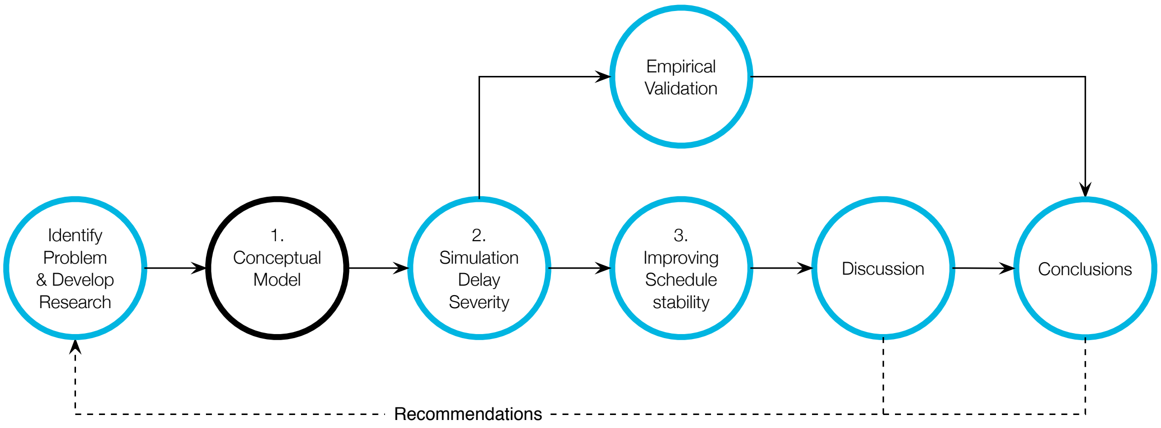

Figure 4.1. Placing the conceptual model in the thesis outline. *Creating the model forms the first research step. A conceptual model forms the basis for the simulation experiment.*

4.1 Formalizing the flight schedule representation

This section introduces the basics of the flight schedule representation, and the terminology used throughout the model.

The general framework for the flight schedule representation is based on the work of Abdelghany et al. (2004), who investigated projected downstream slack for crew and aircraft. Figure 4.2 is a graph

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[1] The spread or dissemination of the delay downstream the flight.

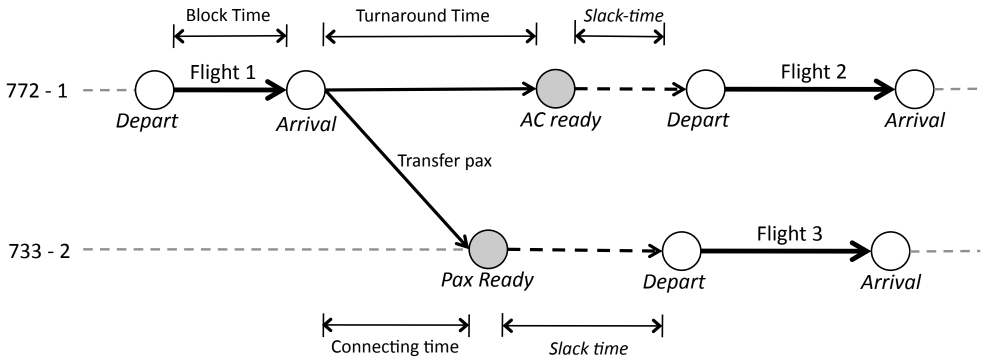

Figure 4.2. ***The high level concept of the delay propagation model.*** *The model is based on Abdelghany et al. (2004), but extended with the passenger connectivity onto a time-line representation.*

representing the approach chosen, with all components conceptualized. A flight can depart if all resources are ready. A flight may be delayed if a resource is late, however an early departure is limited for non-slot restricted airports only.

The representation is based on event nodes, with an activity arc between. As is shown in figure 4.2, the main building blocks are the flight, the Turnaround, and the passenger connection. The three main activities can be formalized in a time-line network representation and are assumes stochastic and independent of the time of arrival of the flight. The stochastic modeling of the building blocks will be further clarified in the next section. Validating the independence of the building blocks is discussed in chapter 7.

The time-line network representation chosen considers anonymous tails in rows, with the development of time on the longitudinal axis. This approach is suited to visualize the delay propagation trees and explain specific terminology.

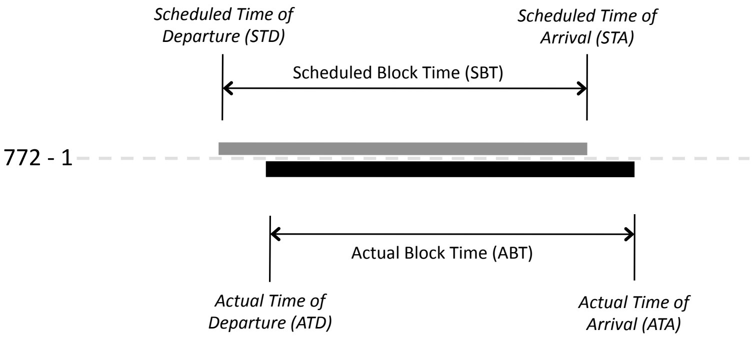

Figure 4.3. ***Block time formalization.*** *The formalization of the block time is done in a time-line network representation.*

A flight leg is modeled according to the block time, which is the time between departure from the bay (chocks off) and arrival into the bay (chocks on). A flight consists of one flight number and one or more flight legs. Shown in figure 4.3, both the scheduled and the actual times are described. Formalizing the relationship, the difference between the Scheduled Time of Arrival (STA) and the Scheduled Time of Departure (STD) is the Scheduled Block Time (SBT). The difference between the Actual Time of Arrival (ATA) and the Actual Time of Departure (ATD) is the Actual Block Time (ABT).

The departure performance of the flight can be directly extracted from this representation. As is seen in figure 4.3, if the ATD is after the STD, the flight is delayed. Formalizing this relationship, flight i is delayed when it departs after the STD:

$$D_i^{dep} = max\{0, ATD_i - STD_i\} \tag{4.1}$$

The flight arrival delay of flight i, D_i, depends on the flight slack, which is defined as the difference between the SBT and ABT. This relation is formalized as:

$$D_i^{arr} = max\{0, (ABT_i - SBT_i) - D_i^{dep}\} \tag{4.2}$$

A delay is propagated if the departure delay exceeds the slack programmed in the flight, resulting in an arrival delay.

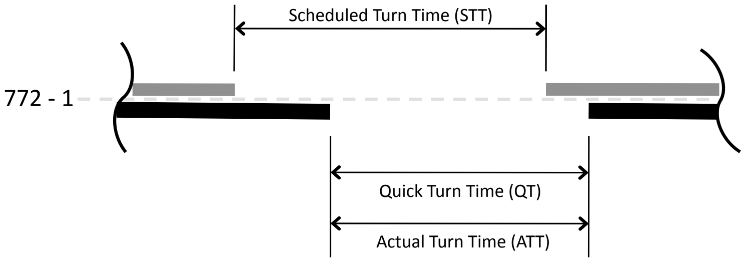

Figure 4.4. Turnaround formalization. *The formalization of the turn around in a time-line network representation, conceptualizing the difference between the Scheduled - and Actual Turn Time.*

The aircraft Turnaround is formalized in figure 4.4, where the difference between the Scheduled Turn Time (STT) and Actual Turnaround Time (ATT) is shown. The STT is the ground time that is programmed into the flight schedule, and includes possible slack. However, upon a delay the ground team is able to reduce the required ground time to the Minimum Turnaround-Time (MTT). This is a minimum required time to turn an aircraft around and is stochastically determined.

The delay propagation to the next flight, $i+1$, can be extracted from this representation, as can be seen from figure 4.4. The departure delay of the next flight, D_i^{dep}, is defined as:

$$D_{i+1}^{dep} = max\{0, (ATT_i - STT_i) - D_i^{arr}\} \tag{4.3}$$

A delay is propagated through the line of flight if it exceeds the Turnaround slack, which is the difference between the STT and the ATT.

Passenger connectivity occurs between anonymous tails from the originating flight onto connecting critical flights k, as is shown in figure 4.5. Critical flights k are considered subsequent flights where there are sufficient transfer passengers such that upon a delay these flights will wait.

The difference between the STD of the outbound flight and the STA of the inbound flight is the Programmed Connecting Time (PCT). Upon a delay, ground operations can reduce the Actual Connection Time (ACT) to the Minimum Connecting Time (MCT). An inbound delay can propagate along critical passenger connections, a relationship that is defined as:

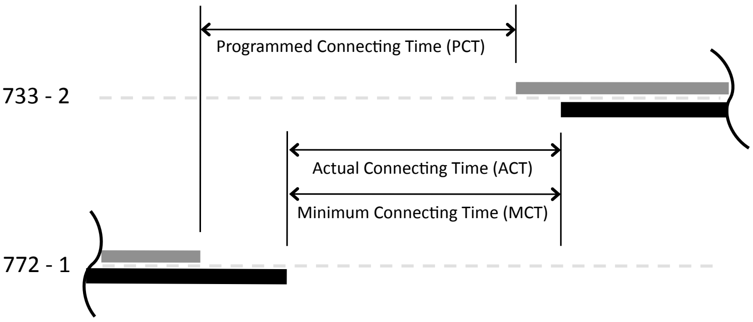

Figure 4.5. Passenger connectivity formalization. *The formalization of the passenger Programmed - and Minimum Connecting Time, in a time-line network representation.*

$$D_{i+1}^{dep} = max\{0, ACT_{k,(i+1)} - MCT_{k,(i+1)}) - D_k^{arr}\} \tag{4.4}$$

An inbound delay is propagated if it exceeds the connecting slack, and the number of passengers are sufficient to accept the outbound delay.

Concluding the introduction of the flight schedule representation, the propagation of delays is recapitulated and formalized.

As is described, a delay propagates through either the lines of flight, or via a passenger connection. The next flight, flight $i+1$, is delayed if the previous arrival delay exceeds the resource slack for the aircraft and all critical passenger connections. The relationship can be formalized as follows:

$$D_{i+1}^{dep} = max\begin{cases} 0 & \text{no delay} \\ (ATT_i - STT_i) - D_i^{arr} & \text{delay via line of flight} \\ (ACT_{k,(i+1)} - MCT_{k,(i+1)}) - D_k^{arr} & \text{for each critical flight } k\text{, delay via passenger connection} \end{cases} \tag{4.5}$$

The propagation of a primary delay can be found using a shortest path algorithm which runs acyclic from the source node downstream through all affected flights, until all delay is absorbed.

The next section will discuss the modeling of the main events.

4.2 Block-times

This section describes how the performance of block times is modeled in the stochastic delay propagation model.

As is discussed in section 4.1, the block time is the time between the departure out of the bay (chocks off) and arrival (chocks on) into the bay.

4.2.1 Historical Block-time dataset

When modeling the performance of the block time in the delay propagation model, flights are assumed independent and the performance of their ABT depends on:

$$\text{ABT} = \begin{cases} \text{Citypair} \\ \text{Direction} \\ \text{Aircraft Type} \\ \text{Season} \end{cases}$$

The reason for modeling the block time performance on season is that a main contributor for enroute delays, as is explained in chapter 2, is weather. As such, seasonality is taken into account.

The performance data is extracted from Sabre, and is imported into a developed Excel tool. Further data manipulation is discussed in Appendix B. The excel tool creates the transparency on how block times are dependent on routes, direction, aircraft type and season. As is explained in Chapter 6, this module allows the department of Network Planning to plan for scheduled block times with a sufficient confidence level.

A limiting effect on using historical data for block time performance is that there is limited historical data for new routes or existing routes flown by new aircraft types. A work around solution is required, and is based on the original Flight Operations Engineering work to estimate flight durations for different weather and Air Traffic Control scenarios. This estimate is used to set a SBT with the aim to deliver an 80% confidence. As such, the solution within the conceptual model is to take the ABT as 80% of the SBT for new routes or existing routes with new aircraft[2].

4.2.2 Determining stochastic estimators for Block-times

For the purpose of the simulation, the stochastic parameters are estimated using a probability distribution that is based on a historical dataset. The assumption is made, and validated in section 7.2.1, that block times are independent. Furthermore, a stochastic estimator needs to be efficient and unbiased(Kraaikamp and Meester, 2005). Efficiency is measured according to the Mean Squared Error. Bias is measured according to the spread of the residual estimation errors throughout the range of the historical dataset.

Blocktimes are estimated using the Log-normal distribution. Other probabilities considered: Gamma, Weibull, Extreme Value and Pearsons Sytem. Figure 4.6 shows an example of the probability analysis performed for two probability distributions[3]. It is concluded that the LogNormal function has the smallest Mean Square Error throughout all flight data sets. Figure 4.6 shows the example analysis of a Boeing 767 flying to Lilongwe (LLW). Figure 4.6b indicates that both the Gamma and the Log-normal distribution fit unbiased, however the Log-Normal distribution has a lower Mean Square Error. The differences between flights is not large, however for flights with smaller Block-times there is a difference. This is because of the asymmetric behavior of the Log-normal distribution skewed to non-negative numbers.

The Log-Normal variables μ_{log} and σ_{log} can be calculated with the mean, m, and standard deviation, σ, of the historical dataset.

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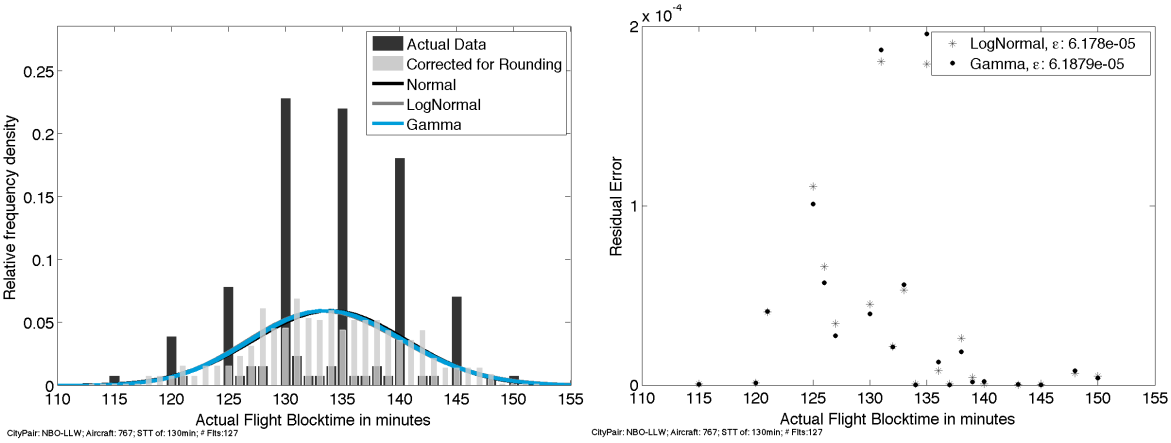
[2] From interviews with Edward Kamau (Jet Fuel Manager) and Agnes Kamau (Flight Operations Engineering)

[3] Data is fitted on data smoothed to compensate for the rounding off of data measurements, see appendix B

$$\mu_{log} = \log\left(\frac{m^2}{\sqrt{\sigma^2 + m^2}}\right) \tag{4.6}$$

$$\sigma_{log} = \sqrt{\log\left(\frac{\sigma^2}{m^2} + 1\right)} \tag{4.7}$$



(a) Fit **(b)** Residual

Figure 4.6. Example block time probability fit. A probability distribution fit analysis indicates that the log normal distribution is the best fit for block times. This example shows the results for the outbound flight to Lilongwe (LLW) for a Boeing 767. (Data from September 2010 till September 2011, 127 flights for a Boeing 767-300)

Table 4.1 shows a sample of the block time estimations to indicate the outcome of the data analysis. Each route consists of a summer and winter data set, with an estimation for all aircraft types that have flown that route.

Table 4.1. Block time probabilties. 55,655 flights between September 2010 and September 2011 are used to build up this set. Used to approximate log normal behavior of block times depending on season, route , direction and aircraft type.

Season	**DepAp**	**ArrAp**	**AcType**	**# Flights**	**Mean (m, Min)**	**Std Dev (σ)**
Summer	CAI	KRT	738	198	155.4	8.4
Summer	CAN	BKK	767	233	181.7	10.3
Summer	NBO	AMS	772	428	509.1	14.6
Summer	NBO	BOM	772	206	356.4	10.3
Summer	NBO	MBA	733	3214	58.9	5.5
Summer	MBA	NBO	733	3209	62.3	5.1

4.3 Turnaround-times

This section discusses how the performance of the Minimum Turnaround-Time (MTT) is measured. MTT is set as the minimum ground time required by ground operations to turn an aircraft around. The difference between the STT and the MTT is the build in schedule slack, ensuring for a timely departure of the plane in case of a nuisance delay.

The Turnaround time is modeled according to the aircraft type, and is independent of the airport. This is in line with Kenya Airways' set guidelines on MTT. These have been brought forward after internal studies and took various ground operations and technical requirements into account.

4.3.1 Historical Turnaround dataset

The stochastic estimator on the performance of the Turnaround time is based on a dataset of flights that have been delayed due to aircraft rotation only.

A choice for this dataset is made as this data contain flight events where the Turnaround was the bottleneck process, yet it was performed without other disruptions occurring simultaneously. As such, the interaction between disruptions have been removed. This dataset forms a good basis to study study historical MTT.

The performance data is extracted from Sabre, and is imported into a developed Excel tool, as is discussed in Appendix B. The dataset runs from September 2010 and September 2011. The number of flights delayed only due aircraft rotation in this periode is 1,811. This dataset forms to stochastically model MTT on an aircraft type level.

4.3.2 Determining stochastic estimators for the Turnaround

For the purpose of the simulation, the stochastic Minimum Turnaround-time is estimated as an independent event using a probability distribution that is based on a historical dataset. The procedure is similar as to the Block time approximation and attempts to find an efficient and unbiased estimator.

Minimum Turnaround-times are estimated using the Log-normal distribution. Figure 4.7 shows an example of the probability analysis performed[4]. For all aircraft types, both narrow- and wide-body, it is concluded that the LogNormal function has the smallest Mean Square Error.

Table 4.2 shows the result of the probability fit of Actual Turnaround-times that are modeled aircraft type dependent. Dependencies on the time of the day were not found to be significant. These probabilities form a direct input for the computational simulation.

4.3.3 Early departures at non-slot restricted airports

Early departures have as a great influence on the schedule robustness as it re-allocates slack time to a future point increasing the effectiveness against disruptions. In cooperation with the Network Planning department and the IOCC the model includes the possibility for flights to depart early for non-slot restricted airports when all flight resources are ready. The assumption is based on a performance incentive scheme at KQ's to reward Turnaround teams for early departures.

The possibility for flights to depart early is validated with a statistical correlation analysis. At airports where early departures often occurs, there will be a high correlation between early arrivals and early departures. Whereas, at airports where early departures are not common this relationship will not be

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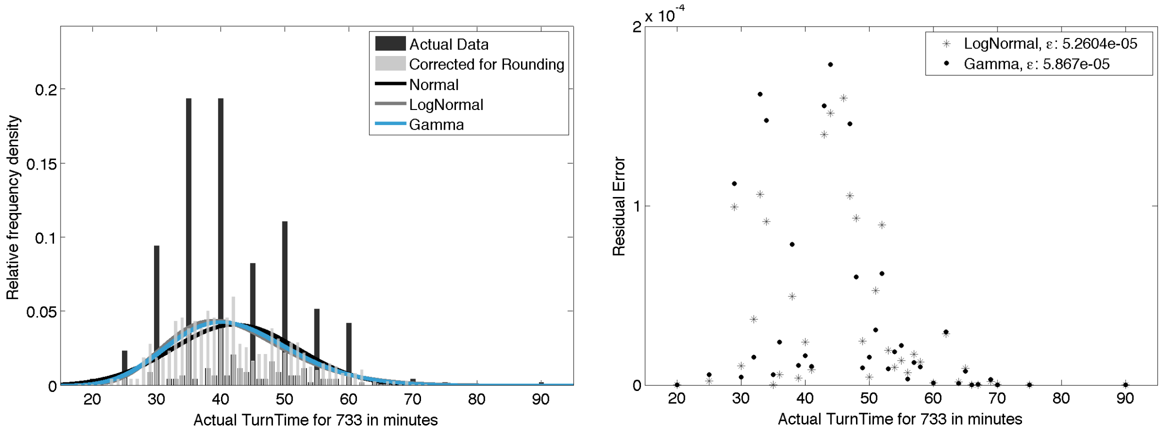
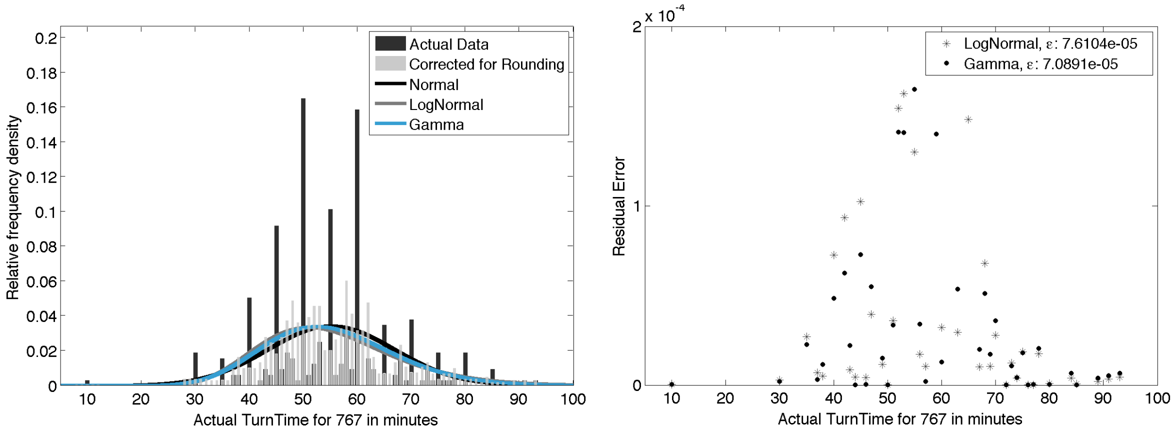
[4] Data is fitted on data smoothed to compensate for the rounding off of data measurements, see appendix B



(a) Probability fit, Boeing 737-300 **(b)** Residual error variance, Boeing 737-300

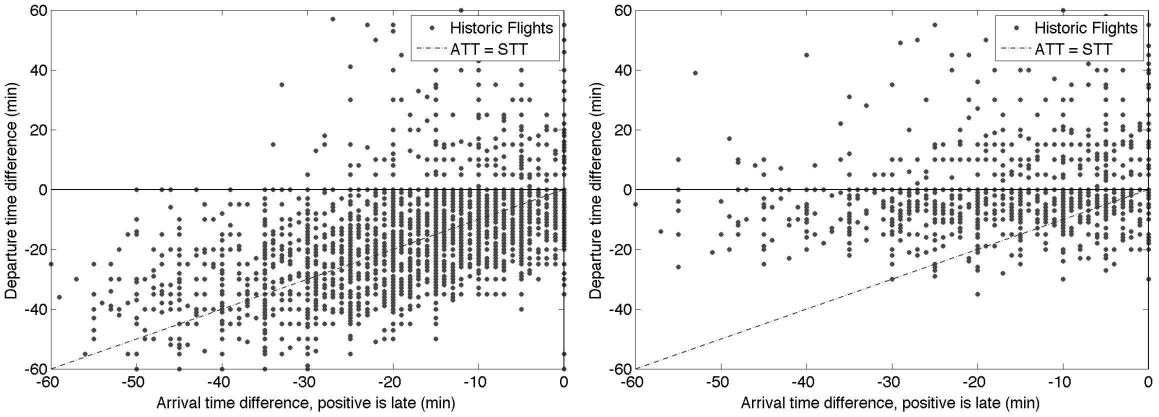


(c) Probability fit, Boeing 767-300 **(d)** Residual error variance, wide, Boeing 767-300

Figure 4.7. Modeling of Turnaround times. An example of a Minimum Turnaround-time approximation for a Boeing 737-300 and a 767-300 where flights are only delayed due reactionary. (Data from September 2010 till September 2011, 423 flights for a Boeing 737-300, 315 flights for the Boeing 767-300)

Table 4.2. Minimum Turnaround-time probabilities. Flights that are delayed only due reactionary are used to estimate historic Minimum Turnaround-times. The data is fitted with a Log-Normal distribution. 1811 flights between September 2010 and September 2011 are used to approximate log normal behavior of aircraft Turnaround.

AcType	MTT guideline	Flights Counted	Mean (m, Min)	Std Dev (σ)
772	75	66	62.6	13.7
767	60	304	55.0	11.8
733	50	423	42.2	9.7
737	50	268	45.1	9.6
738	50	458	48.5	11.0
E70	45	271	37.4	10.3
E90	45	21	43.3	9.0



(a) Non-slot restricted airports, ρ = 0.33

(b) Slot-restricted airports, ρ = -0.014

Figure 4.8. Influence of slot-restriction on early departures. *The model allows for early departures at non-slot restricted airports, which is validated using a statistical correlation analysis on the aircraft ATA and ATD for flights arriving early. When a flight arrives early, at non-slot restricted airports the next flight may also depart early. (Data between September 2010 and September 2011. 11,718 flights at non-restricted airports. 2,618 flights at slo-restricted airports)*

present. As such, the historical correlation between the arrival time difference of early arriving flights and the departure time difference of subsequent flights is studied. The question is whether flights can depart as soon as all resources are ready, which is more likely to happen after a flight has arrived earlier than planned.

Intuitively, a difference is made between airports according to their slot restricted nature. This corresponds to the Ground Operations incentive scheme, and can be validated from data. Figure 4.8 shows a statistical correlation analysis for slot restricted and non-slot restricted outstations. The dataset of flights chosen is flights arriving early. In conclusion, the correlation between the arrival time difference and the departure time difference for non-slot restricted outstations is 0.33. This correlation is higher than on slot-restricted airports, where a correlation of -0.014 is found. Even though the relationship at non-slot restricted airports is not very strong, early departures will be accommodated.

The flights arriving at Jomo Kenyatta International Airports (JKIA) form a third category, next to slot restricted and non-slot restricted outstations. This is because at Nairobi there are no slot restrictions, however the correlation between early arriving flights and early departing flights is 0.017. As such it is chosen that flights departing out of nairobi cannot depart early.

Concluding the discussion on early departures, an overview of all flown airports and their slot restricted nature is found in table A.2, Appendix A.

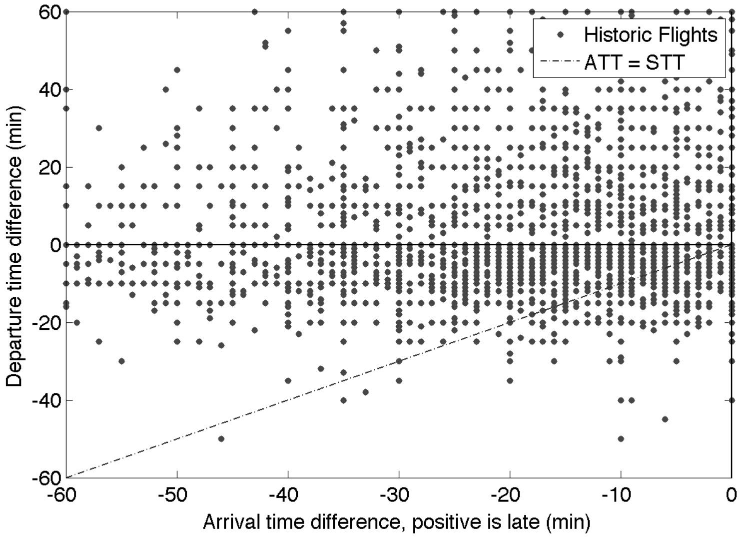


Figure 4.9. Early departures at JKIA. *In Nairobi, the correlation of early arrivals with early departures is 0.017. As such, the stochastic model does not allow for early departures out of the Nairobi. (10,613 flights between September 2010 and September 2011)*

4.4 Flow of transfer passengers

This section discusses how the flow of transfer passengers is modeled.

4.4.1 Booking dataset used

The number of passengers that transfer between flights can be obtained from historical data. Historical passenger data is obtained form Delorean, a revenue management booking tool licensed from KLM. However, two data manipulations must be made to get a suited dataset for the simulation model.

First, the number of passengers booked in a schedule can be found in two ways. When simulating specific weeks for post operational analysis, actual booked loads can be used. When analyzing proposed seasonal schedules, expected booked loads can be computed from historical data. However, when averaging expected passenger loads, seasonality has to be taken into account[5].

A second consideration is to translate the Origin and Destination (O & D) based data to flight legs. The passenger flows are formalized into four types and are conceptualized in figure 4.10. For purpose of this model, focus is on a flight leg basis which implies both connecting and commencing transfer passengers are to be considered. A sample of the passenger data is shown in table 4.3, and shows that the historical data from Delorean is Origin and Destination based. As such, a translation to flight legs has to be made considering both the connecting and commencing transfer passengers.

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[5] Kenya Airways accommodates tourist routes, such as Amsterdam to Nairobi. The loads on these routes are seasonal dependent as they rely on tourist demand. Demand for tourism in Kenia is higher during the summer holidays and the winter break.

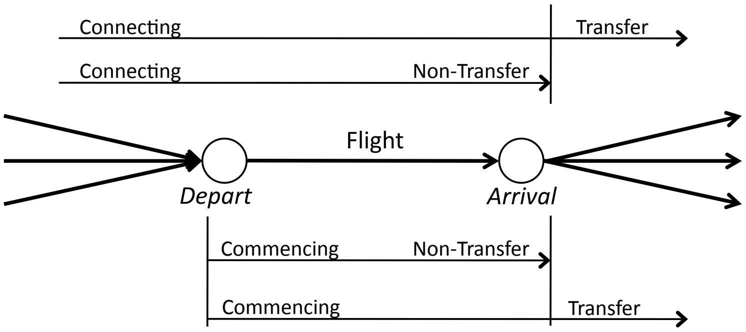

Figure 4.10. Passenger categorization. For the model we only consider transfer passengers.

Table 4.3. Examples of passenger Origin and Destination data. The data on passenger bookings are differentiated on Origin and Destination. A few examples are given to illustrate how the passenger categorization works.

Flt DepAp	Flt ArrAp	O&D	Season	Pax	*Pax type*
LHR	NBO	LHR-EBB	Summer	12	*Commencing, Transfer*
LHR	NBO	LHR-EBB	Winter	15	*Commencing, Transfer*
NBO	DXB	LOS-DXB	Summer	16	*Connecting, non-Transfer*
NBO	DXB	LOS-DXB	Winter	14	*Connecting, non-Transfer*
NBO	BKK	LOS-HKG	Summer	15	*Connecting, Transfer*
NBO	BKK	LOS-HKG	Winter	35	*Connecting, Transfer*

An example of how the translation from Origin and Destination to leg-based transfer passengers is done is shown in figure 4.11. Both flight 887 and flight 722 are circular flights. The implication is that four passenger flows have to be considered. As can be seen from figure 4.11, a total of 9 passengers can be expected to transfer in Nairobi from flight 887 to flight 722. This logic has been formed into an algorithm and is found in Appendix B.3.

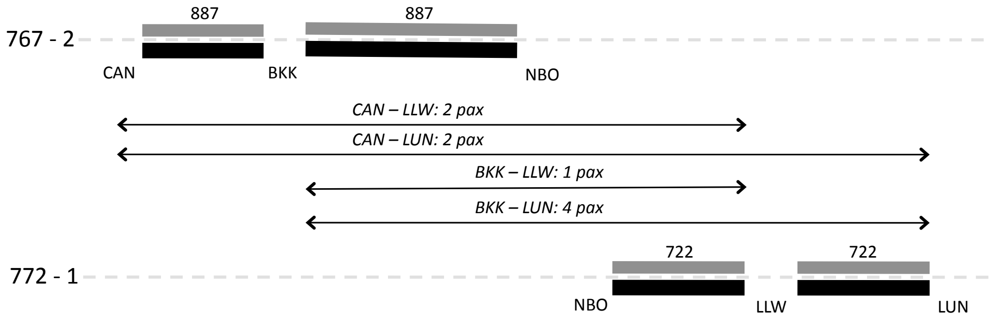

Figure 4.11. An example of the passenger flows between circular flights. An example of the number of transfer passengers that can be expected. As can be seen, four passenger flows have to be considered as both flights are circular. A total of 9 passengers can be expected to transfer in Nairobi from flight 887 to flight 722.

4.4.2 IOCC propagation of passenger delays

Delaying a subsequent flight depends on the frequency and number of flights. The essence is to minimize the delay costs. If it costs less to delay a flight than to misconnect the passengers[6]. However, to streamline the process official guidelines have been set. These guidelines have been set by the IOCC, and are shown in figure 4.4.

These guidelines are adhered strictly[7]. However on some occasions IOCC can choose to force a passenger connection through a propagation of delay. As an example, 18 minutes load connection delay was approved because the passenger in question was the president of Hilton Hotels Kenya. It is assumed that not connecting this passenger would lead to a opportunity cost due to loss of future business.

A note is that all domestic flights, except Malindi, are multi-daily. As such the model only considers international to international passenger transfers.

Table 4.4. Guidelines on forcing transfer passenger connection. *Kenya Airways guidelines on when to force a passenger connection through the propagation of a delay*[8].

Onward flight frequency	**Minimum Passengers**
Weekly	≥ 4
Double weekly to Daily	≥ 5
Daily and double-daily	≥ 10
$\geq$ 3 frequencies daily	No propagation

4.5 Actual connection-times

The passenger ACT are dependent on the number of passenger transferring between two flights. Formalizing the modeling of the passenger connection times, only international to international traffic is considered. Furthermore, a differentiation is made between transfer passengers groups that are less than or greater than 10 people. This differentiation is made following Kenya Airways Guidelines on actual passenger connectivity.

Domestic traffic, except for Malindi, is not considered to be a source of passenger connection delay as these are multi-daily. Section 4.4.2 discusses how the IOCC will not delay multi-daily flights to wait for transfer passengers.

4.5.1 Historical dataset used for ACT

The stochastic estimator for the performance of ACT is based on a dataset that considers historical flights with only load connection delays (RL). The performance data is extracted from Sabre, and is imported

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[6] At the IOCC, only the direct passenger delay costs are taken into account. These are a reimbursement of tickets and hotel accommodation. Other soft costs such as the loss of future opportunity (EuroControl, 2011) that will occur are not taken into consideration by the IOCC

[7] From interviews with Thomas Omondi (Head of Operations Control) and Gordon Anyimu (Manager Hub Control Center).

into a developed Excel tool as is discussed in Appendix B.

Between September 2010 and July 2011, there where 559 flights with a RL delay. These concerned only international to international transfers. However, the delay documentation is not standardized, and the previous flight and number of transfer passengers is not always reported. From 559 flights, only 293 flights correctly reported the number of transfer passengers and the previous flight.

With this dataset of flights, the ACT can be computed as the difference between the ATD of the outbound flight and the ATA of the inbound flight.

4.5.2 Determining stochastic estimators for the ACT

For the simulation, the stochastic ACT is modeled as an independent event and estimated using a probability distribution that is based on a historical dataset. The procedure is similar as to the Block time approximation, and attempts to find an efficient and unbiased estimator.

A standard probability distribution analysis concludes that the Log-normal distribution fits best as an unbiased and efficient estimator. Figure 4.12 shows the probability distribution results for both group sizes of transfer passengers[9]. Figure 4.12b and 4.12d indicate an unbiased Log-normal distribution fit.

The result of the analysis is shown in table 4.5. Dependencies on the time of the day or the season were not found to be significant. However, the group size of the transfer passengers did result in a average difference of 8 minutes, as such the MCT is modeled dependent on this. The mean and standard deviation of the ACT will directly be used as an input in the computational simulation.

Table 4.5. Actual Connecting Time probabilities. *RL data shows these probabilities best. 293 flights between September 2010 and July 2011.*

Number of Transfer Pax	MCT guideline	Flights Counted	Mean (m, Min)	Std Dev (σ)
< 10	25 minutes	65	34.2	13.4
≥ 10	50 minutes	199	42.5	13.0

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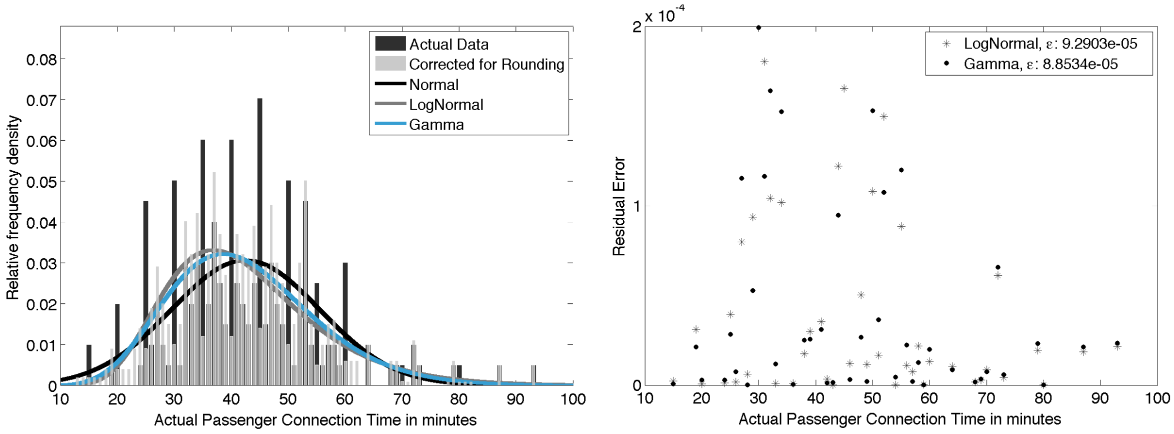
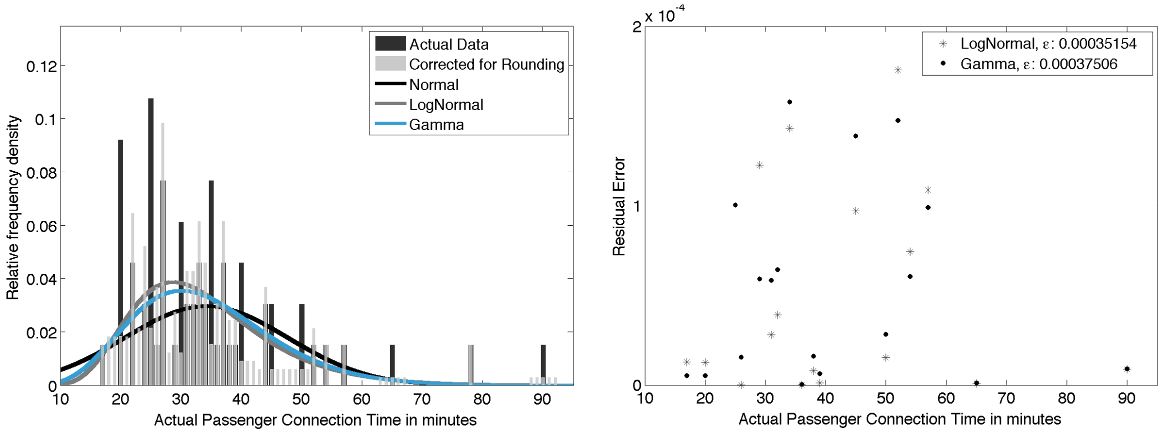
[9] Data is fitted on data smoothed to compensate for the rounding off of data measurements, see appendix B



(a) Fit, pax groups $\geq$10

(b) Residual, pax groups $\geq$10



(c) Fit, pax groups $<$10

(d) Residual, pax groups $<$10

Figure 4.12. Modeling of Minimum Connecting Times. *Example of a Minimum Connecting Time approximation where flights are only delayed due reactionary. (Data from September 2010 till September 2011, 199 flights larger groups, 65 flights for smaller groups)*

5. Stochastic Simulation

This chapter discusses and describes the transition from a conceptual model into a computerized simulation. Figure 5.1 indicates how the simulation is anchored into the research.

The purpose of the simulation is to visualize per flight a simulated relation between the duration of the primary delay and the delay severity[1]. Furthermore, a robustness metric is proposed to compare the robustness of flights and the stability of flight schedules.

The basis for the stochastic Monte-Carlo delay scenario simulation is the delay propagation model that is described in chapter 4. The analogy of the simulation is the toppling of dominoes, where the fall of the first domino illustrates the primary delay. The delay severity is the number of dominoes effected by the first topple. The algorithm is a Monte-Carlo simulation which implies that the scenario of toppling that first domino[2] is repeated until a clear picture can be made as to which dominoes are affected. A formal description of this process is a self-iterative shortest path algorithm that runs acyclic from the source delay node downstream till all delay is absorbed.

The development of the simulation is done in Matlab R2010b, a choice based on development speed and ability to program object-oriented. Then the simulation experiment is described, which aims to simulate delay propagation trees and delay severity curves.

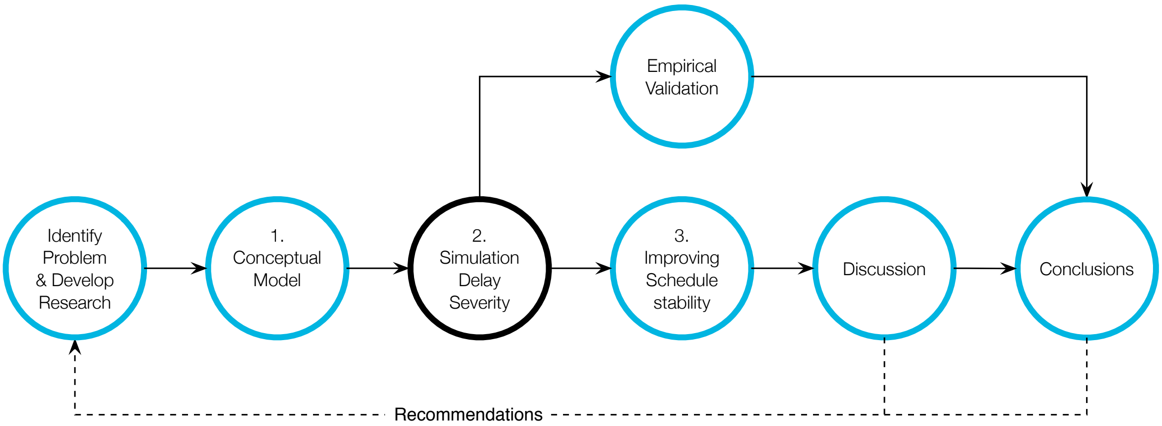


Figure 5.1. The transition from a conceptual model into a delay severity simulation. *Creating the model forms the first research step. A conceptual model forms the basis for the simulation experiment.*

The chapter contains three parts. First, the data input for the simulation is discussed. Then, the specification of the conceptual delay propagation model into a computerized simulation is discussed. The chapter finishes with the simulation experiment concerns on how the delay severity simulation can

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[1] delay severity is defined as the number of flights the primary delay affects downstream.

[2] A simulation run could be, for example, a 15 minute delay on flight KQ0550.

be applied to increase schedule stability.

5.1 Simulation Data Input

This section contains a general overview of the three data sources used for the simulation model input. The formalization of the stochastic parameters is discussed in Chapter 4. An in depth discussion on the extraction of the data from the sources is found in Appendix B.

The first dataset is retrieved from Netline, a Lufthansa schedule management system (Appendix B.2). The files contain the schedule information and the possible flight connections. The first file contains all flight timing data. The second file all the possible passenger connections for transfers in Nairobi.

Flight Schedule: Flight number, Date, Aircraft Type ,Departure Airport, Arrival Airport, STA, STD. Onward Flight Number, Onward STD, Onward Date

Flight Connections: Hub, Inbound Flight Number, Inbound Departure Airport, Inbound STA, Inbound STA date, Outbound Flight Number, Outbound Arrival Airport, Outbound STD, PCT,

The second dataset is the historical flight performance data extracted from Sabre Movement Control Flight Following System (Appendix B.1). This dataset contains required parameters to describe the stochastic nature of the Block-time, Turnaround-time and Passenger Connection-times.

BlockTime data: Season, Departure Airport, Arrival Airport, Aircraft type, Mean$_{ABT}$, StdDev$_{ABT}$

Turnaround times: Aircraft type, Mean$_{ATT}$, Std$_{ATT}$

Minimum Connecting time: Passenger Group Size, Mean$_{ACT}$, STD$_{ACT}$

The third dataset is extracted from Delorean, a passenger booking analysis tool (Appendix B.3), and contains the expected transfer passenger load on a Origin and Destination level.

Origin and Destination Demand: Flight Leg Departure Airport, Flight Leg Arrival Airport, Passenger Citypair, Season, Number of Passengers

Following the overview of the simulation model input, the simulation can be specified in the next section into a computational model.

5.2 Model specification

The model specification describes the procedures within the simulation, and consists of two main steps. The first step is to pre-process data for a schedule scenario simulation. Then the simulation of delay propagation trees is discussed, which is a monte-carlo simulation that iterates through a set of delay scenarios from which a delay severity curve is constructed. Both steps are discussed.

5.2.1 Data pre-processing

The first step is to prepare a schedule with historical flight data; flight schedule data and passenger data. The relationship between the scripts and the classes in this step is shown in figure 5.2. The description of the objects and classes is done through Unified Modeling language (UML). The relations between the classes are visualized and forms the basis for the documentation of the simulation. The data input of the simulation is discussed in section 5.1.

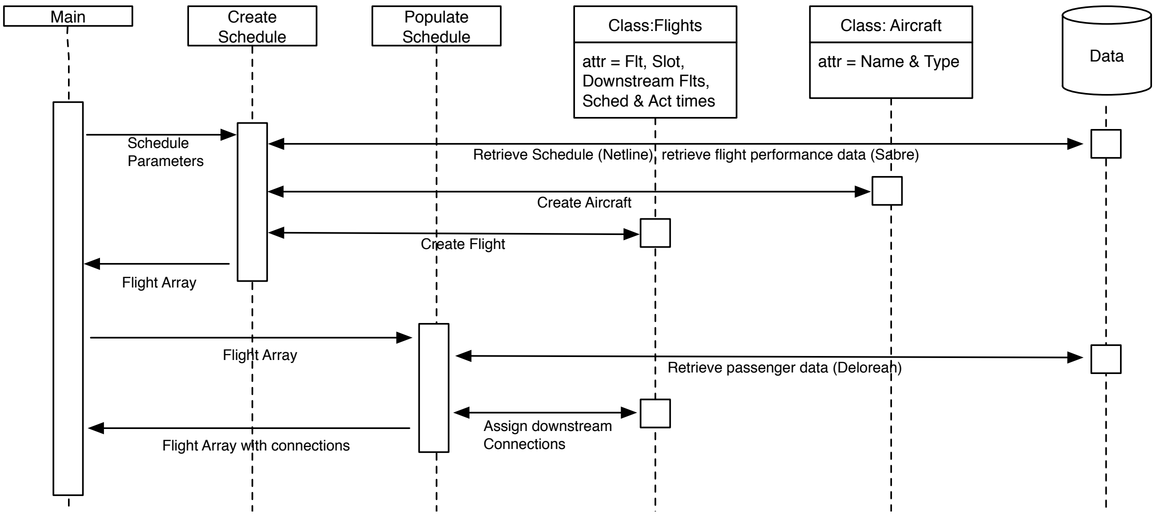


*Figure 5.2. **Specification of the data pre-processing step.** Pre-processing consists of two steps to create an array of flights from a schedule, and populate the flight array with passenger connections.*

The data pre-processing is required to create a collections of flights constructed from the schedule information and containing required stochastic parameters. A two stage process is required.

The first step, *create schedule*, is to create an array of flights from the flight schedule data and loaded with the flight performance parameters. This step is discussed in more depth in Appendix B.2.

The second step, *populate schedule*, is to load the flight schedule with populated passenger data. For this step a translation from Origin and Destination passenger data to flight connections is discussed. Further discussed in Appendix B.3.

The output of preprocessing input data for the simulation is an array of flights connected to an array of aircraft tails. The properties of the objects are as follows:

Flight: Object properties:

Identification: Code, Week Day, Flight Number, Tail
Schedule: SlotRestricted, STD, STA, SBT, STTt, Weekly Frequency
Array Location: Next Flight, Previous Fligh
Block time: Departure Airport, Arrival Airport, Mean$_{ABT}$, Std$_{ABT}$
Simulation Passengers: Mean$_{ACT}$, Std$_{ACT}$, Upward Pax Flight Array, Upward Pax Flight Array

Aircraft: Object properties:

Name, Aircraft Type, Netline Aircraft Type, Mean$_{ATT}$, Std$_{ATT}$

Following the data pre-processing is the simulation of delay scenarios, discussed in the following section.

5.2.2 Simulation

The simulation is run iteratively through all flights, a series of root delays and a preset number of simulation runs to ensure valid outcomes. The main simulation flow is shown in figure 5.3.

Both the flight object and the aircraft objects are called for when simulation the delay propagation tree. The processing of the data for the inputs of the objects is discussed in section 5.2.1.

The simulation is considered a recursive Monte-Carlo simulation as it iterates through a number of simulation cycles until valid outcomes are ensured. This section will discuss the the simulation cycle itself. How the simulation is used in a simulation experiment is discussed in section 5.3.

The delay propagation model is a self-iterative sub method within the flight object. The formalization is a shortest path algorithm, running acyclic from the source node downstream till all delay is absorbed. The conceptualization of the delay model is described in Chapter 5. Figure 5.3 shows the algorithm flow chart.

The simulation starts with a specified root delay on a flight that is set to occur during the turnaround. The ATD of the flight is determined as the STD plus the root delay. This ATD starts off an iteration along all downstream flights, and ends when the Delay is absorbed.

If there is a delay, ATD > STD, then the ATA is determined. The ATA depends on the stochastic ABT, which is stochastically determined. Then the iteration running along aircraft and passenger connections is started.

Firstly, the aircraft connection is analyzed. The earliest that an aircraft can depart is dependent on the stochastic ATT of the aircraft and if the airport is slot restricted. The outcome is a minimum ATD, which is the earliest time that the aircraft can depart.

Secondly, all feasible passenger connections are analyzed. The earliest the next flight can depart depends on the criticality of the passenger connection, and the stochastic MCT. The criticality of the connection is a boolean value that is determined from set IOCC passenger propagation guidelines (refer to section 4.4.2) and is a function of the onward flight weekly frequency and the number of passengers. The MCT is a function of the number of passengers and the type of traffic and is stochastically determined. The outcome is a minimum ATD, which is the earliest a connecting flight can depart for the passengers to connect.

From both the aircraft connection and the critical passenger connections, a minimum ATD is found that can be used as an input for the next flight. If the minimum ATD is after the STD of the flight, a delay results. The iteration along the branches of the delay propagation tree continues until the delay is absorbed in the system slack.

The outcome of the simulation is a set of flights with actual departure and arrival times, forming the basis for the creation of a delay propagation tree and a delay multiplier curve. How the outcome of the

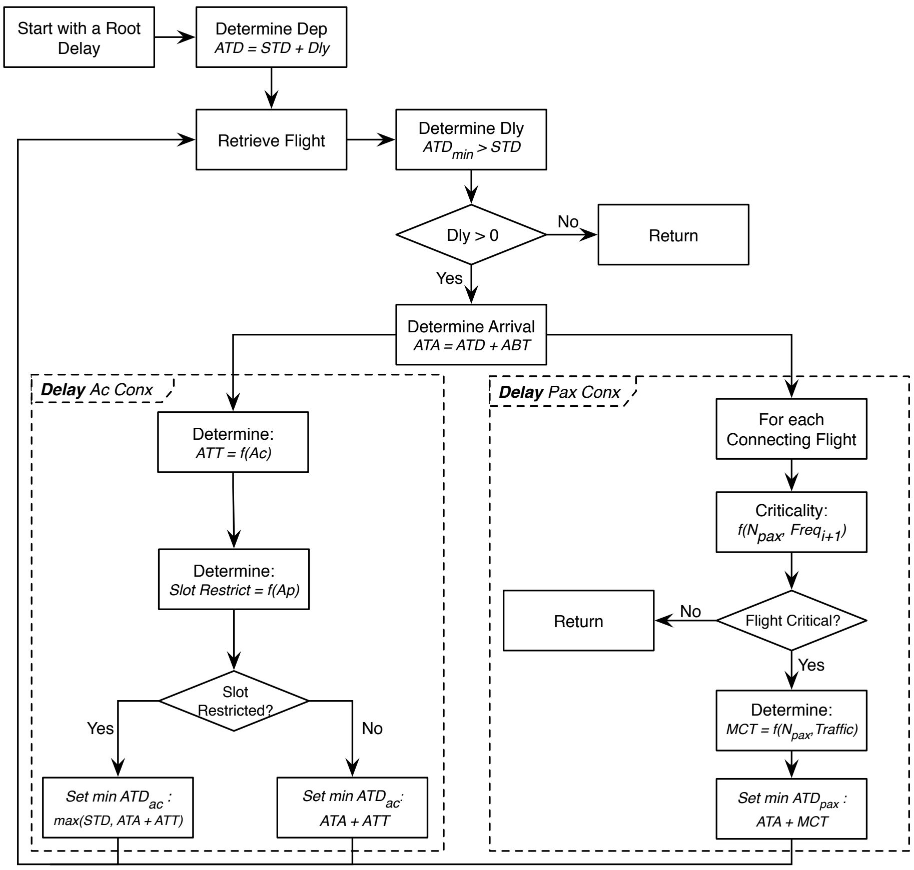


Figure 5.3. Specification of the stochastic simulation. Zoomed in version of the simulation. A shortest path algorithm that stops once all delays have been absorbed.

simulation is used in a schedule sensitivity experiment is discussed in section 5.3. First the required simulation run-length is discussed.

5.3 Schedule Sensitivity Experiment

This section describes how the previously discussed simulation is used to simulate the schedule sensitivity. As is discussed in the previous sections, the basis for the schedule sensitivity experiment is a Monte-Carlo simulation of a delay scenario forced on a flight.

The schedule sensitivity experiment is the result of 3 preliminary steps, and each can be related to the number of Flights involved, delay scenarios simulated and simulation cycles performed:

1. results in a delay propagation tree:
    - 1 Flight
    - 1 Delay scenario
    - 1 Simulation iteration
2. **Simulation run** is a series of simulation cycles that results in a range of probable delay propaga-

tion outcomes. The simulation run-length is discussed in section C. The outcome is a probability histogram of delay severities:

- 1 Flight
- 1 Delay scenario
- Multiple simulation iterations

3. **Flight delay severity simulation** results in a stochastic delay severity curve:
   - 1 Flight
   - Multiple delay scenarios
   - Multiple simulation iterations
4. **Schedule sensitivity experiment** results in a comparable list of expected delay severities per flight:
   - Multiple flights
   - Multiple delay scenarios
   - Multiple simulation iterations

The four parts of the simulation experiment are explained and illustrated with the example of delaying flight 550 to Brazzaville (BZV) on a Tuesday. This flight is the first leg of a circular flight that follows onwards to Kinshasa (FIH) and back to Nairobi (NBO). Furthermore, once arriving there is a passenger connection to Bombay (BOM).

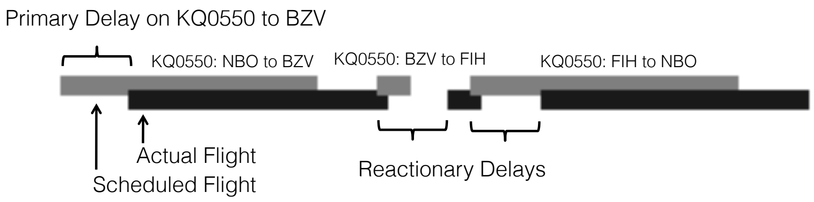
5.3.1 Simulation cycle and run

The first step in explaining the schedule sensitivity experiment is a discussion on how a simulation run (a series of simulation cycles on a specific delay scenario) leads to a range of outcomes. This forms the basis for the next step, which is the creation of a stochastic delay severity curve.

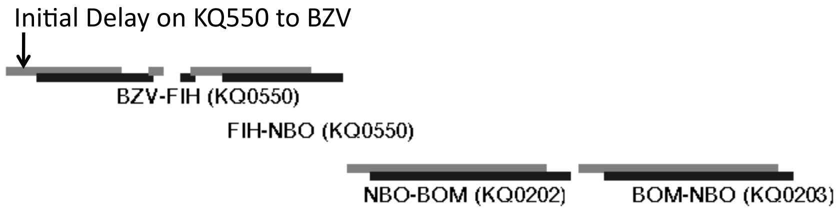
The output of the simulation cycle is a possible delay propagation tree. These trees can be visualized for comprehension of the delay impact and to aid the validation. The visualization is explained in the conceptualization phase, figure 4.2 in section 4.1. The grey top bar represents the Scheduled Block Time (SBT), and the bottom black bar represents the Actual Block Time (ABT).

To illustrate the visual outcome of a simulation cycle, figure 5.4 shows the three most likely delay propagation trees for a 30 minute delay of flight 550 to Brazzaville (BZV) on Tuesday. Most probable is that the delay will be propagated through the aircraft line of flight to Kinshasa (FIH) and back to Nairobi (NBO). This results in a delay severity of 2. A second scenario is the 30% possibility that the flight delays the outbound flight to Bombay (BOM) due protection of passenger connections. The flight to Bombay (BOM) experiences a low Block-time confidence, as such the return leg will most probably be delayed as well (see Chapter 6 with a discussion on possible schedule stability improvements).

The outcome of a simulation run is a series of simulation cycles resulting in a set of possible delay severities. The simulation run-length required is such to ensure that the outcome if valid, explained in more detail in Appendix C. This can be extended to a histogram indicating the range of probable delay severities. To explain in further detail the example of a 30 minute delay to Brazzaville (BZV) is extended. When running through one simulation run for this delay scenario a set of delay severities is found. The



(a) Scenario 1: delay impacts 2 flights downstream



(b) Scenario 2: delay impacts 4 flights downstream

Figure 5.4. Example of two simulated delay propagation trees. In the schedule scenario example, a 30 minute root delay on the flight outbound to Brazzaville (BZV) results in several delay severities. The two most likely are visualized to explain that there is range of likely delay impacts for each delay scenario.

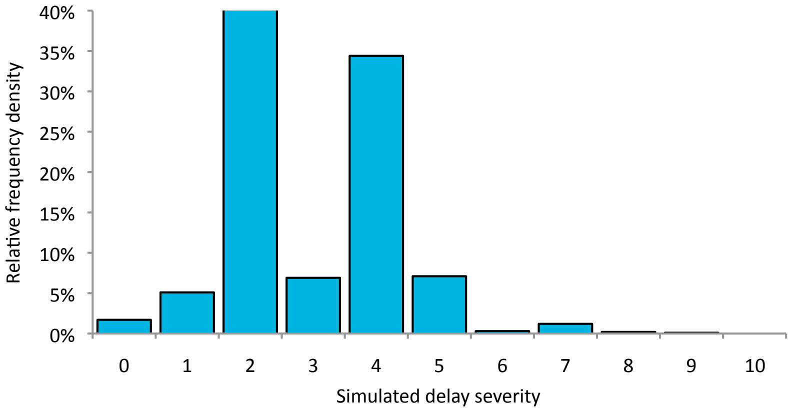


Figure 5.5. Example of a histogram of probable delay severity outcomes. A simulation run of a 30 minute primary delay on the flight outbound to Brazzaville (BZV) results in a range of delay severities which can be plotted in a probability histogram. It shows two likely scenarios of delay either 2 or 4 flights downstream.

current required simulation run-length n_{req}, is 1500 simulation cycles. These can be plotted onto a delay severity histogram as is done in figure 5.5. From this it is clear that there is a high probability that a 30 minute delay to Brazzaville (BZV) impacts 2 or 4 flights downstream. This is equivalent to the previous probability delay propagation trees explained in figures 5.4a and 5.4b.

In conclusion, a delay scenario can be simulated with a number of simulation cycles. The outcome of a simulation run is a set of delay severities which can be plotted onto a probability histogram. This forms the basis for a stochastic delay severity curve that is explained in the next section.

5.3.2 Flight delay severity simulation

The flight delay severity simulation produces a delay severity curve. This is the outcome of a series of simulation runs done per flight with an increasing primary delay. The delay severity curve plots the expected delay severity against the length of the root delay.

This concept can be illustrated by extending the example of delaying flight 550 to Brazzaville (BZV). The bounds for the duration of the root delays between 0 and 30 minutes are chosen in accordance to the academic scope as is discussed in chapter 3. The focus of this academic research project is to improve schedule robustness against nuisance delays under the assumption that the IOCC propagates delays without flight swapping or misconnecting passengers.

Figure 5.6 shows the stochastic delay severity curve for flight 550 to Brazzaville (BZV). It is an outcome of 4 simulation runs with 0 minutes, 10 minutes, 20 minutes and 30 minutes delay. The probability contours are of interpolated from the histograms of each delay scenario. The average delay severity is plotted to create a comprehensive understanding of the flight robustness.

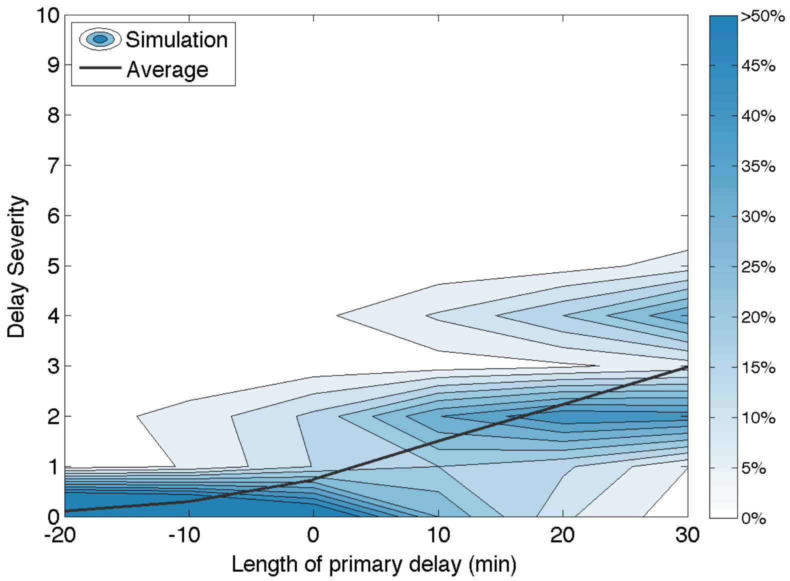


Figure 5.6. Example of the delay severity curve for flight KQ0550 to Brazzaville. An example delay severity curve to illustrate how it works. The contour plot is an indication of the probability of the delay severity as a function of the duration of the primary delay that disrupts flight KQ0550 to Brazzaville.

The stochastic delay severity curve is read along longitudinal lines of delay duration. When reviewing figure 5.6, the 30 minute delay scenario can be analyzed. From this it follows that the highest probability is a delay severity of 2 or 4. This is equivalent to the histogram found in figure 5.5.

In conclusion, a series of delay scenarios can be simulated each resulting in a histogram of expected delay severities. These can be plotted in a contour plot. The stochastic delay severity curve forms the basis for the robustness metric which ways the average delay probability over the range of primary delays.

5.3.3 Schedule sensitivity experiment

The schedule sensitivity experiment simulates the delay severity curve for each flight. From this, a robustness metric for the flight and the flight schedule is found. A robustness metric is a unit of measure proposed to compare the robustness of flights and flight schedules. It is derived through an iterative approach in cooperation with Network Planning and IOCC. The initial basis is the delay multiplier as described by Beatty et al. (1999) and AhmadBeygi et al. (2008).

The flight robustness metric proposed to compare flights is the *Expected Delay Severity* where the delay severity curve is weighed against the probability of a primary delay. This section will describe how the weights are derived and illustrate the measure according to the example of the flight to Brazzaville (BZA).

To compare flight schedules, the total of the expected delay severity can be taken. This is defined as the *Aggregated Expected Delay Severity*. Changes in the schedules stability between flight schedules can be compared.

To begin, the probability of a primary delay as this forms the basis for the weights of the robustness metric. For the scope of this research project departure delays are considered and as such the duration of a delay can be extracted from historical flight performance. The durations of historical delays can extracted from Sabre, and is shown in figure 2.8 in Chapter 2.

However, next to the delay duration the on-time and early departure scenario also needs to be taken into account. The reason for considering these scenarios is where the flight departs without delay is to take into account the effects of flight planning with negative slack time. An example of a flight rotation with negative slack-time is flight 202 to Bombay.

Figure 5.7 shows the delay probability of -20 minutes, -10 minutes, 0 minutes, 10 minutes, 20 minutes and 30 minutes. The range of delays chosen coincides with the departure time difference probability as shown in figure 5.7. The flights considered in this analysis are not delayed due to reactionary because this is the focus of the study. 32% of the flights depart early and as such the scenario of an early departure is analyzed. There is a sharp drop of the probability of a flight departing earlier then 20 minutes ahead of schedule, as such this is considered the lower bound. An upper bound of 30 minutes is chosen due to the scoping of the project to consider nuisance delays.

The robustness metric for flight i is the expected delay severity, $\bar{\zeta}_i$, defined as as a function of the average simulated delay severity at m minutes, $\hat{\zeta}_i(m)$ and the weights:

$$\bar{\zeta}_i = \begin{bmatrix} \hat{\zeta}_i(-20) \\ \hat{\zeta}_i(-10) \\ \hat{\zeta}_i(0) \\ \hat{\zeta}_i(10) \\ \hat{\zeta}_i(20) \\ \hat{\zeta}_i(30) \end{bmatrix} \cdot \begin{bmatrix} 10\% & 22\% & 49\% & 7\% & 5\% & 2\% \end{bmatrix} \tag{5.1}$$

The application of the expected delay severity, the robustness metric, is illustrated using the example of the flight to Brazzaville (BZV). Figure 5.6 shows the delay severity curve of this flight to increase due

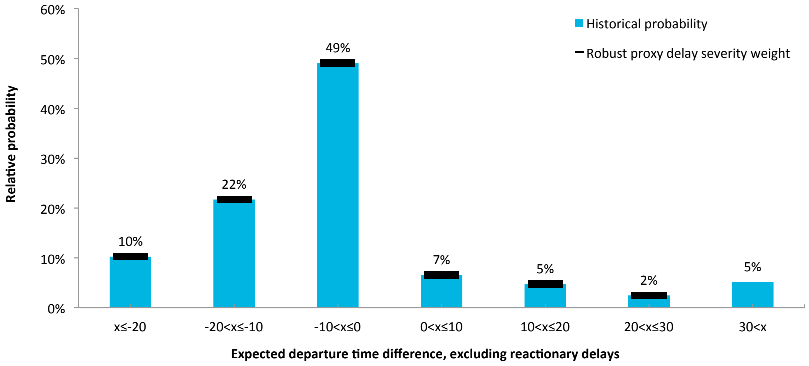


Figure 5.7. Weights of delay severity for robustness metric. *Weights chosen from data an in cooperation with the department of Network Planning to coincide with the departure time difference of flights without including flights delayed due to reactionary delays. (Flight data from September 2010 till September 2011)*

aircraft rotation and passenger connectivity delays:

$$\bar{\zeta}_{(550-BZV)} = \begin{bmatrix} 0.1 \\ 0.3 \\ 0.7 \\ 1.5 \\ 2.2 \\ 3.0 \end{bmatrix} \cdot \begin{bmatrix} 10\% & 22\% & 49\% & 7\% & 5\% & 2\% \end{bmatrix} = 1.03 \tag{5.2}$$

The found expected delay severity indicates the of robustness of the flight. When comparing this figure to other flights, which will be done in the next chapter, the criticality of the flight to the schedule is quantified. Non-critical flights have sufficient planned slack time and have an expected delay severity of 0. The light outbound to Lagos, that will be shows to be a critical flight, has a maximum expected delay severity of 4.6.

From the expected delay severities, $\bar{\zeta}_i$, measured for all flights, an aggregated expected delay severity can be computed as an overall robustness measure for the flight schedule. This figure is then comparative to use between flight schedules.

In conclusion, the schedule sensitivity experiment consists of simulating the expected delay severity for each flight. This allows to compare flights and assess overall schedule robustness by aggregating the expected delay severity for each flight. The purpose of the analysis is to study the schedule wide robustness and improve schedule stability as will be discussed in the following chapter.

6. Improving schedule stability

The preliminary analysis, discussed in chapter 2, concluded that there is a potential for Network Planning to broaden the focus on schedule stability by realizing a pro-active plan. This chapter will discuss a pro-active methodology that uses the stochastic simulation of delay propagation to improve schedule stability during the design of a seasonal schedule.

The aim of this chapter is twofold. The first goal is to describe how the simulation of the delay severity curve in combination with the analysis of historical flight performance and passenger booking data can be translated into a methodology to help improve schedule stability at Kenya Airways. During the course of this academic research, this methodology has been implemented and applied by the department of Network Planning to improve overall schedule stability.

The second goal is to explain how this methodology was applied and which results where booked in three steps. Firstly, the simulation of the baseline summer schedule is analyzed. Secondly, an alternative flight timing to Lagos (LOS) is discussed in more detail to illustrate how the methodology can help to improve schedule stability on a flight basis. Lastly, a comparative study of the improved alternative flight schedule against the baseline schedule is presented.

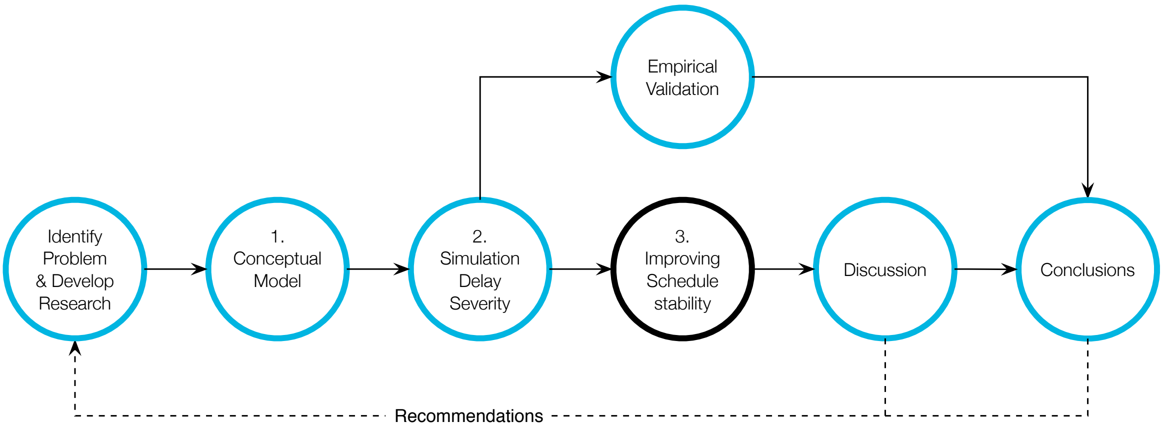


Figure 6.1. A methodology is developed and illustrated to improve schedule stability. *A methodology is made to aid Kenya Airways with improving schedule stability.*

6.1 Methodology of improving schedule stability

The first part of the chapter discusses the methodology developed to improve schedule stability using the simulation of delay severity. The methodology is shown in figure 6.2, and is used to identify critical flights and come up with a retiming plan to improve flight flight robustness.

The aim is for the Network Planning department to work structured and pro-actively towards improving the stability of the seasonal schedule. The main activity taking place is approximately 4 months prior to the start of the season[1], when a seasonal schedule is made based on improvements over the previous seasonal schedule.

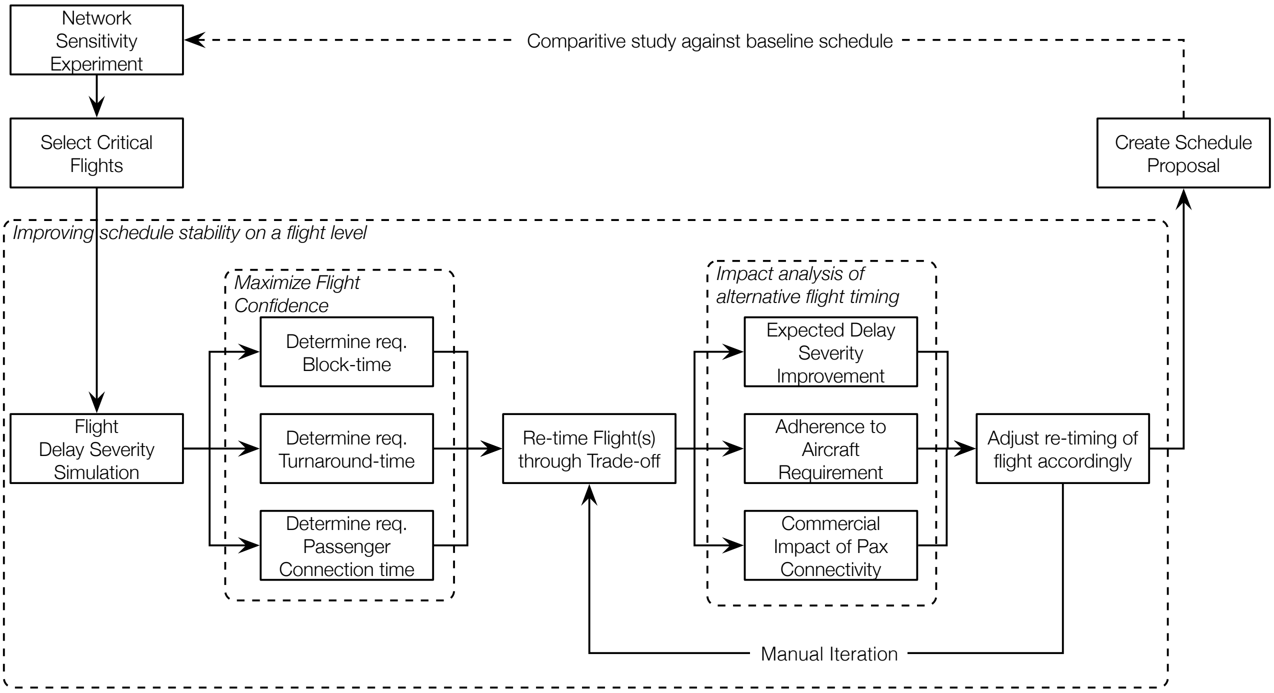


Figure 6.2. Methodology diagram for increasing schedule stability. *An existing or proposed schedule is simulated on robustness. First by comparing all flights based on the delay severity curve gradient, then zooming in to critical flights and delay scenarios. Alternative flight timings can then be made for the critical flights. An alternative flight schedule can be created to improve schedule stability.*

The methodology to improve schedule stability, shown in figure 6.2, starts by analyzing the baseline schedule. The primary robustness measure to analyze the schedule is the aggregated expected delay severity[2]. From there, to maximize effectiveness, the most critical flights are selected and further analyzed.

The improvement of the robustness on a flight level is a five-step procedure, conceptualized in figure 6.2. The first part is to analyze the flight delay severity curve through the range of delay durations.

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[1] An overview of the schedule rollout is shown in figure 2.9 in chapter 2.

[2] The simulated expected delay severity is aggregated over all flights to measure the robustness of a schedule. See chapter 5

Then, it can be determined what a confident flight timing could be, based on historical data. This considers a confident Block-time; Turnaround-time; and Passenger Connection-time. Confident Block-time levels are determined based on the historical performance on a flight leg, aircraft type and season level. For the latter two, the interaction with the preceding or subsequent flights has to be incorporated.

The third step is to create an alternative flight timing through an informal trade-off. The trade-off is informal as this allows to incorporate less formalized requirements in the re-timing decision. Such as, connectivity from non-partner airlines or the aircraft balance at Nairobi Airport to consider schedule feasibility on ground operations.

The fourth step is to determine the impact of an alternative flight timing. This step has three aspects. Foremost the improvement of the robustness of the flight, measured in expected delay severity. Secondly, the schedule improvement has to be loaded into the Netline Schedule System as to determine if the alternative schedule can still be flown by the fleet available. The third aspect to be considered is the commercial impact on the possible passenger connections.

The fifth step is to manually[3] iterate back to re-time the flight. The critical flight analyzed can be re-timed to make a concession towards schedule stability. Subsequent flights or preceding flights can also be re-timed to protect passenger connectivity where possible[4].

After several alternative flight timings are combined into one alternative flight schedule, a comparative study against the baseline flight schedule is done to understand the effects of the re-timing decisions on a schedule level. The aggregated delay severity, which is the measure of schedule robustness, is used to compare the schedules.

In collaboration with the department of Network Planning an alternative flight schedule has been created to improve the overall schedule stability. First by analyzing the baseline schedule; then by improving critical flights; and finally by studying the improvements of the alternative flight schedule. The following sections will further discuss this process. In this study, the improvement of the robustness on a flight level is illustrated using the example of the flight rotation to Lagos (LOS).

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[3] It is beyond the scope of this academic research to optimize the full schedule, as such a manual iteration is made in the trade-off between re-timing the flight for stability and the impact of the re-timing decision.

[4] This continues as the passenger connectivity of either the preceding or subsequent flights also will be considered.

6.2 Computational results of current flight schedule stability

As indicated in the previous section, the first step in improving schedule stability is to analyze the baseline schedule[5]. The analysis in this study consisted of two parts.

First, the computation of the aggregated expected delay severity and the identification of the most critical flights. Second, a fundamental analysis to understand the relationship between the three network drivers behind the schedule stability. These are identified as the Block-time confidence, Turnaround-time confidence and Passenger Connection-time confidence.

6.2.1 The baseline schedule sensitivity experiment

The base line scenario was found to have an aggregated expected delay severity of 192. This is considered the overall schedule robustness metric as it aggregates the expected delay severity[6] over all flights in the schedule.

Shown in figure 6.3, it can be concluded that there is an imbalance in the contribution of the flights to the aggregated expected delay severity. It shows that 80% of the aggregated delay severity is caused by 30% of the flight legs. This shows that the focus on improvement of a minority of flights can have a great impact on the overall schedule stability.

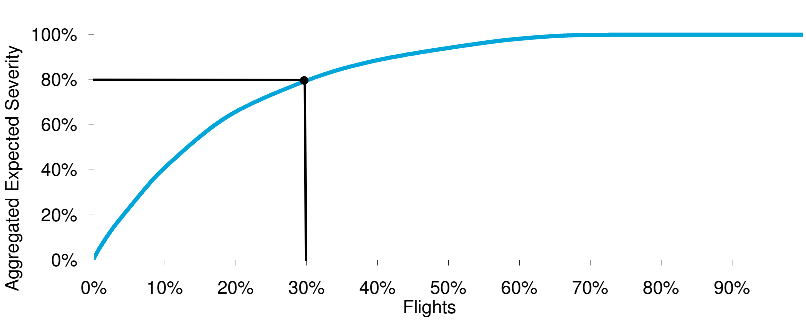

Figure 6.3. Majority of the severity is caused by the minority of the flights. *This follows the Theory of Constraint, and it can be seen from the data 30% of the flights contribute to 80% of the aggregated expected delay severity.*

Table 6.1 shows the overview of the most critical flights[7] for the schedule stability baseline schedule. The unit of robustness is the expected delay severity, $\bar{\zeta}$. From this it is found that the flight rotation to Lagos (LOS) is most critical for the stability of the schedule at Kenya Airways.

In conclusion to the schedule analysis, the critical flights can be improved to improve schedule stability. An overview of flight timing improvements is given in Appendix D. To illustrate how a flight can be

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[5] This section assesses the robustness for a busy summer week (August 22 to 28, 2011).

[6] For each flight i the expected delay severity, $\bar{\zeta}_i$, is the weighted average of the simulated delay severity through a range of primary delay scenarios increasing in duration. Discussed in chapter 5

[7] The overview presents the flights in a condensed fashion for presentation purposes. As such, flights occurring multiples times a week or consisting of multiple flight legs are presented as one. The indicated minimal and maximum expected delay severity, $\bar{\zeta}$, consider the range of legs.

Table 6.1. Overview of the critical flights. This table has the overview[7] of them 30% sensitive flights that account for 80% of the aggregated expected delay severity found during schedule sensitivity experiment of the last week of august, 2011.

FltNum	DepAp	Via	ArrAp	Max(ζ)
KQ0533	NBO		LOS	2.4
KQ0702	NBO	HRE	LUN	2.3
KQ0311	DXB		NBO	2.2
KQ0532	NBO		LOS	2.1
KQ0320	NBO	KRT	CAI	2.0
KQ0560	NBO	NDJ	COO	1.9
KQ0542	NBO	LOS	COO	1.8
KQ0548	NBO	COO	OUA	1.7
KQ0546	NBO	OUA	COO	1.6
KQ0321	CAI	KRT	NBO	1.6
KQ0722	NBO	LLW	LUN	1.6
KQ0550	NBO	BZV	FIH	1.4
KQ0724	NBO	LUN	LLW	1.2
KQ0574	NBO	BGF	DLA	1.1
KQ0714	NBO	HRE	GBE	1.0
KQ0202	NBO		BOM	0.9
KQ0310	NBO		DXB	0.9
KQ0552	NBO	FIH	BZV	0.9
KQ0700	NBO		HRE	0.8
KQ0576	NBO	BGF	DLA	0.7
KQ0500	NBO		DLA	0.7
KQ0101	LHR		NBO	0.7
KQ0554	NBO		FIH	0.7
KQ0586	NBO	FBM	NLA	0.6
KQ0468	NBO	BJM	KGL	0.6

retimed, the alternative flight plan for the rotation to Lagos (LOS) is discussed in section 6.3.

6.2.2 The relation between the network drivers and the schedule stability

The second step is to study the fundamental relationship between the three network drivers and the schedule stability. These have been identified as the Block-time confidence, the number of critical downstream passenger connections, and Turn-time confidence.

Figure 6.4 shows a statistical correlation analysis for all flights relating the expected delay severity with the Block-time confidence[8]. The correlation is -0.39, indicating a medium strong relationship. This can be expected because if the Block-Time confidence is low the probability of the aircraft arriving late for the next flight is higher.

The relationship between the downstream passenger connectivity and the expected delay severity

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[8] Block-time confidence is the historical probability that the flight's Actual Block-Time (ABT) is shorter then the Scheduled Block-Time (SBT).

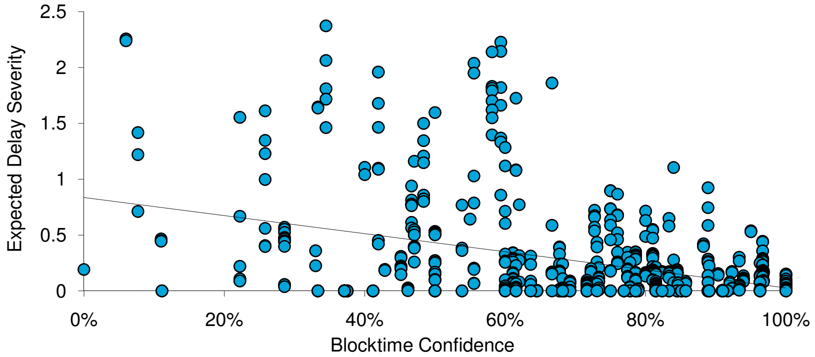

Figure 6.4. Impact Block-time confidence on delay severity. The simulation shows a correlation of -0.39 between the Block-time confidence level and the expected delay severity.

is shown in the statistical correlation analysis in figure 6.5. It indicates the number of downstream critical passenger connections. Defined here as passenger connections with less than 30 minutes slack-time [9] and critical according to the IOCC rules on protecting passenger connectivity. The results is that there is a positive correlation of 0.19, however mathematically this relationship is considered weak. The flight shown in figure 6.5 with over 4 critical connections is flight 311 inbound from Dubai (DXB).

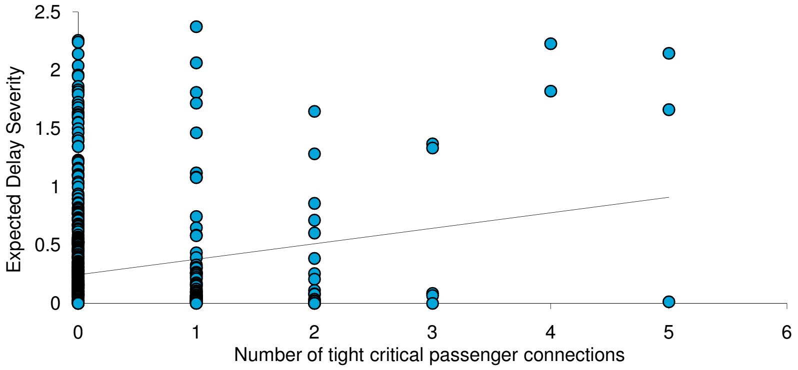

Figure 6.5. Impact downstream passenger connectivity on delay severity. The simulation shows a positive weak correlation of 0.19 between the number of critical passenger connections and the expected delay severity.

The third network driver is the Turnaround slack-time. The relationship with the expected delay severity is shown in figure 6.6. As the turnaround performance is measured on an aircraft type basis, the theoretical Turnaround slack-time can be computed as the difference between the Programmed Turnaround-Time (PTT) and the aircraft-type average turnaround time. The correlation is then taken between the theoretical Turnaround slack-time and the expected delay severity, shown in figure 6.6 that the correlation is -0.21. This coincides with what is expected, as the probability of a delay propagating to the next flight increases if there is less ability on absorbing the slack during the turnaround. However, there are some anomalies which are related to propagating delays through passenger connections.

In conclusion, it can be said that all three network drivers are correlated to the expected delay severity as is intuitively expected. However, all correlations are considerable weak by itself. As such, it can be concluded that the impact on the schedule stability lies in the combination of the Block-time; Turnaround-

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[9] This amount has been chosen as the simulation studies nuisance delays of up to 30 minutes

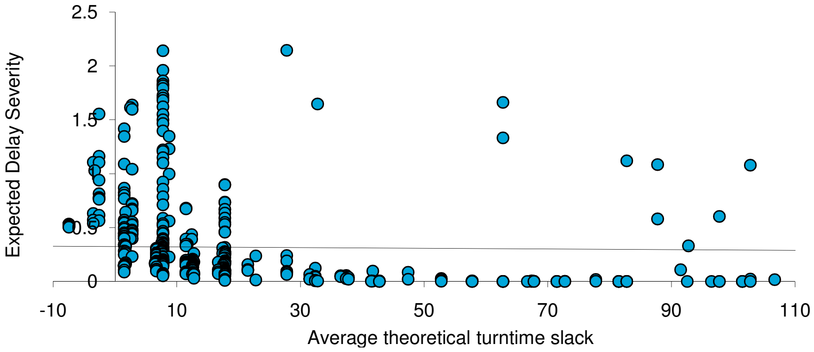

Figure 6.6. ***Impact Turn-time confidence with delay severity.*** *The simulation shows a negative correlation of -0.21 between the theoretical amount of Turn-time slack the expected delay severity.*

time; and Passenger connections. This can be found by simulating the flights individually.

6.3 Case: Improvement of Lagos rotation

This section illustrates how flight rotations can be retimed in order to improve schedule stability using the example of the flight to Lagos (LOS). As discussed in the previous section, the flight rotation to Lagos (LOS) is the most critical flight as the contribution to the aggregated delay severity is largest. As such, in collaboration with Network Planning Department a plan to retime the flight rotation was made. This process is the synthesis of the exercise using the delay severity simulation as a tool to improve schedule stability.

This section follows the workflow diagram shown in figure 6.2. First the expected delay severity curve; Block-time; Turnaround-time and Passenger Connection-time are analyzed. Then, a plan to retime can be made that is a trade-off between maximizing the robustness and minimizing the impact on passenger connectivity whilst considering the aircraft constraint.

That said, a note must be placed to indicate that the improvement scenario considers flying a Boeing 767-300 to Lagos. This is the case the majority of the year. The reason to underline this is the flight performance difference between a Boeing 767 and 777.

6.3.1 Analysis of the expected delay severity curve

The rotation to Lagos can be analyzed on schedule stability using the delay severity curve[10], shown in figure 6.7 for the flight outbound to Lagos. The expected delay severity, $\bar{\zeta}$, for this flight is 2.46. This found to be high due to two reasons.

Firstly, when flight KQ0352 is not delayed the average delay severity is simulated to be 1.7. This figure indicates that the probability of arriving on-time in Lagos is low. It must be concluded that focus should be placed to create slack in the rotation to Lagos.

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[10] Explained in more detail in chapter 5.

Secondly, in the higher ranges of delays the average delay severity increases to 6. This indicates that there is a tight connectivity towards onwards flights which results in a large cascading effect. As such, focus should be placed in creating connectivity slack for aircraft and passengers.

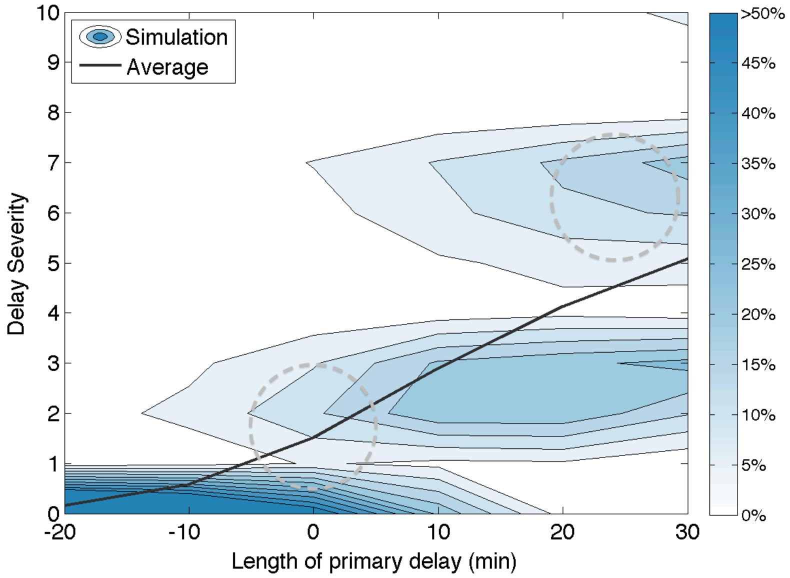

Figure 6.7. An analysis of the delay severity curve for flight KQ0352 to Lagos. The simulation of the flight for the baseline scenario shows a high expected delay severity, $\bar{\zeta}$, of 2.46. In both the shorter and longer ranges of the delay scenarios the impact on subsequent flights is large due to low Block-time confidence and short connections for both the aircraft and passengers.

6.3.2 Analysis of block-time confidence

The Block-time of the rotation is analyzed for flying a Boeing 767-300. As shown in figure 6.8, the block-time confidence level is low. The low Block-time confidence causes a high probability of the aircraft arriving late for a next flight or downstream passenger connection. This shows in the current arrival punctuality into Nairobi is 21% and directly impact the performance at the hub airport.

It should be concluded from this analysis that block times should be increased on both directions. The outbound flight could benefit from 5 minutes and the inbound flight from 15 minutes.

6.3.3 Analysis of turnaround confidence

The Planned Turnaround Time in Nairobi is tight due to the connected aircraft rotations from Lagos and Dubai. Currently the aircraft rotation of Lagos (LOS) is such that when Flight KQ0533 returns from Lagos to Nairobi (NBO) it departs to Dubai (DXB) on flight KQ0310 after 50 minutes PTT. When the flight returns from Dubai on KQ0311, it mostly continues to Lagos (LOS) on flight KQ0532 after 60 minutes on ground.

The turnaround time confidence can be found based on historical flights[11]. Figure 6.9 shows that the Turnaround confidence for a Boeing 767-300 with 50 minutes is about 45%.

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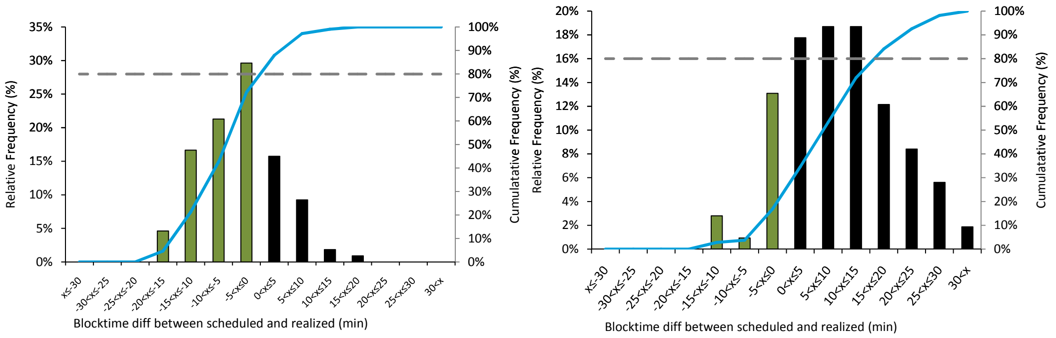
[11] The Minimum Turnaround-Time (MTT) is estimated using dataset with flights delayed only due to aircraft rotation as this generates an accurate estimator. Further discussed in chapter 4.



(a) Flight KQ0532 to Lagos, confidence of 72%
(b) Flight KQ0533 from Lagos, confidence of 19%

Figure 6.8. Lagos Block-time analysis. Block-time analysis to Lagos on a Boeing 767. The Block-time confidence is analyzed for the summer season on both directions.

It should be concluded from this analysis to split the aircraft rotations of Dubai and Lagos. When the aircraft returns from either Lagos or Dubai, it should depart on a later flight that allows for a longer Turnaround-time.

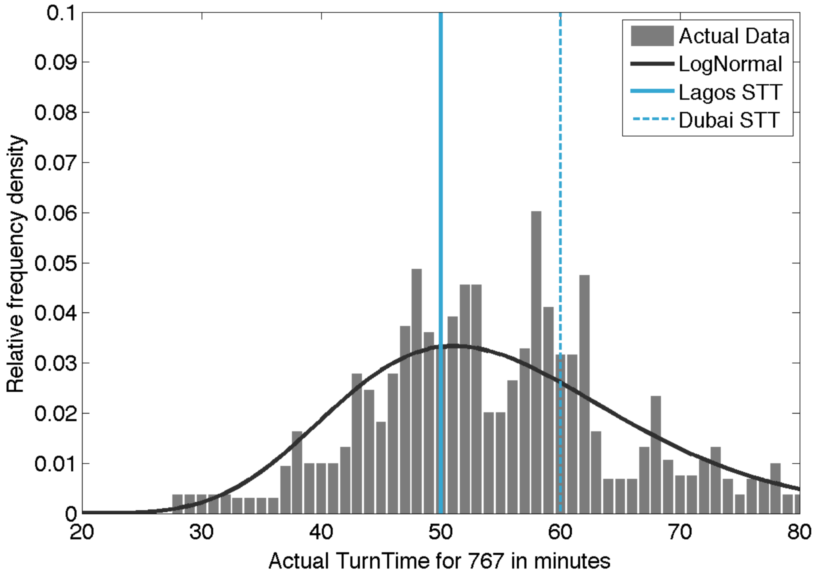


Figure 6.9. Turnaround confidence for Lagos and Dubai flights. With 50 and 60 minutes, there is a low turnaround confidence..

6.3.4 Analysis of passenger connectivity

Increases in the Block-time of the Lagos (LOS) rotation requires advancing the STD of flight KQ0532 or delaying the STA of flight KQ0533.

Advancing the STD of Flight KQ0533 can be done if all connections can be made, meaning no breach of the 50 minutes MCT requirement. The inbound feeding connections are shown in table 6.2. As can be seen, the connection from flight KQ0311 inbound from Dubai (DXB) is at a minimal guideline of 50 minutes.

Similarly, delaying the STA of Flight KQ0533 can be done if all connections remain. The de-feeding connections are shown in table 6.3. Just as the feeding connections, here the Dubai (DXB) de-feed of flight KQ0311 is at a minimal guideline of 50 minutes.

In conclusion, there are no possibilities to retime the flight rotation as to create additional Passenger Connecting slack without breaking a passenger connection. By either advancing or delaying the Lagos (LOS) rotation will break the connection into or from the Dubai (DXB) flight.

Table 6.2. Overview of the passenger connectivity onto flight KQ0532. The shortest connecting flights to flight 532 to Lagos that connect in Nairobi. There is no slack with the connection from Dubai as the guideline require 50 minutes connecting time to transfer an expected 14 passengers. (Schedule 22 august to 28 august 2011)

FltNum In	WkDy Pattern	DepAp	Via	STA	PCT	FltNum Out	ArrAp	nPax
KQ0311	1234567	DXB	NBO	340	50	KQ0532	LOS	14
KQ0417	1234567	EBB	NBO	320	70	KQ0532	LOS	5
KQ0406	1…5.7	JIB	NBO	315	75	KQ0532	LOS	2
KQ0720	12.4.6.	HRE	NBO	310	80	KQ0532	LOS	8
KQ0861	…4.67	BKK	NBO	305	85	KQ0532	LOS	21
KQ0887	1.3.5	BKK	NBO	305	85	KQ0532	LOS	16

Table 6.3. Overview of the passenger connectivity out of flight KQ0533. The shortest connections that flight KQ0533 from Lagos connects to in Nairobi. With 15 passenger transferring to Dubai, guidelines require a Minimum Connecting Time of 50 minutes, which means that there is no slack on the connection to Dubai. (Schedule 22 august to 28 august 2011)

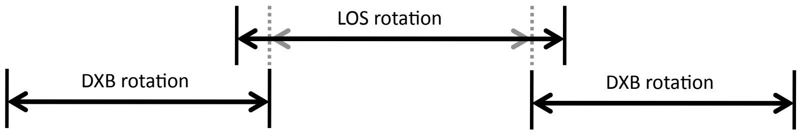
FltNum In	WkDy Pattern	DepAp	Via	STA	PCT	FltNum Out	ArrAp	nPax
KQ0533	1234567	LOS	NBO	1530	50	KQ0310	DXB	15
KQ0533	1234567	LOS	NBO	1530	90	KQ0618	MBA	3
KQ0533	….5.7	LOS	NBO	1530	115	KQ0552	FIH	2
KQ0533	1234567	LOS	NBO	1530	130	KQ0764	JNB	5
KQ0533	4	LOS	NBO	1530	195	KQ0734	LUN	7
KQ0533	6	LOS	NBO	1530	195	KQ0732	LLW	4

6.3.5 An alternative flight timing for Lagos

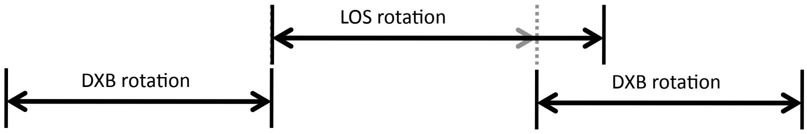
The rotation to Lagos (LOS) is a rotation with negative slack during the Block-time; tightly planned turnarounds in Nairobi; and tight passenger connections. This is shown and discussed in the previous sections.

An alternative flight timing for Lagos (LOS) is made in collaboration with Network Planning Department as a tradeoff between achieved levels of schedule stability; adherence to aircraft requirements; and the commercial impact of passenger connectivity.

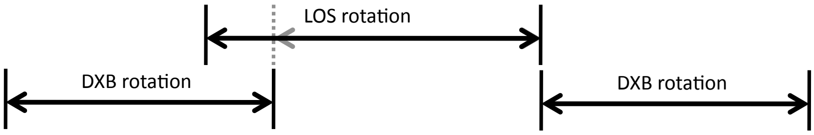
The basis for the alternative flight timing is to lengthen the rotation as to increase Block-time confidence. Figure 6.10 visualizes the planning conundrum of how the Lagos rotation connects to the Dubai rotation. Maintaining full connectivity is not possible when increasing the Lagos rotation. For example, by advancing the Lagos rotation it is on time to connect to Dubai. However, this disconnects the flight from Dubai. This conundrum is solved by daily alternating flight times of Lagos to accommodate connections to and from Dubai.



(a) Current situation, Lagos requires more block time



(b) Delaying the Lagos rotation will allow for a connection from Dubai, but disconnect the connection to Dubai.



(c) Advancing the Lagos rotation will allow for a connection to Dubai, but disconnect the connection from Dubai.

Figure 6.10. Conceptualization of the connectivity conundrum between Lagos and Dubai. The current situation, 6.10a, requires an increase in block time to and from Lagos. However, this interferes with the connectivity with Dubai. The possibility to either delay, 6.10b, or advance, 6.10c, will disconnect with a Dubai flight.

The alternative flight timing, shown in table 6.4, is based on daily alternating connectivity between Lagos and Dubai. The days chosen to connect, as is shown in figure 6.11, was done in cooperation with the department of Revenue Management for a clear market view and a passenger analysis from Delorean.

On Tuesday, Wednesday, Thursday and Saturday the Lagos rotation is advanced with 20 minutes as to connect passengers from Lagos to Dubai. 20 minutes advancement does not breach further minimum passenger connection times, shown in table 6.2.

By delaying the Lagos rotation on Monday, Friday and Sunday a connection from Dubai to Lagos is made with 70 minutes passenger connectivity. This increases the passenger connectivity slack and reduces the probability of a large cascading delay propagation. Furthermore, the connection on Tuesday and Thursday of flight KQ0318 from Dubai (albeit via Muscat) to Lagos can be considered as it arrives at 0200 UTC with 2hr30min Passenger Connecting Time.

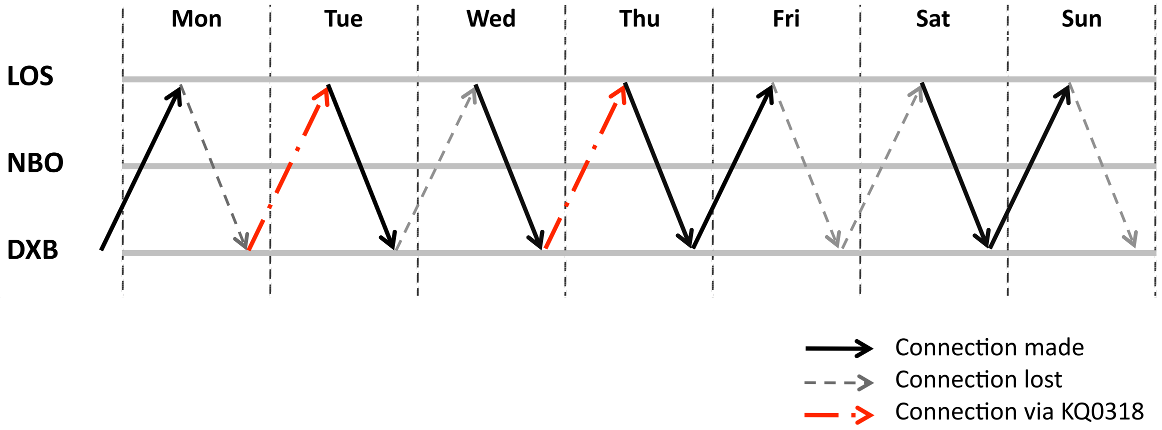


Figure 6.11. Alternating connectivity proposal for Lagos. *The proposal advanced or delays the Lagos flight to increase block time. Connectivity to Dubai is daily alternating. When using flight KQ0318 from Dubai (albeit via Muscat) as a viable connection to Lagos, delaying only on day 1, 5 and 7 allows for a balanced connectivity capacity between Lagos and Dubai.*

Table 6.4. The alternative flight plan proposed for the flight to Lagos. *The flights to Lagos can be retimed as to allow for more Block-time, Turnaround-time and Passenger Connection-time. The connectivity between Lagos and Dubai is daily alternating. The implementation date for the proposal is set at february 2012.*

Flt Num	**DepAp**	**ArrAp**	**Wk**	**Proposed ∆BlkTime**	**Proposed ∆STD**	**Proposed ∆STA**
KQ0532	NBO	LOS	1..5.7	+5	+20	+25
KQ0533	LOS	NBO	1..5.7	+15	+25	+40
KQ0532	NBO	LOS	.234.6.	+5	-20	-15
KQ0533	LOS	NBO	.234.6.	+15	-15	0

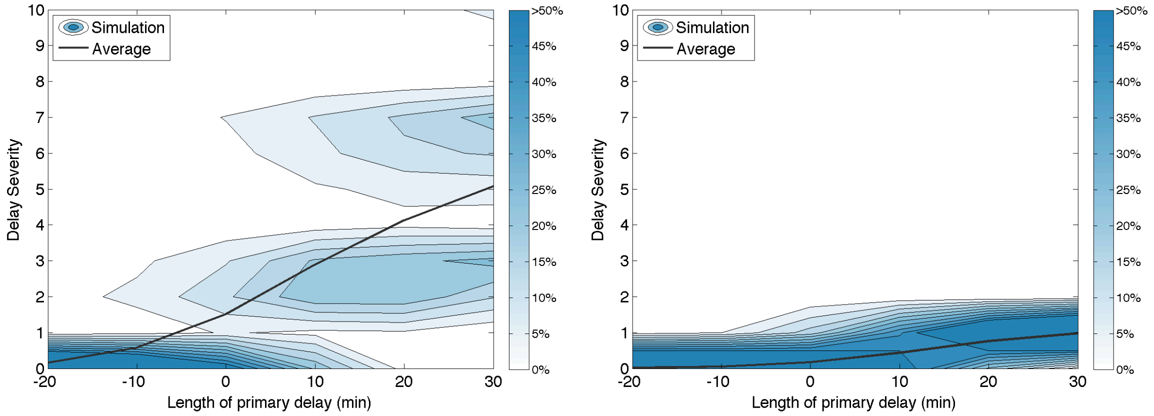
6.3.6 Impact analysis of the alternative flight plan

This section discusses the impact analysis of the alternative flight plan, shown in table 6.4, on the flight robustness and on the required aircraft.

The improvement of alternative flight timing to Lagos (LOS) on the delay severity curve is shown in figure 6.12. Throughout the range of delay durations, an improvement is realized.

The effect of adding Block-time is visible in the reduction of expected delay severity along the shorter range of delays. Figure 6.12a shows that flights departing on-time to Lagos will probably delay the flight back and flight KQ0311 to Dubai. By removing the negative slack-time through an addition of SBT, an improvement in schedule stability in the shorter ranges of delays is visible.

The effects of increasing slack in the connectivity on aircraft and passengers is visible in a reduction of expected delay severity along the longer range of delays. This is done by increasing the turnaround times at Nairobi and increasing the Passenger Connection Times (PCT) between the flight from Dubai, KQ0311, and the flight to Lagos, KQ0532. The latter is advantageous for the heavy cargo transferred from Dubai to Lagos. Furthermore, as is discussed by AhmadBeygi et al. (2008), adding slack half-way the delay chain is optimum. This is done by alternating daily on a greater PCT or a full disconnect.



(a) Base, $\bar{\zeta}$=1.4 **(b)** Improvement, $\bar{\zeta}$=0.2

Figure 6.12. Improvement in robustness for flight KQ0532 to Lagos. *Improvements are visible throughout the range of delays due to extra Block-time and additional Passenger Connection-time from Dubai onto Lagos.*

The final step in this study is to discuss is the impact of the alternative flight timing on the requirements of the number of aircraft used. The current proposed flight timing does not allow for an aircraft to fly both rotations to Dubai and Lagos. When integrating the schedule into Netline, it showed that the current number of 767-300's cannot handle the required set of flights whenever there was large maintenance planned. As such, the alternative flight plan as suggested in this study will be implemented per February 2012. By then, the fleet will be strengthened with an extra leased 767.

In conclusion, the re-timing proposal will have a large impact on improving schedule stability. In the next section it will be described how the implementation of this alternative flight time together with other flights will lead to an overall more stable schedule.

6.4 Computational results of the alternative flight schedule stability

The purpose of the synthesis in this section is to simulate the improvements in robustness that the combined alternative flight timings have. In collaboration with Department of Network Planning, a set of alternative flight timings have been made to improve on overall schedule stability. A full overview of these is found in Appendix D.

When the alternative flight schedule is simulated, the aggregated expected delay severity[12] computed has decreased from 192 to 157. This shows that an overall increase of schedule stability is possible. The improvements in stability can also be analyzed on a flight level.

In an overview shown in table 6.5 of the top 25 most critical flights, 13 have a decreased expected delay severity, $\bar{\zeta}$. The largest improvement is found on the Lagos (LOS) route. The alternative timing on the circular flights Khartoum (KRT) and Cairo (CAI) also decreases the expected delay severity, $\bar{\zeta}$, of the feeder flight to Lusaka (LN) and Lilongwe (LLW).

In conclusion, simulating the alternative flight schedule has shown a positive impact on schedule stability with minimal consequences of passenger connectivity and adherence to the required number of aircraft. As such, the implementation of several low impacts flight timings has been realized per September 2011. The alternative flight timing to Lagos is being implemented as per February 2012. A full overview of the alternative flight schedule, and the individual effects on schedule stability, is found in Appendix D.

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[12] The aggregated expected delay severity is discussed in section 5.3.3 to be the robustness metric to compare flight schedules.

Table 6.5. Overview of the robustness improvements of the critical flights *Overall aggregated improvement from 303 to 252. Initial analysis shows that 30% sensitive flights account for 80% of the aggregated expected delay severity. The consequences of the alternative flight schedule on the schedule stability is that 13 of the most in-stable flights improve their expected delay severity,* $\bar{\zeta}$.

FltNum	DepAp	Via	ArrAp	Max($\bar{\zeta}$)	Difference of Max($\bar{\zeta}$)
KQ0533	NBO		LOS	1.1	-1.3
KQ0702	NBO	HRE	LUN	0.5	-1.8
KQ0311	DXB		NBO	2.2	0.0
KQ0532	NBO		LOS	0.7	-1.5
KQ0320	NBO	KRT	CAI	1.2	-0.8
KQ0560	NBO	NDJ	COO	1.8	-0.1
KQ0542	NBO	LOS	COO	1.5	-0.4
KQ0548	NBO	COO	OUA	2.3	0.6
KQ0546	NBO	OUA	COO	1.6	0.0
KQ0321	CAI	KRT	NBO	1.2	-0.4
KQ0722	NBO	LLW	LUN	0.5	-1.1
KQ0550	NBO	BZV	FIH	1.2	-0.2
KQ0724	NBO	LUN	LLW	0.4	-0.8
KQ0574	NBO	BGF	DLA	1.1	0.0
KQ0714	NBO	HRE	GBE	1.0	0.0
KQ0202	NBO		BOM	0.6	-0.4
KQ0310	NBO		DXB	0.9	0.0
KQ0552	NBO	FIH	BZV	0.9	0.0
KQ0700	NBO		HRE	0.8	0.1
KQ0576	NBO	BGF	DLA	0.7	-0.1
KQ0500	NBO		DLA	0.7	0.0
KQ0101	LHR		NBO	0.9	0.2
KQ0554	NBO		FIH	0.5	-0.2
KQ0586	NBO	FBM	NLA	0.7	0.2
KQ0468	NBO	BJM	KGL	0.6	0.0

7. Verification and Validation

Verification is the process of establishing the transformational correctness, whereas validity deals with the model representational accuracy.

The verification and validation occurs on the simulation of the delay severity. It is only if there is acceptance of the simulation results by Kenya Airways that the conclusions and recommendations can be implemented, shown in figure 7.1 This occurs after four criteria are satisfied. (1) if the assumptions are reasonable; (2) the data is valid; (3) there are no computational errors; and (4) the simulation results are viable.

This chapter will discuss two main aspects. Firstly, the independence of the building blocks[1] that form the conceptual model. Secondly, the simulated flight delay severity curve is validated using empirical delay duration against delay severity points.

With that, a note should be made. The purpose of the validation processes discussed in this chapter is not to prove the absolute correctness of the simulation. it is the aim for the validation process to prove, within the prescribed conditions and set constraints, that the simulation model has realistic outputs. Kaplan (1998) argues that it is sufficient to show that the model provides correct results and the findings are sufficiently validated such that the study of the simulation provides sufficient insight into the factual world.

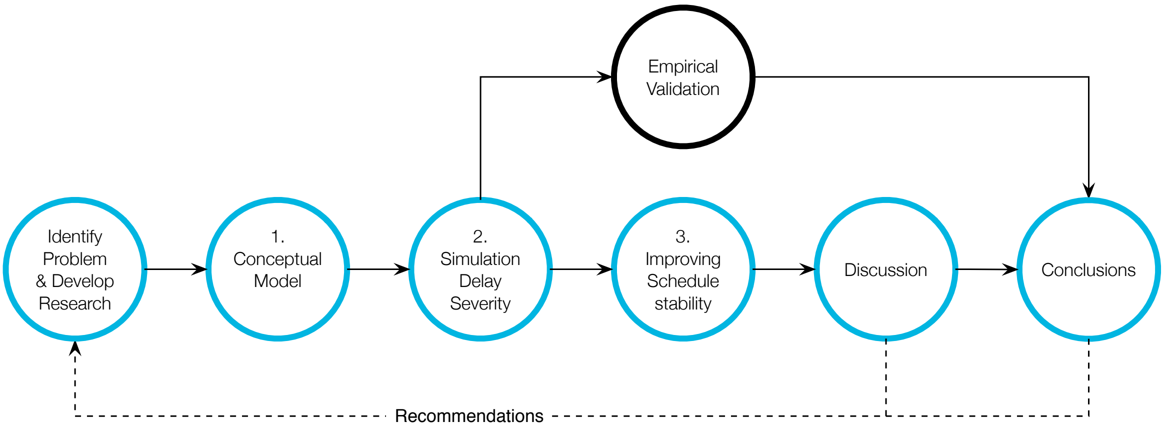

Figure 7.1. The simulation is validated and verified. *Validation and verification follows the build of the simulation.*

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[1] The building blocks are the Block-time, Turnaround-time and Passenger Connecting-time. The purpose of the validation is to ensure independence of the event with respect to the previous flight Actual Time of Arrival.

7.1 Overview of verification and validation methods used

To set the scene, the main points of the verification and validation theory applied in this academic research are discussed. Balci (1998) describes how the purpose of the verification and validation process is to ensure that the simulation fully comprehends the problem; credible and accurate simulation results are made; sufficient confidence by Kenya Airways is created as to accept the recommendations. Sargent (1984) discusses the four main methods of verification and validation to achieve this:

Conceptual model validity performed on the conceptual design to ensure correct assumptions and that the representation is reasonable. The approach used is based on ensuring face validity and empirical validation. Face validity is the process performed by knowledgeable persons as they intuitively assess if the model outcomes are reasonable Hermann (1967). Section 7.2 will discuss validating the independence of the building blocks for the conceptual model using a statistical correlation analysis on historical data.

Data validity ensures that the data and manipulation operations are correct. An important aspect of simulation models to to ensure that required data input is correct. Geoge Fuechsel (1950's) emphasized that bad inputs can form a condition that leads to bad outputs (Lidwell et al., 2010).

To ensure valid input data, Perry (2006) discusses three main aspects that needs to be addressed. First, it must be ensured that correctly defined data is used. For example, ensuring that all flight numbers are three digit numerical values. The second aspect is to ensure that proper data manipulation operations are applied. For example, when transforming the operational flight dates into by the simulation usable formats. The third aspect is to ensure that the data is properly used during the simulation. A further discussion on the import of data for the simulation is found in Appendix B.

Computational verification In order to achieve this, the development of the model occurs in a cyclic approach, where new features are added and verified sequentially. This approach increases moments of model verification. During these, several methods have been applied.

First, the informal technique considered as a desk check, or the self-inspection of one's work. To be effective, it is performed by another person as it is difficult for the developer to identify the errors in the form of code walkthroughs and inspection (Adrion, 1982). During the development of the Block-time confidence module mainly Sammy Muaa (Senior Schedule Analyst), Doreen Maiteri (Senior Schedules Analyst) and Maxine Kibas (Schedules Analyst) were involved.

Second, the visualization of simulation process maps using Unified Modeling Language diagrams isused to examine the correctness of the simulation structure. Balci (1998) discusses that this can ensure that there are no anomalies, excessive levels of nesting or unconditional branches on a programming code level of the simulation.

Operational validity is required to ensure acceptance of findings. The main purpose of this chapter is to describe the process of achieving operational validity through finding the empirical relationship between delay duration and severity. Discussed in section 7.3, this backward testing assesses if the simulation of a flown flight schedule coincides with what has occurred.

7.2 Modeling of independent events

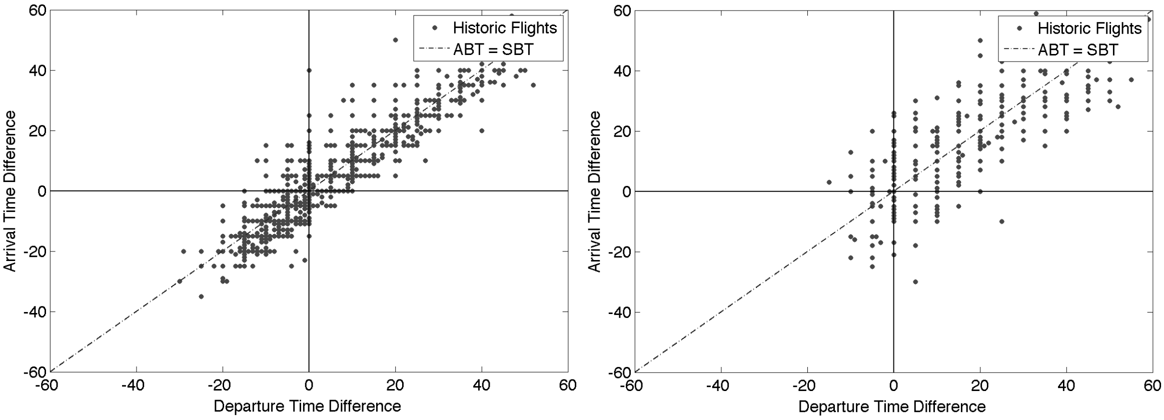
This section discusses how from historical data the modeling of the building blocks independent of the delay is justified. This forms the assumption that processes do not speed up if the flight is delayed.

The building blocks are the Block-time, Turnaround-time and Passenger Connecting-time. The Block-time should be independent of the Actual Time of Departure (ATD). The Turnaround-time and the Passenger Connecting-time should be independent of the Actual Time of Arrival (ATA). Validating this assumption can be done using the historical flight performance dataset from Sabre. Each will be discussed.

7.2.1 Validating independent modeling of BlockTime

The assumption to model the Block-time as an independent event with respect to the ATD can be validated through a statistical correlation analysis between the departure and arrival time difference. A high correlation indicates that are no structural measure in place to speed up the flight if the aircraft departs late.

Figure 7.2 shows two examples of the correlation analysis, showing a high correlation for both. The difference in correlation between the two examples indicates that even for slot restricted airports such as Dubai, the correlation is sufficiently strong. As such, it is concluded that it is a valid assumption to model the Block-time as an independent event with respect to the ATD.



(a) Nairobi to Mombasa, ρ=0.93 **(b)** Dubai to Nairobi, ρ=0.78

Figure 7.2. Validating the independent modeling of the Block-time. *The relationship between departure and arrival time difference of two sets of scheduled flights is shown through a statistical correlation analysis. The high correlation indicates possibility to model the Block-time as an independent event. Two examples include Mombasa (7.2a) and Dubai (7.2b) flights. (Data from September 2010 till September 2011)*

7.2.2 Validating the modeling of independent turn-arounds

The assumption to model the Minimum Turnaround-time as an independent event with respect to the ATA can be validated through a statistical correlation analysis between the arrival time difference and the Actual Turn-around Time (ATT) of an aircraft.

The assumption is if the required Turnaround-time can decrease if there is a time pressure due to a delayed aircraft. This notion does hold ground when there is sufficient slack programmed. However, when analyzing flights that are only delayed due aircraft reactionary it shows that there is little room for shortening the processes.

Figure 7.3 shows the correlation analysis for a 767-300 between the arrival time difference and the Actual Turn-around Time, indicating a positive correlation of 0.07. This indicates that, statistically speaking, when aircraft are arriving later the ATT is more likely to increase than decrease. However, the correlation is low and as such it can be concluded that it is a valid assumption to model the MTT as an independent event.

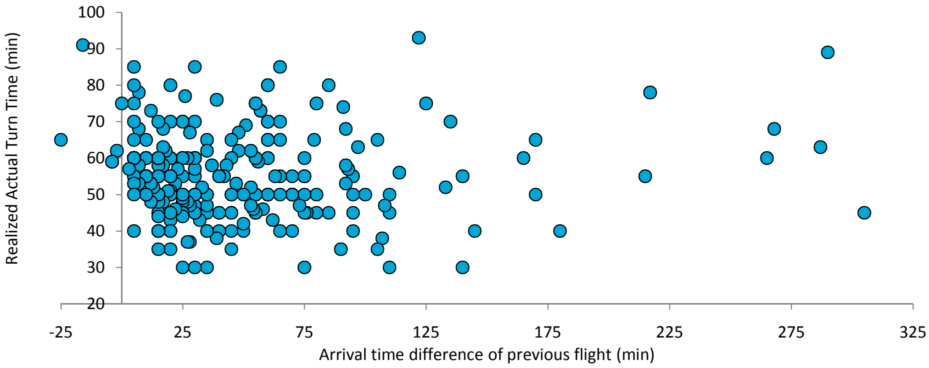


Figure 7.3. Validating the independent modeling of the MTT. *A statistical correlation analysis is made to show a low correlation between the arrival time difference and the ATT. The example shows the correlation for a Boeing 767-300 to be 0.07. This validates the notion to model the MTT as an independent event. (Data between September 2010 and September 2011. 305 flights analyzed for a Boeing 767-300)*

7.2.3 Validating the modeling of an independent ACT

The assumption to model the Actual Connecting Time (ACT) as an independent event with respect to the ATA can be validated through a statistical correlation analysis between the arrival time difference and the ACT. The question is if the actual connecting time can decrease if the flight is delayed.

Using a dataset of 317 flights that have been delayed only by a load reactionary delay, it can be concluded that the connection time does not decrease if flights arrive late. Figure 7.4 shows the analysis, where a low and positive correlation of 0.04 was found. This is a low correlation, and from this it can be concluded that modeling ACT as independent events is a valid assumption.

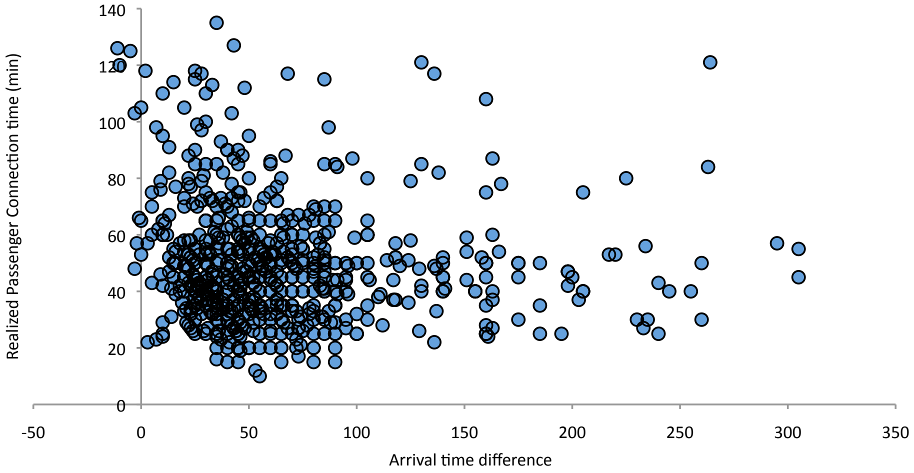


Figure 7.4. Validating independent modeling of the MCT. *A statistical correlation for flights that are delayed only due load reactionary, the correlation between the arrival time difference and the PCT is 0.04. As such, the assumption to model the flight as an independent event is validated. (Data from September 2010 till September 2011, 317 flights)*

7.3 Operational validation of simulation findings

The purpose of the model operational validation is to assess the accuracy of the simulation findings within the range it is intended to be applied (Sargent, 1984). Since the simulation models are descriptive, simulation results must be interpreted and accepted. The methodology to evaluate the simulation findings is to validate the delay curve severity with empirical delay curve severities. By backward testing it can be assessed if the simulation of a flown flight schedule coincides with what has occurred.

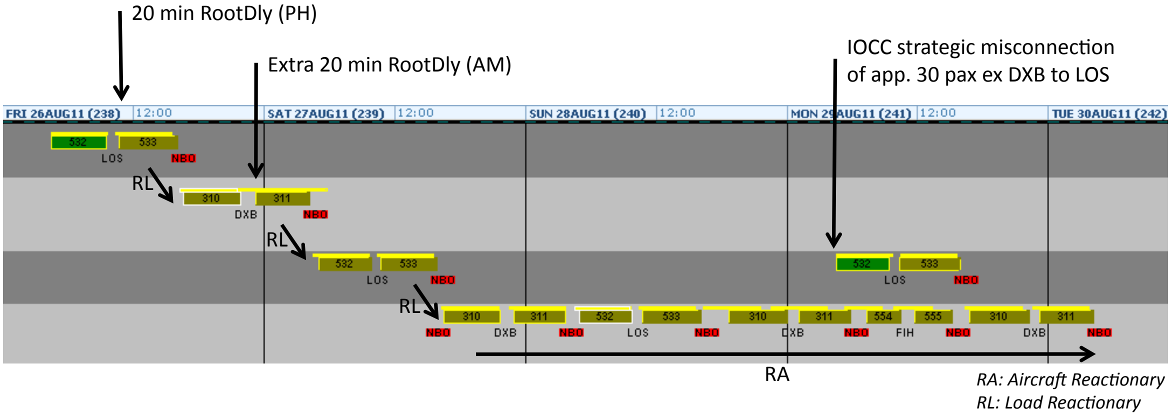


Figure 7.5. Example of empirical delay propagation tree. *Both flights KQ0533 and KQ0311 experienced a 20 minute delay. The delay propagation halts after a strategic misconnection by the IOCC three days later.*

Figure 7.5 shows an empirical delay curve and illustrates how an empirical delay propagation can be tracked through delay documentation. Delays propagate through the flight schedule primary through aircraft lines of flight (delay code RA) and by protecting passenger connections (delay code RL). These are documented by the IOCC into the flight tracking system Sabre.

7.3.1 Algorithm to find historical delay severity

Using the current delay documentation, a two-step algorithm is developed to connect delayed flights with the originating flight.

The first step is to identify the flight from which the reactionary delay originates. Flight delayed due to load connection (RL) rely on the delay reason to describe the flight number causing the reactionary delay. The majority of the delays identify a previous flight by documenting 'KQ311' or 'ex 311'. Extracting this can be automated, however a manual overlay is necessary as to capture documentation that did not adhere to this format. Some flight delay documentation at Kenya Airways contains too little information to identify an originating flight, such as 'Load Rotation' describing a flight delay outbound from Nairobi. Table 7.1 shows an impression of the delay reasons that could not be used. [2]

Table 7.1. Example of incorrectly documented load connection flights *There are 119 load connection delayed flights which originating flight could not be identified. The reason for this is incomplete information. To illustrate this, five delay descriptions can be shown.*

```
LEG      FLT
DATE     NUM  DEP  DST    CODE    AMOUNT  REASON
-------  ---  ---- ----   ------  -----   -------------------------------------------
02DEC10  310  NBO  DXB    RL      25      LOAD CONNECTION OF 6 PAX  AUTHORITY BRAM
19DEC10  886  NBO  BKK    RL      30      LOAD CONNECTION
23DEC10  500  DLA  LBV    RL      86      LOAD CONNECTION NBO
02JAN11  321  CAI  KRT    RL      20      DLY 20 MINS DU EXTRA REVENU FM EGYPTAIR
23JUN11  416  NBO  EBB    RL      55      CONNECTION 15PAX FROM KLM565 AA2225LT
```

Flights delayed due to aircraft rotation (RA) can connect the originating flight by tracking the tail registration upstream. This also works for delay codes such as RE, RO or RP which are all considered on aircraft rotation level but document other root causes.

The second step of the algorithm involves tracking delayed flights to aggregate the delay severity. Each flight has the potential to delay other flights, as such when counting the reactionary delays downwards an aggregated delay severity due to the first flight emerges. This results in an empirical delay duration against delay severity point that can be overlaid onto the simulated delay severity curve for validation.

Table 7.2 illustrates how this works with two examples. In example 1, there is a singular delay propagation tree. When counting the direct impact of each flight, it is seen that each flight causes one reactionary delay. However, by working chronologically through the flights an interim total can be computed that can be tracked back to the primary delay cause. An empirical point can be computed that for flight KQ202 where a 10 minute delay has resulted in affecting 5 flights downstream. Example 2 shows how this works for an example of how a delay of 17 minutes on flight KQ103 resulted in a delay severity of 3.

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[2] Following this, a recommendation has been implemented as to update their delay coding to improve the accuracy of the delay documentation.

Table 7.2. ***Example extraction empirical delay severity.*** *Two delay severities extracted and are illustrated to explain the delay severity algorithm. The two step approach first connects each reactionary delay with the originating flight. The second step is to count the downward impact of each flight. A historical relationship between the flight delay and the delay severity can then be made. This is used to validate the simulation findings.*

Flt	DepAp	ArrAp	Tail	Code	Reason	Dly (min)	Prev Flt	Own	Total
Example 1:									
202	NBO	BOM	KYX	PM	Missing 2 paxs at the gate	10		1	5
203	BOM	NBO	KYX	RA	Aircraft rotation		202	1	4
770	NBO	LAD	KQF	RL	Conx ex203		203	1	3
771	LAD	NBO	KQF	RA	Aircraft rotation AA 0950Z		770	1	2
414	NBO	EBB	KQC	RL	Conx 27 pax ex LQ771		771	1	1
Example 2:									
103	LHR	NBO	KQU	AT	Atc enroute due greece	17		2	3
416	NBO	EBB	KQC	RL	Conx 6paxs ex KQ103		103	0	0
720	NBO	LUN	KYF	RL	Connecting ex KQ103		103	1	1
720	LUN	HRE	KYF	RP	Passenger handling		720	0	0

7.3.2 Limitations of the historical delay severity algorithm

Having discussed the basis of the algorithm to find the empirical relationship between the delay duration and the delay severity, several limitations of the approach have to be highlighted:

- Delay reasons are manually documented, as such RL delayed flights cannot alway be identified. From 876 RL delays, 119 were not identified. The consequence is that not all delay propagation trees are completely captured. For example, the delay scenario shown in figure 7.5 missed the second RL connections and failed to capture the long downstream chain of aircraft delays. The impact this limitation has on the validation process is that some delay severities are underestimated.
- Currently, the simulation is setup to analyze single delay scenarios. The limitation in using empirical delay data is that flight can become delayed due multiple reasons. To take this into account, fractional downstream flight delays are considered for counting the delay severity. The fractional reactionary delay is the duration of the reactionary delay over the duration of the total flight delay. This approach will not impact the validation severely because flights delayed due reactionary have in 75% of the cases no primary delay reason, see figure 7.6.
- The IOCC undertakes measures to mitigate delay impact by swapping flights and misconnecting passengers. These measures cannot be accounted for. As such, some delay severities will be overestimated by the flight delay severity simulation. However, as will be seen later, the empirical delay severity points validate the simulation closely. This confirms that the IOCC does not swap flights frequently due to a low fleet uniformity.

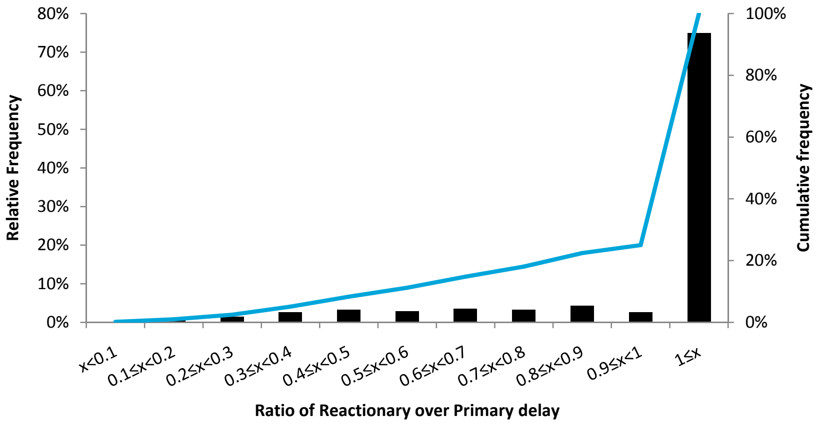

Figure 7.6. Frequency of flights with multiple delay reasons. *This figure shows that flights delayed due reactionary have in 75% of cases no primary delay reason. As such, the restriction of considering single is found to be limited. This chart plots the ratio between the reactionary delay duration and the primary delay duration. A ratio of 1 indicates that for the flight delayed due reactionary, there was no primary delay minutes.*

7.3.3 Empirical delay severity validation results

This section contains the main results of the historical delay severity analysis to validate the simulation findings. First, an overall statistical impression of the analysis is given. If the historical delay severity coincides with the simulation findings of previous flown flight schedules, the simulation can be validated. To illustrate this, several delay curves are selected to validate specific elements of the delay severity simulation.

Flight data between September 2010 and September 2011 has been used to analyze empirical delay severity. From 45,597 flights, the reports documented 7,533 fractional primary delays and 7,789 fractional reactionary delays[3]. During the flight period analyzed there were 7,378 flights delayed due to aircraft rotation. From these, 30 delays were not identified due to tail swaps. Furthermore, there were 876 flights delayed due to load connectivity. From these, 119 were not identified because it could not be identified what the originating Kenya Airways' flight was.

The validation is that empirical duration severity points are visualized in a diagram of the flight severity simulation[4]. The results can be interpreted as validated if the empirical duration severity points coincide with the flight severity curve.

Five main simulation examples have been identified and are presented to validate the simulation. Each flight (rotation) example is selected to validate a certain aspect of the simulation.

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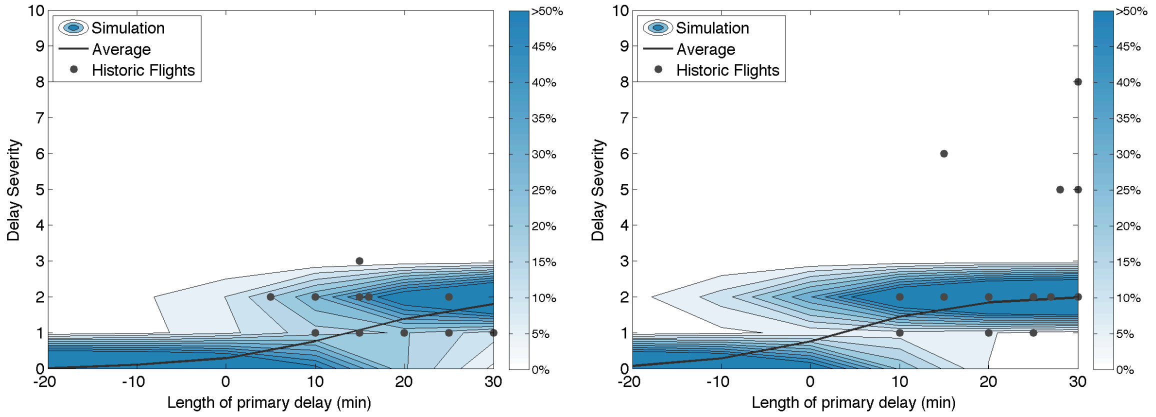
[3] A fractional reactionary delay is the duration of the reactionary delay over the duration of the total flight delay. It allows to split a delay into several delay causes. This is a workaround for the limitation that the simulation incorporates singular delays

[4] The flight severity simulation is described in chapter 5

The first example are two flights that can propagate delays through aircraft rotation only. Both flight rotations shown in figure 7.7 are planned tight, but have sufficient slack after returning to Nairobi to absorb disruptions. The expectation as such is that disruptions most probably cause 2 delays downstream, and this is validated accordingly.

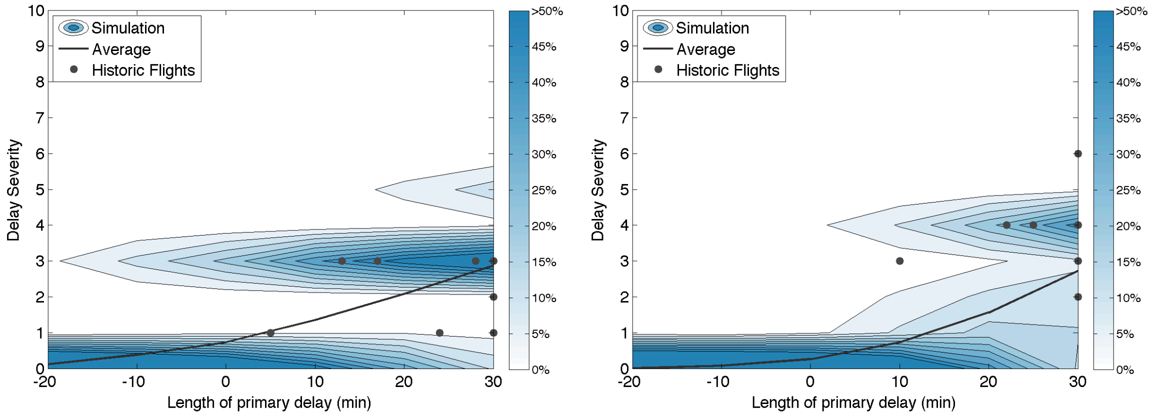


(a) Flight 442 outbound to BJM

(b) Flight 500 outbound to DLA

Figure 7.7. ***Validating the delay severity due to aircraft rotations.*** *These two flights that have been identified to only be able to delay subsequent flights due aircraft rotation. The empirical points coincide with what the simulation expects.*

The second example validates load connectivity delays. Figure 7.8a shows the inbound flight from London (LHR) that can propagate delays onto a tight 3 leg rotation to HRE and GBE, thus resulting in a delay severity most probably of 3. Figure 7.8b shows that if the flight from Kinshasa (FIH) delays, the flight towards Khartoum (KHR) and Cairo (CAI) will most probably also delay.

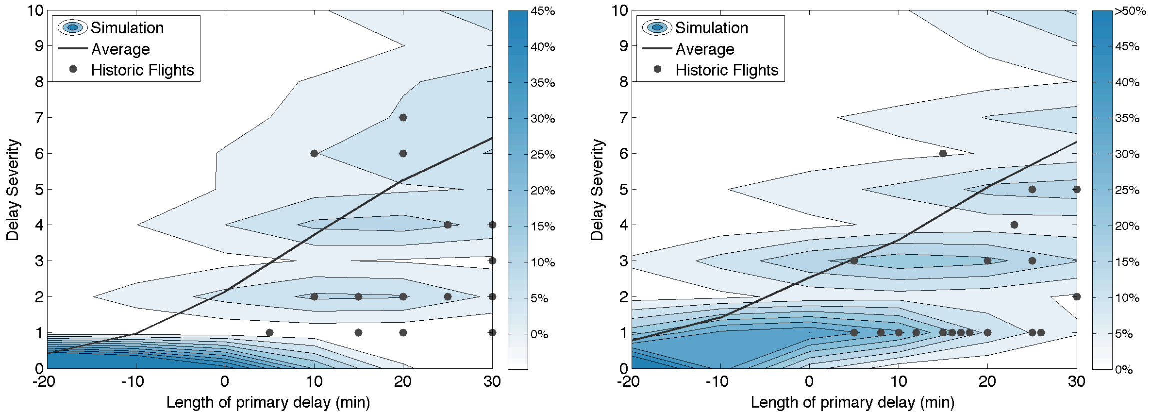


(a) Flight 101 inbound from LHR

(b) Flight 555 inbound from FIH

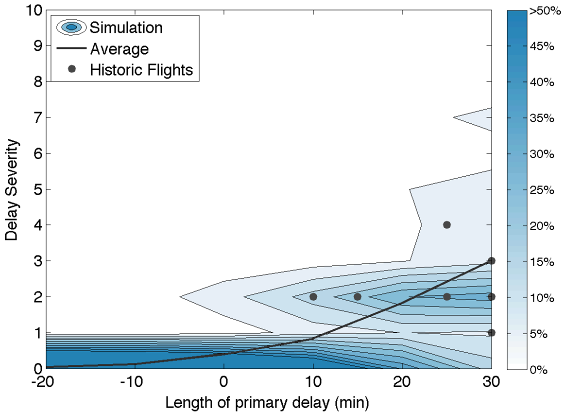
Figure 7.8. ***Validating the delay severity due to passenger connectivity.*** *Two examples of flights that are prone for passenger connection delays. The simulation results agree with historical delay severity points, as such validating the findings.*

A third example shows how the delay severity decreases throughout a circular flight. Figure 7.9 shows the flight rotation to Harare (HRE) and Lusaka (LUN). The inbound flight connects to Bombay (BOM), and an extra two delays could be expected. However, the series of flight severity curves illustrate how the expected delay severity would decrease further in the rotation. The first leg expected 2 delays (due to the rotation) or 4 delays (due to Bombay if not absorbed in the rotation). In the second leg to Lusaka (LUN) this becomes 1 or 3. In the final leg back to Nairobi only Bombay is expected to be be delayed.



(a) Flight 702 outbound to HRE

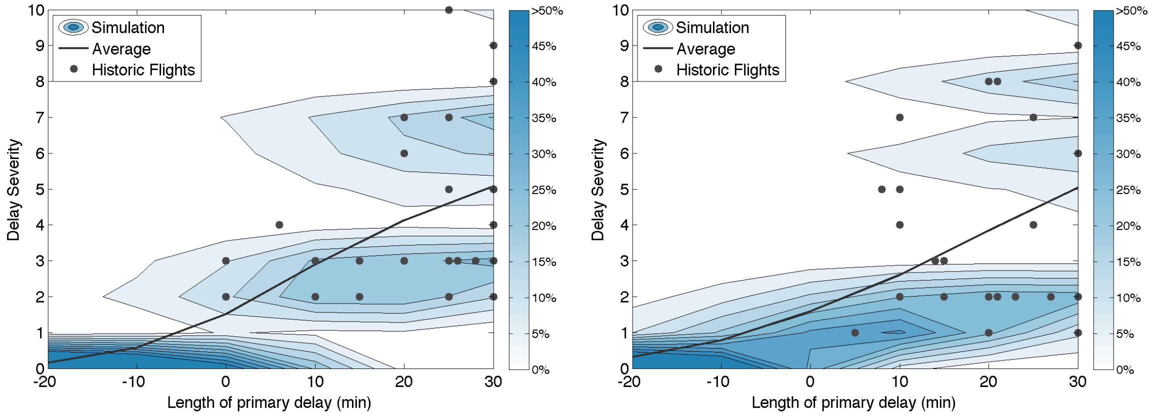
(b) Flight 702 from HRE to LUN



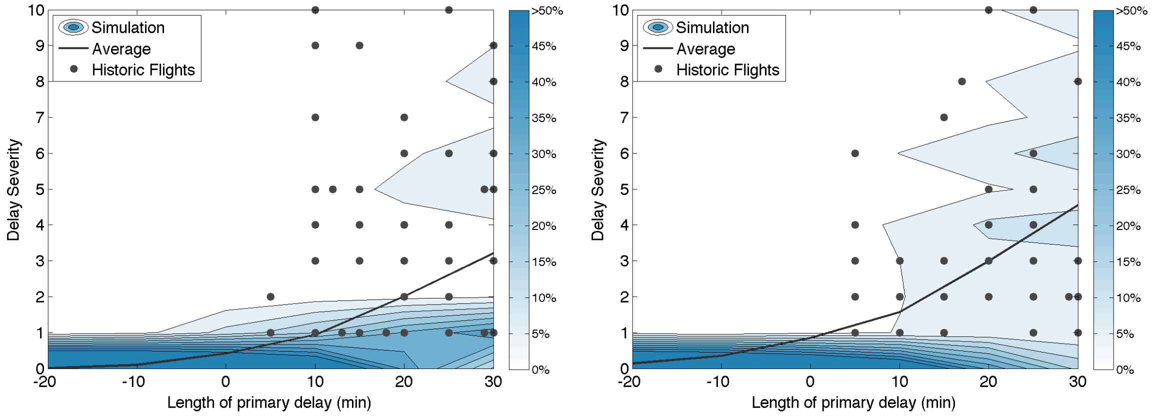
(c) Flight 702 inbound from LUN

Figure 7.9. Validating the delay severity in a circular flight. *Three flight delay severity curves are simulated for the rotation to Harare (HRE) and Lusaka (LUN). When overlaying the historical delay severity points, the decrease in severity throughout the circular rotation appears.*

The fourth example is the sensitive rotation to Lagos (LOS) and Dubai (DXB) as shown in figure 7.10. Figure 7.10a and 7.10b shows the rotations to Lagos (LOS) and show good resemblance between the simulation and the data. The simulation of the rotation to Dubai (DXB) as shown in figure 7.10c and 7.10d undervalues the expected delay severity. Flight 311 has 5 critical short connections that are sensitive to delay.



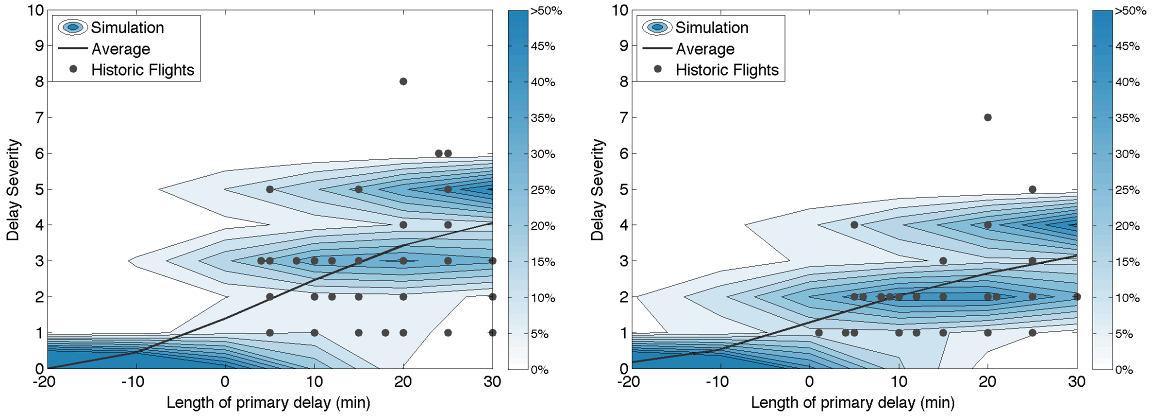
(a) Flight 532 outbound to LOS **(b)** Flight 533 inbound from LOS



(c) Flight 310 outbound to DXB **(d)** Flight 311 inbound from DXB

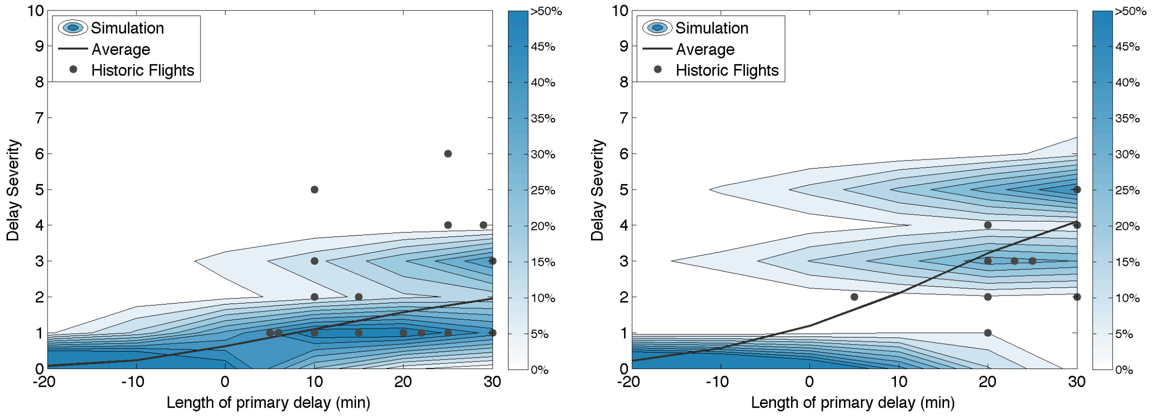
Figure 7.10. Validating the delay severity in Lagos and Dubai rotation. *Validation of the simulation can occur is the simulation fits the historical delay severity.*

A fifth example is the sensitive rotation to Khartoum (KRT) and Cairo (CAI), shown in figure 7.10. As expected the simulated delay severity decreases through the rotation. The remaining delay severity expected in the inbound flight from Khartoum (KRT) is the connection to Brazzaville (BZV). The empirical delay points follow the simulation, and therefore validating the findings.



(a) Flight 320 outbound to KRT

(b) Flight 320 from KRT to CAI



(c) Flight 321 from CAI to KRT

(d) Flight 321 inbound from KRT

Figure 7.11. Validating the delay severity in the Cairo and Khartoum flights. *Validation of the simulation can occur is the simulation fits the historical delay severity.*

7.4 Concluding words on operational validity of overall model

This section concludes the verification and validation process of the simulation model for delay propagation. Balci (1998) describes the goal of the validation and verification theory to ensure that three key errors are controlled for.

The first possible error occurs if the wrong problem is solved or if the simulation does not fully comprehend the problem. This has been overcome by a proper feasibility study towards the drivers of on-time departure performance prior to the start of the research project Schellekens (2011). Furthermore, the model's assumptions have been made in agreement with key decision makers at Kenya Airways.

The second error occurs when invalid simulation results are accepted as if they are sufficiently valid. To ensure valid simulation results, involvement by the department of Network Planning has been intense throughout the development of the simulation. Furthermore, the flight severity simulation has been validated with empirical data. Five examples are discussed in this chapter to illustrate the validity of several aspects of the simulation. The conclusion is that the simulation is sufficiently valid as the historical delay severity points coincide with the simulation of historical flight schedules.

The third error is if the simulation results are rejected, whilst it is found that they are sufficiently credible. This has been overcome by sufficient involvement with the key decision maker's in the academic project. The presentation in the Operational Leadership Team meeting, chaired by Bram Steller (Chief Operational Officer), ensured that an implementation time line for the alternative flight timing to Lagos (LOS) recommendations could be decided upon.

In conclusion, it can be said that there is sufficient confidence in the quality of the model within the range of the intended use.

8. Discussion

This chapter contains a discussion on the application of the simulation in a broad context and follows the methodology created to improve schedule stability as is shown in figure 8.1. First, a discussion on how this simulation fits into the overall target for punctuality and profitability. Second, how this simulation forms ground to research the sub processes of the Block, Turnaround and Passenger Connections as to form directives for levels of slack-time. Third, the simulation of the delay propagation model will be discussed, as well as directives for future research. Fourth, the current and future application of the stochastic simulation of delay propagation is discussed. The chapter ends with a discussion of the simulation model on the applicability on other airlines.

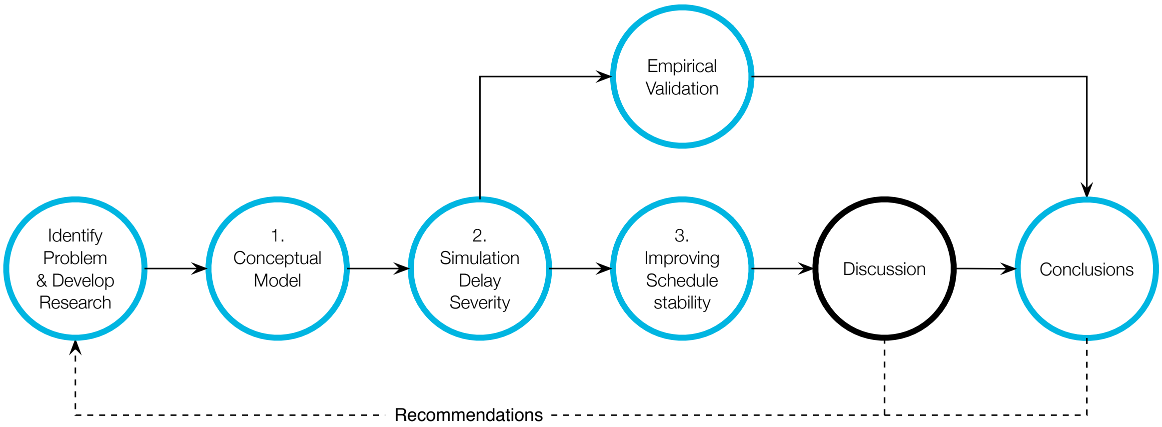


*Figure 8.1. **Following the research done, a reflection is made.** The chapter describes the discussion on the applicability of the model and directions for future research.*

8.1 The simulation in context of punctuality and profitability

The purpose of the stochastic simulation of delay propagation is to create an understanding the behavior of reactionary delays due to nuisance delays[1] and to assist in retiming flights to increase schedule stability. The question arises as to how the main punctuality metric of Kenya Airways, On-Time departure Performance (OTP), and overall profitability ties in.

Decreasing the network impact of nuisance delays is only a part of the solution. The framework discussed in section 2.1.4, segments solutions in three areas. One area being decreasing the network

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[1] Disruptions with a duration of 20 minutes or less are considered nuisance delays.

impact of nuisance delays is discussed in this thesis. Of the other two, the first is the reduction of probability for avoidable disruptions through the pursuit of operational excellence. Second, is the improvement of the recovery of operations after systemic non-avoidable disruptions.

It is only when the previous explained three delay reducing methods are addressed holistically that a sustainable increase can be realized in punctuality as the three are closely tied together. Initial research shows how 57% of the primary delays are caused during the turnaround due to the execution of the process[2]. Arguably, this is the reason for the variability in OTP that can be addressed by ensuring a stable process. The amplitude of the variability is greatly influenced by the impact of these primary delays as these translate into, possibly multiple, reactionary delays. The outliers or extremes in low OTP are caused by systemic (non) avoidable delays which can be reduced when the operations recover more effectively.

This leads to the question, what OTP should an airline strive to be most profitable. Cook describes in the report of EuroControl (2011) that: 'It cannot be economic best practice to arbitrarily set punctuality targets, such as 99% of flights within 5 minutes of schedule.' Following this rationale, one could ask at what level of punctuality is an airline most profitable? If the OTP is low there is a direct increase in delay costs (both passenger, crew and aircraft related). However, if the OTP is high this could mean a decrease in aircraft utilization and (for a hub and spoke network) a high level of intentional misconnections for transfer passengers and their bags. Both extremes are intuitively not the most profitable.

A rough calculation of the potential decrease in costs and revenue for the alternative timing of the Lagos (LOS) flight can be done to illustrate how this could play a role. The potential loss in revenue is €38,000 per week due to losing transfer passengers on the route from Lagos (LOS) to Dubai (DXB). This considers the average amount of passengers during the Summer 2011 at an average V-class fare of €370. The potential reduction in delay costs can be estimated at €31,000, which is a rough estimation that takes into account an average delay cost per minute for the flights to Lagos (LOS) and Dubai (DXB) only [3]. The average delay cost per minute is adapted from Enk (2010) to be €52 per minute.

Looking at the limitations of this calculation in potential profit decrease, several assumptions are made which make both the calculated loss in revenue and reduction in costs difficult to accept. First, the calculation of a loss in revenue fails to account for the recovery of spill in demand[4]. Furthermore, the improvement of service level resulting in a long-term improvement of revenue should also be quantified.

Second, the limitation concerning the calculation of a potential reduction in delay costs applied from Enk (2010). The research applies a linear regression found by Cook et al. (2004) between the delay cost per minute versus the aircrafts' seat capacity and extrapolates that to the fleet buildup of Kenya Airways during the Winter 2010 season. As such, the delay cost per minute applies European cost reference model values extended onto the specifics of Kenya Airways.

In conclusion to the a rough calculation on changes in profitability, the limitations currently found restrict the applicability. This illustrates the opportunity to adapt the European cost delay reference model (EuroControl, 2011) to the specifics of Kenya Airways. This could incorporate the specifics of the network;

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[2] See chapter 2.

[3] As such, it does not consider the value of the reactionary delays onto other flights, such as KQ0550 to Kinshasa (FIH) and Brazzaville (BZV).

[4] Recovery of spill in demand focuses on regaining the passengers you ought have lost due to a termination of operations onto a different flight itinerary. For example, Operating a tri-weekly connection will not per se result in losing 4/7th of the passengers. Some passengers will be willing to fly a day later or earlier.

operational environment at JKIA; and the geo political environment Kenya Airways operates in.

The European delay cost reference model has the downside that it cannot quantify reactionary delays accurate. As such the potential is identified to incorporate the stochastic stimulation for delay propagation to improve the delay cost reference model. With a more thorough understanding of the propagation of delays that result in reactionary delays (accumulating to 51% of all delays at Kenya Airways) a more in depth cost-benefit analysis would be possible.

8.2 Opportunities to optimized planned block, turnaround and passenger connection times

Developing an in depth cost-benefit analysis can lead to a justified OTP target and aircraft utilization level, however it will not describe how the schedule ought to be designed considering planned slack-time.

The stochastic simulation of delay probability assumes stochastic values for the Block, Turnaround and Connection times. A subsequent research is to apply the stochastic simulation of delay propagation on flight specific targets for guidelines of required levels of slack time during the Block, Turnaround and Connection times. A better understanding of flight specific guidelines allows for corrections of differences in expected delay severity which requires different levels of slack-time.

To achieve this, the stochastic simulation of delay propagation needs to be refined on several aspects. First, the simulation itself will benefit from an integration with an optimization algorithm. Then the accuracy of taxi times (influencing the Block-time) and the interdependencies of subprocesses during the Turnaround and Passenger Connections is required. The former can be split up in the Minimum Turnaround-time and Minimum Connecting-time.

To start with, the manual iteration currently proposed in the methodology to improve schedule stability will benefit from an automation in optimization[5]. The flight schedule can be optimized to maximize stability, under the constraint to maintain all passenger connections at the same aircraft utilization level. This ensures that the flight inbound confidence is higher to connect the transfer passengers.

The second refinement of the stochastic the stochastic simulation of delay propagation could be to incorporate the interdependencies of subprocesses to gain a more detailed insight into target confidence levels for the Block-times, Turnaround-times and Passenger Connecting-times.

Currently, KQ's internal target for Block-time confidence is 80%. This rather arbitrary target could be refined on a guideline dependence on the duration of the flight; the time of arrival; and the criticality of the downstream passenger connectivity. To illustrate this, the required confidence levels for long-haul flight inbound from Dubai (DXB) with the flight inbound from Kisumu (KIS) are compared. The probability of the aircraft arriving in-time might be similar (due to the same target confidence levels), yet the variability in minutes is larger due to the duration of the flight. Furthermore, the impact of a late arriving Dubai (DXB) flight is larger due to the downstream passenger connectivity. As such, should the target Block-time

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[5] The direct concern is the performance issues related to large scale Monte-Carlo simulations. Currently, the performance of simulation the full flight schedule with large boundaries for required simulation run-lengths on a single core 920 MHz processor is just under 30 minutes. Application on faster processors and parallel computing have not been investigated, as well as creating smaller flight schedules as to investigate the singular behavior of certain aspects.

confidence levels be similar?

Similarly, the Minimum Connecting Time (MCT) is standardized company wide to 50 minutes between international flights. However, a less uniform guideline could allocate slack-time more strategically and stabilize the schedule efficiently. To illustrate this, the twice-weekly flight to Bangui (BGF) is often delayed due to a tight connection with KQ0321 from Khartoum (KRT) and Cairo (CAI), KQ0311 from Dubai (DXB) and KQ0203 from Bombay (BOM)[6]. As such, this flight has a below average on-time departure performance of 42%. By ensuring a larger Passenger Connecting Time (PCT), the expected delay severity will be decreased.

The further research could analyze the MCT on a sub process level and structure the possible steering methods to reduce the needed time. This reasoning is along the line of the work of Muzik (2011) on real-time decision support for saving passenger transfer connections. If the steering activities are incorporated into the simulation, the guidelines on MCT can be further sharpened.

When analyzing historical data on the Minimum Turnaround Time (MTT) of flights delayed due to aircraft rotation only, it is found that in some instances the Reactionary due to Aircraft rotation (RA) delay code was applied for ground times of up to 90 minutes where 60 minute guideline is prescribed (for a Boeing 767-300). This discrepancy could be caused by two reasons. Firstly, the delay documentation at the IOCC is faulty. However, this would indicate that over 15% of the reactionary delays on a Boeing 767 would be documented wrongfully. The second possible reason, is that the natural variability in sub processes are the cause for longer ground times[7]. As such, the variability is influenced by a number of factors and has to be studied. Examples of these factors are: the service level of the turnaround and the location of the turnaround. The solution would be to further analyze requirements on the Minimum Turnaround Time from a bottom up perspective which incorporates the variability between sub processes.

8.3 The stochastic delay propagation model and directives for future research

This section will discuss the current proposed simulation of the delay propagation model, where it stands with respect to current other academic work and what directives there are for future research.

Flight specific robustness has been shown to be an important component in schedule stability, hence the emphasis of this thesis on flight specific reactionary delays to develop a methodology to understand the effects of alternative timings. To realize this, it was opted to develop a simpler and quicker simulation model that can simulate a delay propagation tree recursively by starting from the point of disruption.

The main academic argument of this thesis is that this approach shows how stochastically simulating delay propagation whilst considering passenger connectivity results in more accurate results. The studies towards the simulation of delay propagation reviewed so far, however, are limited to deterministic models that analyze the propagation of delays through aircraft and crew. There are several reasons for

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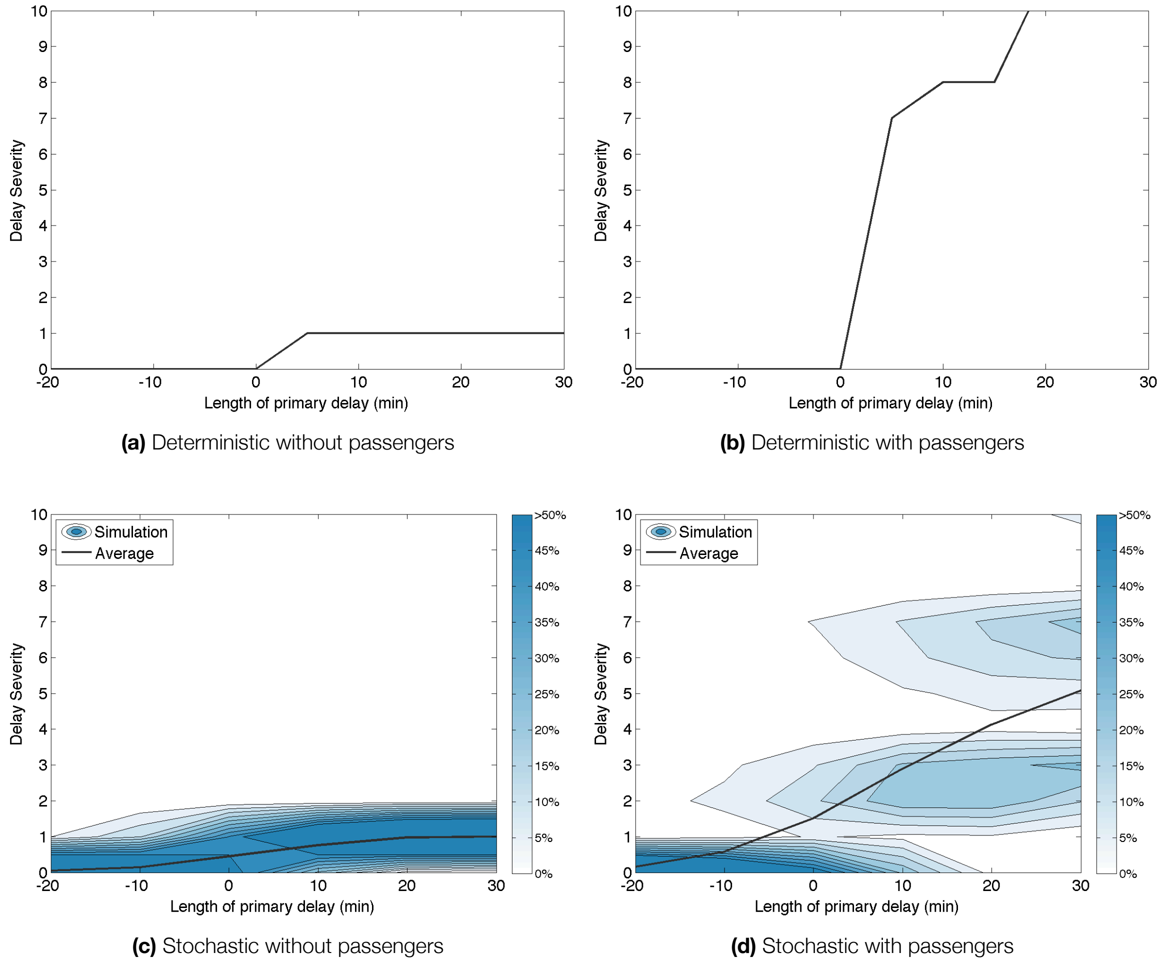
[6] All three flights have been central in the discussion to improve schedule stability, discussed in chapter 6.

[7] if this is the case, then how can you standardize the processes as to stabilize and optimize them?

this. For example, Duck et al. (2011) researches robustness deterministically using guidelines for set required ground times because of the limitation of using only publicly available data. Lan (2003) proposes an deterministic optimization strategy to maximize MCT for passenger connectivity in a schedule, but acknowledges a lack of a method to accurately evaluate proposed changes.



(a) Deterministic without passengers

(b) Deterministic with passengers

(c) Stochastic without passengers

(d) Stochastic with passengers

Figure 8.2. Comparing delay severity simulation between types of simulations. *Flight KQ0532 outbound to Lagos (LOS) can be simulated using a deterministic or stochastic simulation*

The delay propagation model developed in this thesis has been shown to accurately estimate delay scenarios[8]. Figure 8.2 illustrates the possible model outcomes when neglecting passenger connectivity and the effects of stochastic parameters for flight KQ0532 to Lagos (LOS). This case is illustrative as it shows clearly that the deterministic model does not take into account the variability of the operations and the importance of assuming passenger connectivity.

By assuming only a propagation through aircraft, the influence of transfer passengers in a hub and spoke network will result in underestimating reactionary delays. To illustrate, figure 8.2a and 8.2c shows a simulation setup without incorporating passenger connectivity. The criticality of flight KQ0532 to Lagos (LOS) is that delays affect the flight to Dubai (DXB) due to the connectivity of transfer passengers, hence, by not taking this into account reactionary delays are undestimated. The model used in figure 8.2a is

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[8] The validation of the delay scenarios has been done using empirical data, discussed in chapter 7.

based on Lapp et al. (2008), but with the extension that it systematically computes the delay severity as a function of the primary delay duration. Based on this model, AhmadBeygi et al. (2008) studied delay propagation in a hub and spoke passenger network and concluded that nearly 40% of flights have no propagating effect up to 180 minutes of primary delay. However, the findings of the current study do not support this as the research did not incorporate passenger connectivity.

Furthermore, figure 8.2b shows that incorporating passenger connectivity but assuming fixed historical averages for the Block-times, Turnaround-times and Passenger Connection-times the reactionary delays are overestimated. This is consistent with earlier observations made by Arikan et al. (2010), which discussed how deterministic approaches will lead to an overestimation of reactionary effects.

In conclusion to the discussion of simulation methods, the intuitive knowledge that the operationalization of a hub and spoke schedule behaves stochastically can be taken into account revealing accurate and validated results on a flight level as is shown in figure 8.2d.

A natural extension to the proposed stochastic model for delay propagation is a further elaboration of the delay propagation model from a flight perspective simulation to a full schedule. The current approach, when analyzing the full flight schedule, is limited as it takes the sum of the expected delay severity throughout the flights which does not translate into the variability of how the full flight schedule behaves.

A possible directive to take is to translate the current simulation into a generic simulation method, such as a Discrete Event Simulation[9].The advantages of such generic methods is that the developed stochastic delay propagation model can be extended with new features including the possibility to swap flights. By more realistically model the delay mitigating actions of the IOCC a larger range of delays, beyond 30 minutes, can be studied. This will allow to simulate to a fuller extend how a schedule behaves with respect to punctuality and profitability. Work on integrating stochastic parameters into the modeling of schedule robustness with a Discrete Event Simulation approach has started with Jacobs et al. (2006) who used a Java based, Discrete Simulation Open Source Library (DSOL) to simulate a model of the KLM network for aircraft robustness only.

8.4 Applications at Kenya Airways

This thesis focuses on increasing schedule stability. Two deliverables have been presented to Kenya Airways, being the Block-time analysis module and the stochastic simulation of delay propagation. Their current and (near) future application will be discussed.

The first, a Block-time analysis module has been developed to support the proposed methodology to improve schedule stability by giving insight into Block-time confidence. Developing and implementing it as a separate tool enabled the department of Network Planning to advice on changes and allow to monitor variances in Actual Block-times.

The implementation as a separate tool was done because, following the previous simulation results shown in chapter 6, there is a large influence of the Block-time confidence level on schedule stability.

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[9] The basic principles of discrete event simulation is introduced in chapter 2 to model flights as events which are queued in a heap and executed chronologically on departure time, see Banks (1998) and Leemis and Park (2006).

From both a schedule perspective as well as an operational perspective having accurate Scheduled Block-Times (SBT) is important.

For the department of Network Planning, the Scheduled Block-Times can directly influence possibilities in aircraft rotations as well as selling connectivity. For the department of Ground Operations, accurate Scheduled Block-Times increases the possibility to plan equipment and man power efficiently. What is interesting is that for the Ground Operations, both over and under confident Scheduled Block-Times are harmful. This thesis already discussed on how a low Block-time confidence can lead to a higher probability of the aircraft arriving late for the next flight. However, one can also discuss the operational challenge of aircraft arriving earlier than planned. Bays may not be available as well as Ground Service Equipment (GSE) and ground operational personnel.

The final product of this academic research is the stochastic simulation of delay propagation and is in a conceptual phase. As such it served a fundamental purpose as to deepening the understanding of the stochastic nature of delay propagation. Being an accurate and validated tool, implementation into a schedule design tool is recommended and requires further development in connecting actual passenger booking (Delorean) and flight performance (Sabre). The further steps can be done with the business development unit of the department for Information Systems at Kenya Airways.

The implementation of the stochastic simulation of delay propagation will allow the schedule rollout at Kenya Airways to benefit during the design of a seasonal schedule to identify critical flights in the design process itself rather than during the day of operations. The proposed methodology (see chapter 6) to improve schedule stability can then be applied to improve the robustness of the flights.

A second possibility to integrate the stochastic simulation of delay propagation is during the tail assignments. This opportunity lies further ahead, yet the basics of the proposed methodology can be applied. Having accurate passenger and line maintenance data, slight retiming decisions can be made without significant commercial impact. As such, minor retiming adjustments can be made (under the assumption as to protect passenger connectivity) to stabilize the operations.

To illustrate this, between 19 to 20 October, 2011, the flight from Amsterdam (AMS) took 45 minutes longer to get back to Nairobi due to a closure of the Greek airspace as the Air Traffic Control was striking. However, this was known more than 2 weeks ahead of time. The current state is that the arrival of KQ0117 was delayed causing 4 reactionary delays. A pro-active flight planning could have advanced the departure slightly and reduce the propagating delay effect.

For last minute flight retiming during tail assignments to succeed, a shift from reactive to pro-active management is required. This would need an improved information sharing between the Airline, Airport and Passenger. The implementation of this is that a Scheduling team, joint by operations control, crew planning, flight schedules and maintenance planning, is start focusing on crew roster changes, last minute charters and tail assignments. The purpose would be to adapt the flight planning to be tailored to the variability in operations.

8.5 Applications in other airlines

It is important to reflect the thesis' relevance on the industry. To discuss how the methods developed for the stochastic simulation for delay propagation that incorporates passenger connectivity can be applied elsewhere to other airlines. To explore if airlines need to incorporate passenger connectivity as a form of delay propagation during the design of a stable schedule.

First, a discussion on the application of the stochastic nature of the simulation to other airlines. Passenger airline operations are similar and as such the mechanisms of a delay propagation model can be used. However data used to research stochastic variables on flight performance, schedule and passenger bookings are airline specific. As such, it is argued that the support of stochastic simulation can benefit other passenger airlines.

The second aspect is on the need to incorporate passenger connectivity as a form of delay propagation. Hub and spoke networks gain from collecting and re-distributing large amounts of passengers through their hub. To operate a sustainable hub and spoke network the customer perception of the quality of the hub is quintessential. As such, delays incurred due to misconnecting transfer passengers are costly and should be taken into account when designing a stable flight schedule.

However, one can argue that larger airlines have the problem of misconnecting passengers less as they can afford to fly more frequently to destinations. Putting transfer passengers on a later flight would then result in a smaller delay. The counter example for this is KLM. They have a strategy to operate a large network as to maintain passengers with a global demand. Therefore, some parts of their flight schedule is less frequent, such as the twice-weekly flight to Luanda (LUN). In this respect they face the same challenges of incurring delays to protect passenger connections.

When considering direct passenger costs, misconnecting passengers for KLM could be more expensive then for KQ due to European Legislations (EU, 2004). Recent jurisprudence stipulated[10] that delay compensation for delays of more than three hours should be equivalent to a cancellation. As such, when disconnecting transfer passengers KLM should find an alternative flight plan within three hours of the scheduled time at commercial rates or incur up to 600 euros per passenger in financial compensation[11].

In conclusion, the study of the stochastic nature of delay propagation as well as incorporating the nature of transporting passengers through a hub is advantageous for other hub and spoke passenger airlines.

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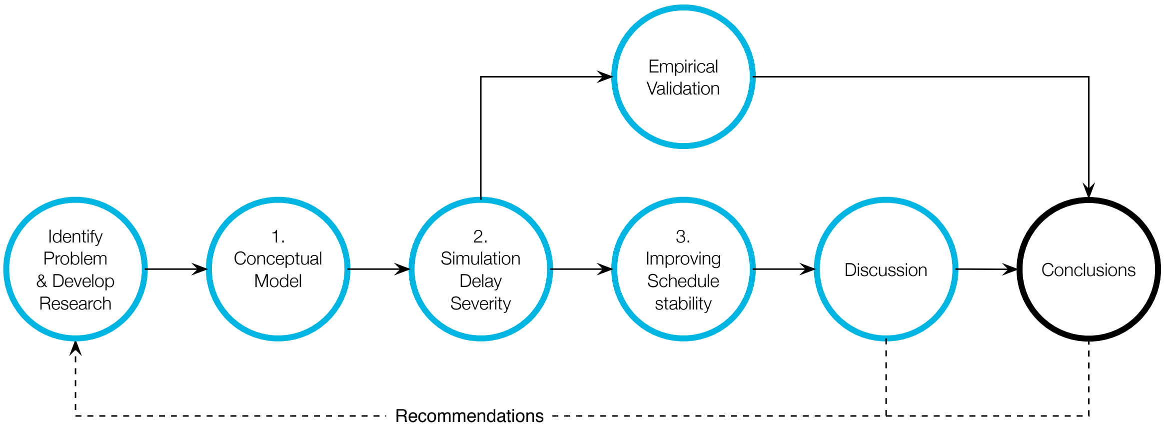
[10] The joint European court cases C-402/07 and C-432/07 of Sturgeon v Condor Flugdienst GmbH and Böck and Lepuschitz v Air France, judgments of 19 November 2009

[11] Compensation depends on the distance of the flight.

9. Conclusions, Limitations and Recommendations

Related to the research question and sub questions, the main conclusions, limitations and recommendation are discussed in this chapter.



The conclusions, limitations and recommendations follow the a discussion.

9.1 Conclusions

The main research question for this academic research:

> *How can the absorption robustness be simulated for a proposed seasonal flight schedule, and how can this be used to aid Kenya Airways in increasing schedule stability?*

The nature of this research project allows to discuss the main conclusions for Kenya Airways and academia separately.

For Kenya Airways, the following deliverables have been achieved:

- **Block-time confidence is the largest driver for flight robustness.** For the schedule simulated there was a correlation of -0.39 between the flight's Block-time confidence level and the expected delay severity, which is the robustness metric of a flight. As such, a Block-time analysis module has been developed to support the proposed methodology to improve schedule stability by giving insight into Block-time confidence. Per august 2011 it has been implemented as a separate tool that enables Network Planning to advice on changes and allow to monitor variances in Actual Block-times.

- **Stochastic simulation of delay propagation.** Currently in a phase of conceptual design and, as such, it serves a fundamental purpose as to deepening the understanding of the stochastic nature of delay propagation. Being an accurate and validated tool, implementation of a schedule design tool is advised and requires further development in connecting actual passenger booking (Delorean) and flight performance (Sabre). The current research has been shown to work and able to create simulations of scenarios to assess schedule stability prior to the day of operations. Acceptance of findings by the department of Network Planning has been achieved though the validation with empirical data.

For Kenya Airways, the following programs for implementation have been made:

- **Routes are planned with improved Scheduled Block-times.** By analyzing the Block-time confidence using the implemented Block-time analysis tool, improvements for 27 flights have been implemented per September 2011. For example, the flight KQ0202 to Bombay (BOM) has increased the Scheduled Block-time by advancing the departure and the tight feeder flights to protect passenger connections. Work on analyzing Block-time confidence has been handed over to the department of Network Planning and will continue by the department of Network Planning.
- **An improvement scenario has been created for two problematic rotations,** using the proof of concept of the schedule sensitivity experiment. The key challenges of these routes lied in interlocked passenger connectivity for preceding and subsequent feeder flights. By understanding the required improvements for schedule stability and the impact on passenger connectivity, alternative flight timings for these flight rotations have been made. The alternative flight timing for Lagos (LOS) is based on a for a tri-weekly connection to Dubai (DXB) flights. Acceptance of the recommendation to implement has been achieved through a presentation in the Operational Leadership Team meeting, chaired by Bram Steller (Chief Operational Officer), ensuring that an implementation time line for February 2012 could be decided upon.

The main contributions following this research project for academia are:

- **It is shown to be feasible to include passenger connections into the study of schedule stability.** Previous academic work constrain the analysis to aircraft and crew only. However, to simulate delay propagation in a hub-and-spoke passenger network it is shown that incorporating passenger connectivity results in a more accurate representation.
- **The use of stochastic variables has been shown to deliver more accurate insights into the behavior of delay propagation.** The intuitive knowledge that the operationalization of a schedule behaves stochastically is understood, however previous academic research mainly considered deterministic solutions. In the step to work towards a holistic simulation of proposed airline schedules to measure operational profit prior to the day of operations, the use of stochastic variables the Block-time, Turnaround-time and Passenger Connecting-Time is quintessential.

- **The stochastic simulation of delay propagation is validated using empirical data.** The flight oriented model has been validated with empirical data showing the relevance of simulation delay propagation through aircraft and passengers. Furthermore, the validation has lead to an acceptance of findings by Kenya Airways.
- **The proposed metric to measure flight robustness is the Expected Delay Severity.** This is the weighted average of the delay severity curve[1] and can be used as a comparative robustness metric between flights. This academic research simulates the expected delay severity for alternative flight timings and concludes that this is a useful and validated metric to quantify the impact on a schedule re-timing decision.

In conclusion, a pro-active methodology using the stochastic simulation of delay propagation proposed can control system impact of unavoidable disruptions and improve overall punctuality. The strength of the proposed methodology is that it works alongside the Netline Schedules System and, hence, allows for the incorporation of soft issues into the schedule design whilst considering schedule stability. The strength of the solution is that it can determine the impact of retiming decisions on schedule robustness if you deviate from the 'ideal' plan. An environment can be created where less ad hoc delay mitigation management is needed, and more focus can be placed on operational excellence.

9.2 Limitations

The research has been set up to study how the schedule stability can be simulated within clear constraints. Even as the applicability of the use of simulated delay severity curves is demonstrated, it is done with several limitations.

- Block time performance is measured using historical data. However, this does not fulfill the requirements for approximating the performance of new routes or existing routes with new aircraft. Currently, a best estimate is taken from the department of Flight Operations Engineering. An example for this is the new route to Jeddah (JED) beginning October 2011. For all that, this remain an inherent limitation when assuming historical performance data to simulate possible scenarios.
- Passenger demand is approximated using historical seasonal average. However, drastic retiming of flights can impact demand. There are two ways of how this could decrease demand. The perception of a late night flight instead of a morning flight can decrease demand. A second example, is a mis connection of a non code-sharing partner flight. As such, retiming issues have to remain limited.
- The interaction of multiple delays is not considered. However, for the purpose of this simulation model (to simulate schedule stability) the limitation is limited to the validation of delay curves. However, as is shown over 75% of the reactionary delayed flights are only delayed due reactionary.
- Not all delay recovery possibilities of IOCC have been considered in the simulation. As such, the robustness of the schedule cannot be simulated for larger disruptions. However, Absorption robustness increases down time of valuable resources and decreases the network impact of nui-

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[1] The delay severity curve visualizes the relation between the departure delay duration with the impacted delay severity.

sance delays. Therefore, insight into large delays to increase absorption robustness is not per se required.

9.3 Recommendations

Concluding this academic research paper, several recommendations for Kenya Airways and directions for future research to develop the proposed simulation model are discussed.
The main recommendations for Kenya Airways are:

- The schedule sensitivity experiment discussed in this research is in a proof of concept phase, and should be rolled out to the department of Network Planning. However, this requires integration with the main data centers on schedule, passenger and flight performance to be implemented. To create a more pro-active mindset towards reactionary delays, the overall recommendation is to further develop these tools to work alongside the Network Planning department to aid in designing more robust schedules.
- Work has to be done towards setting optimums in robustness. Intuitively the inverse relationship can be made between aircraft utilization and robust scheduling. The academic work in this thesis contributes to the study of robust planning, but effort has to be made to study this inverse relationship in monetary terms. With this, benchmarks in robustness can be set.
- To ensure that reactionary delays are better captured, the documentation of delays should improve. More focus should be placed on documenting reactionary delay to allow for the creation of empirical delay curves. In short, the recommendation is to document reactionary delays always with the previous originating flight and number of passengers, if applicable.

Several directions for future research have been identified:

- Flight specific robustness has been shown to be an important component in schedule stability, hence the emphasis of this thesis on flight specific reactionary delays by modeling the delay propagation tree recursively by starting from the point of disruption. A natural extension to the proposed stochastic model for delay propagation is the extension of the delay propagation model from a flight perspective simulation to a full schedule. The direction of further analysis to take is to translate the current simulation into a generic simulation method, such as a Discrete Event Simulation[2].
- Work can be done towards the integration of the costs of delay versus the costs of system slack. Possibilities to roll out this simulation towards a European Airline allows to include the work done on delay costs by Cook (EuroControl, 2011). The overall question is how much slack is most profitable and how does this coincide with the operational punctuality benchmark of the IATA of a 85% on-time departure?
- The simulation can be integrated as a cost function with an optimization research to optimize the allocation of slack-time throughout the flight schedule. The flight schedule can be optimized according to a maximum stability under the constraint to maintain all passenger connections and under the same amount of aircraft. The overall system then maintains the same aircraft utilization

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[2] The basic principles of discrete event simulation is introduced in chapter 2 to model flights as events which are queued in a heap based executed chronologically on departure time, see Banks (1998) and Leemis and Park (2006).

level, yet ensures that the flight inbound confidence is higher to connect the transfer passengers. Such optimization could be set to work towards de-peaking of the schedules.

Possible optimization research projects include Lan (2003), who proposes a linear programming proposal to retime flights such to optimize for PCT. This idea can be integrated with the proposed stochastic delay propagation model to ensure for a more accurate schedule stability assessment.

- The current model focuses on using historical passenger booking data. This limits the retiming possibilities. Work can also be done into integrating the optimization with passenger spill models or general market data. Then, the constraint of ensuring for passenger connectivity and limiting the retiming options does not need to be upheld.
- The model now focuses on seasonal schedules because this forms the basis for a schedule. However, the extension to tail assignments and robust lines of flight can also add value. Research could be on extended the stochastic simulation of delay propagation for the tail assignment and include maintenance for the schedule in the week before departure. Slight retiming can be done without commercial interference.
- Current propagation rules are set according to internal levels. However, the simulation can also include a cost calculation module on whether to save the passenger connection. Research done by Muzik (2011) can be integrated into the simulation for an accurate approach to simulating operations prior to the day of operations.

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A. Airline terminology

This appendix describes the used airline terminology concerning the IATA airport codes, time definition and season definitions. Furthermore Kenya Airways' fleet is described, as well as the internal used format for delay codes and the belonging delay categorization.

The time used throughout this academic work is Universal Coordinated Time (UTC), used throughout the airline industry as a standard in time reference.

Table A.1 contains an overview of Kenya Airways' fleet, as per October 2011.

The IATA airport codes used throughout Kenya Airways are shown in table A.2. These are the destination Kenya Airways has flow to or still flies to. Furthermore, the slot restricted nature of the airport is indicated as a reference. The current flight network is shown in figure A.1.

Table A.3 shows the seasons used, defined in the IATA scheduling manual. These seasons form the basis for the financial year, and the split of performance data per season.

The delay codes used at Kenya Airways' are adapted from the IATA standard. For the breakdown of delay codes these codes are categorized into a Turnaround process (see table A.4), and other categories (see table A.5). Some delay codes have to be manually categorized according to the delay reason.

Table A.1. ***Kenya Airways' fleet.*** *Fleet of Kenya Airways, as per October 2011.*

AcType	Number of Aircraft	Description
772	4	Boeing 777-200
767	5	Boeing 767-300
733	6	Boeing 737-300
737	4	Boeing 737-700
738	5	Boeing 737-800
E70	5	Embrear 170 LR
E90	3	Embrear 190 AR

Table A.2. IATA airport codes. *IATA airport codes for destinations that Kenya Airways has flown or still flies to, with airport class and slot restricted nature.*

Airport Code	City	Class	Slot
ABJ	Abidjan	1	0
ABV	Abuja	1	0
ACC	Accra	2	0
ADD	Addis Ababa	1	0
AMS	Amsterdam	3	1
APL	Nampula	1	0
ASM	Asmara	1	0
BEY	Beirut	3	1
BGF	Bangui	1	0
BJM	Bujumbura	1	0
BKK	Bangkok	3	1
BKO	Bamako	1	0
BLZ	Blantyre	1	0
BOM	Mumbai	3	1
BZV	Brazaville	1	0
CAI	Cairo	1	0
CAN	Guanghzou	3	1
CDG	Paris	3	1
COO	Cotonou	1	0
DAR	Dar es Salaam	1	0
DKR	Dakar	1	0
DLA	Douala	1	0
DXB	Dubai	3	1
DZA	Mayotte	1	0
EBB	Entebbe	1	0
FBM	Lubumbashi	1	0
FCO	Rome	3	1
FIH	Kinshasa	1	0
FKI	Kisangani	1	0
FNA	Freetown	1	0
GBE	Gaborone	1	0
HAH	Comoros	1	0
HKG	Hong Kong	3	1
HRE	Harare	1	0
JED	Jeddah	3	1
JIB	Djibouti	1	0
JNB	Jo'Burg	3	1
JRO	Kilimanjaro	1	0
JUB	Juba	1	0
KGL	Kigali	1	0
KIS	Kisumu	1	0
KRT	Khartoum	1	0
KUL	Kualar Lumpur	3	1
LAD	Luanda	2	0
LBV	Libreville	1	0
LHR	Heathrow	3	1
LLW	Lillongwe	1	0
LOS	Lagos	2	0
LUN	Lusaka	1	0
MBA	Mombasa	1	0
MCT	Muscat	2	0
MPM	Maputo	1	0
MRU	Mauritius	1	0
MYD	Malindi	1	0
NBO	Nairobi	2	1
NDJ	N'djamena	1	0
NLA	Ndola	1	0
NSI	Yaounde	1	0
OUA	Ouagadougou	1	0
REC	Guararapes	1	0
ROB	Monrovia	1	0
SEZ	Seychelles	2	0
SJK	Sao Jose	1	0
SSG	Malabo	1	0
TNR	Antananarivo	1	0
ZNZ	Zanzibar	1	0

Table A.3. IATA airline scheduling seasons. *IATA airline scheduling seasons.*

Season	Dates
Winter 2009	25 october 2009 to 27 march 2010
Summer 2010	28 march 2010 to 30 october 2010
Winter 2010	31 october 2010 to 26 march 2011
Summer 2011	27 march 2011 to 29 october 2011
Winter 2011	30 october 2011 to 24 march 2012
Summer 2012	25 march 2012 to 27 october 2012

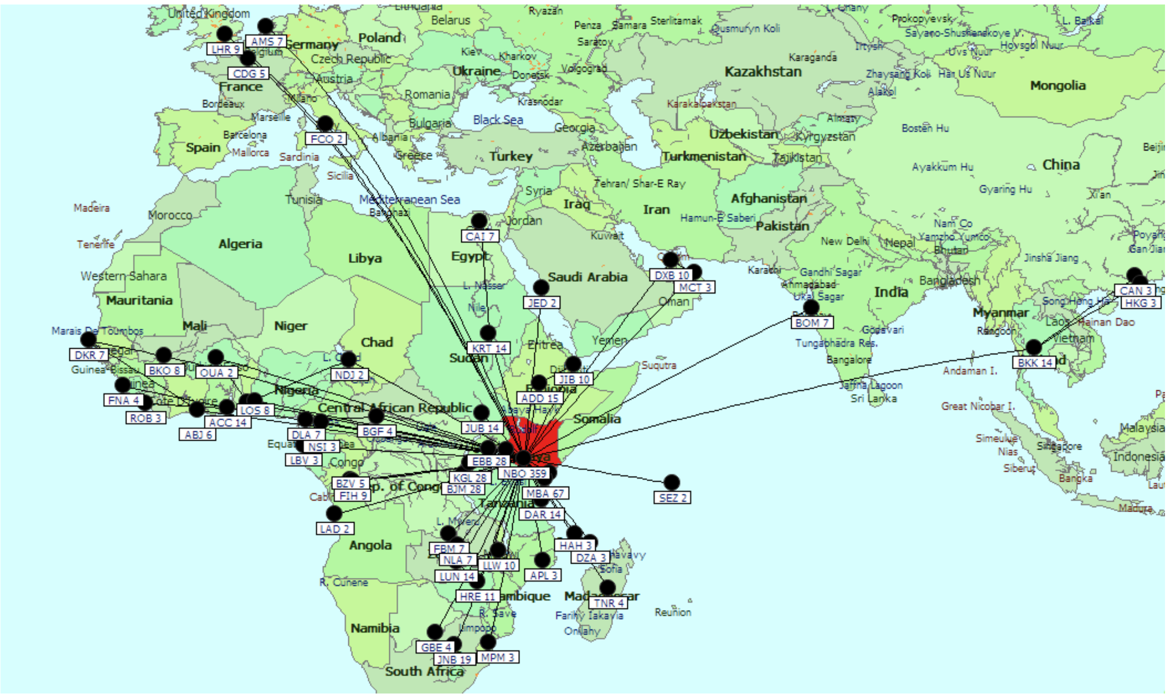

Figure A.1. Flight network of Kenya Airways. All destinations per October 2011.

Table A.4. Categorizing delay codes for Turnaround Execution. KQ Delay Codes for the turnaround process.

Numeric	Delay Code	Description	Delay Category
9	SG	Scheduled ground time	Turnaround Execution
11	PD	Late check-in	Turnaround Execution
12	PL	Late check-in	Turnaround Execution
13	PE	Check-in error	Turnaround Execution
14	PO	Oversales	Turnaround Execution
15	PH	Boarding	Turnaround Execution
16	PS	Commercial publicity /passenger convenience	Turnaround Execution
17	PC	Catering order	Turnaround Execution
18	PB	Baggage processing	Turnaround Execution
21	CD	Documentation	Turnaround Execution
22	CP	Late positioning	Turnaround Execution
23	CC	Late acceptance	Turnaround Execution
24	CI	Inadequate packing	Turnaround Execution
25	CO	Oversales	Turnaround Execution
27	CE	Documentation, packing	Turnaround Execution
28	CL	Late positioning	Turnaround Execution
29	CA	Late acceptance	Turnaround Execution
31	GD	Late / inaccurate aircraft documentation	Turnaround Execution
32	GL	Loading / unloading	Turnaround Execution
33	GE	Loading equipment	Turnaround Execution
34	GS	Servicing equipment	Turnaround Execution
35	GC	Aircraft cleaning	Turnaround Execution
36	GF	Fuelling / defuelling	Turnaround Execution
37	GB	Catering	Turnaround Execution
38	GU	Uld/containers.	Turnaround Execution
39	GT	Technical equipment	Turnaround Execution
44	TS	Spares and maintenance	Turnaround Execution
56	EC	Cargo preparation documentation	Turnaround Execution
57	EF	Flight plans	Turnaround Execution
61	FP	Flight plan	Turnaround Execution
62	FF	Operational requirement	Turnaround Execution
63	FT	Late crew boarding or departure procedures	Turnaround Execution
64	FS	Flight deck crew shortage	Turnaround Execution
65	FR	Flight deck crew special request	Turnaround Execution
66	FL	Late cabin crew boarding procedures	Turnaround Execution
67	FC	Cabin crew shortage	Turnaround Execution
68	FA	Cabin crew error or special request	Turnaround Execution
69	FB	Captain request for security check	Turnaround Execution
92	RT	Through check-in error	Turnaround Execution

Table A.5. Categorizing delay codes other categories. KQ Delay Codes for other processes.

Numeric	Delay Code	Description	Delay Category
47	TL	Standby aircraft	Aircraft Rotation
93	RA	Aircraft rotation	Aircraft Rotation
6	OA	No gate/stand available	Airport/ATC restrictions
81	AT	Atfm due to atc en-route demand / capacity	Airport/ATC restrictions
82	AX	Atfm due to atc staff / equipment enroute	Airport/ATC restrictions
83	AE	Atfm due to restriction at destination airport	Airport/ATC restrictions
85	AS	Mandatory security	Airport/ATC restrictions
86	AG	Immigration, customs, health	Airport/ATC restrictions
87	AF	Airport facilities	Airport/ATC restrictions
88	AD	Restrictions at destination airport	Airport/ATC restrictions
89	AM	Restrictions at airport of departure	Airport/ATC restrictions
94	RS	Cabin crew rotation	Crew Rotation
95	RC	Crew rotation	Crew Rotation
91	RL	Load connection	Load Connectivity
96	RO	Operations control	Manual division
99	MX	Miscellaneous	Manual division
41	TD	Technical defects	Technical state of the aircraft
42	TM	Scheduled maintenance	Technical state of the aircraft
43	TN	Non-scheduled maintenance	Technical state of the aircraft
45	TA	Aog spares	Technical state of the aircraft
46	TC	Aircraft change	Technical state of the aircraft
52	DG	Damage during ground operations	Technical state of the aircraft
55	ED	Departure control	Technical state of the aircraft
51	DF	Damage during flight operations	Unavoidable
97	MI	Industrial action within own airline	Unavoidable
98	MO	Industrial action outside own airline	Unavoidable
71	WO	Departure station	Weather
72	WT	Destination station	Weather
73	WR	En-route or alternate	Weather
75	WI	De-icing of aircraft	Weather
76	WS	Removal of snow or from airport	Weather
77	WG	Ground handling impaired by weather	Weather
84	AW	Atfm due to weather at destination	Weather

B. Data Import

This appendix discusses the three main data imports from their sources.

B.1 Flight performance data

This section discusses the import of the Historical flight performance data which is extracted from Sabre Movement Control Flight Following System. Using Microsoft Visual Basic, the raw data is imported, validated and enriched. The output is in Comma Separated Values that is suited for the stochastic simulation of delay propagation in Matlab to import.

This dataset contains required parameters to describe the stochastic nature of the Block-time, Turnaround-time and Passenger Connection-times. The output of the data processing from Sabre is as follows:

BlockTime data: Season, Departure Airport, Arrival Airport, Aircraft type, Mean$_{ABT}$, StdDev$_{ABT}$

Turnaround times: Aircraft type, Mean$_{ATT}$, Std$_{ATT}$

Minimum Connecting time: Passenger Group Size, Mean$_{ACT}$, STD$_{ACT}$

B.1.1 Data validity of Sabre determines period of study

The period of study for the historical flight performance data is taken as September 2010 to September 2011. The reason for this is that the validity of the flight performance data prior to this period due to the learning curve that implementing this information system had. The Sabre system was implemented in May 2010.

Figure B.1 shows the number of incorrectly documented delays from the month of implementation in May 2010. This figure shows how the number of flights implemented in the system has improved and how the number of incorrectly documented delays have decreased. The algorithm used to determine if a delay is incorrectly documented is if the number of delay minutes assigned to a delay code does not add up to the actual delay.

In conclusion, the period of study is taken from September 2010 onwards as the number of incorrectly documented delays stabilize.

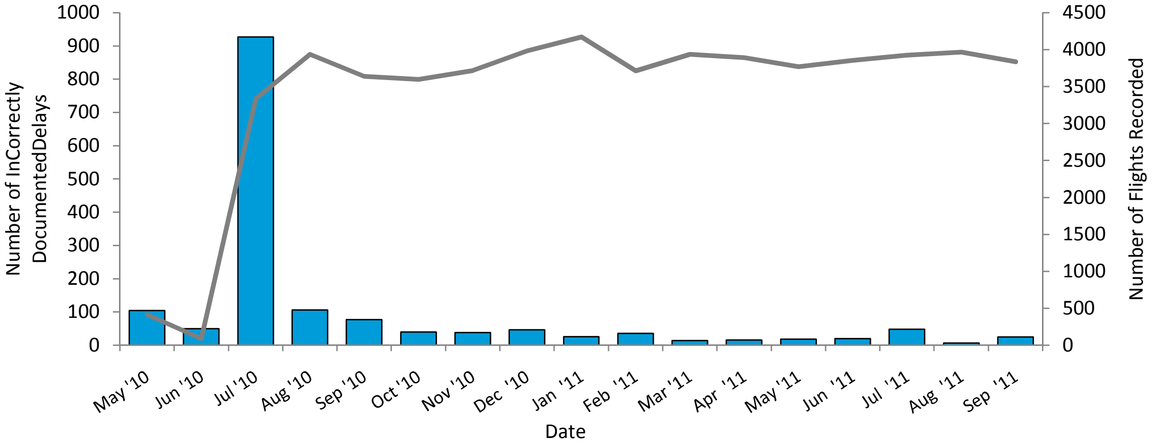

Figure B.1. Incorrectly documented delays. *An incorrectly documented delay is if the number of delay minutes assigned to delay codes does not add up to the actual delay. The graph forms the main argument to fix the period of study from September 2010 onwards.*

B.1.2 Recording flight data rounded to 5 minute multiples

The guideline for flight crew to round off data on multiples of 5 minutes obscures the flight data from aircraft without and Aircraft Communications Addressing and Reporting System (ACARS). As can be seen from the example flight to Johannesburg, figure B.2, there are high peaks of probability on multiples of 5 minutes. However, a growing number of aircraft get fitted with ACARS that transmits departure and arrival data rounded off in minutes.

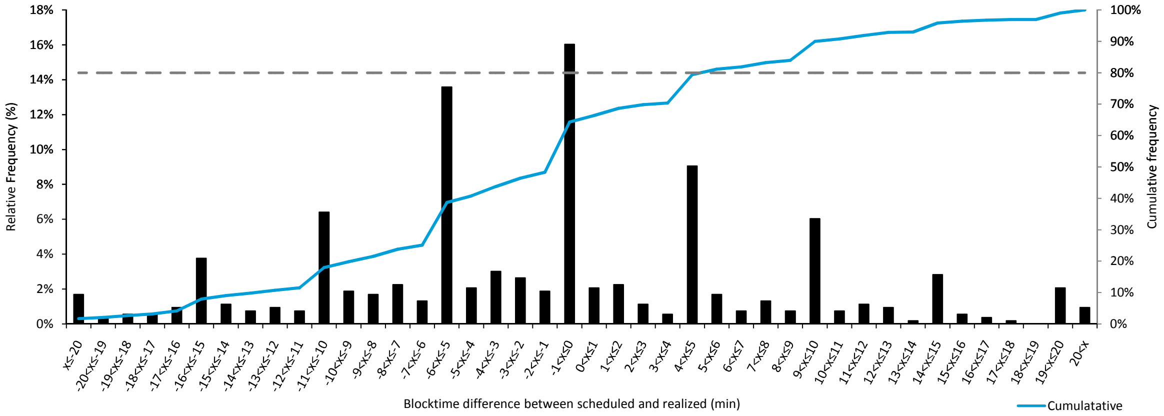

Figure B.2. Operational 5 minute round off guideline. *Pilots manually transmit arrival and departure times rounded off in multiples of 5 minutes in all aircraft not fitted with ACARS resulting in peak probabilities. This example is the outbound flight to Johannesburg, where the frequency of the difference in between scheduled and actual block times is plotted. (data is for 841 flights of a Boeing 737-800, flown between February 2010 and august 2011.*

As such, the flight performance data will be adjusted when approximated. A uniform distribution for peaks on 5 minute multiples is assumed. The reason for this is that there is not information guiding to a more exact approximation. The datasets on multiples of 5 minutes can then be distributed as is shown in figure B.3. The result is the possibility to approximate data more accurate, as is shown in the example in figure B.4.

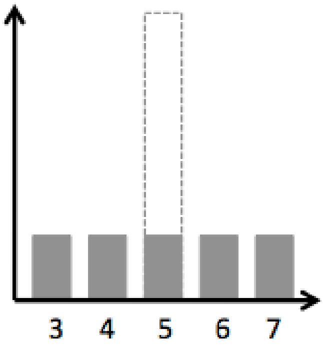

Figure B.3. Smoothening of flight performance data. *This is done due to the requirements given to the flight crew to round off data on multiples of 5 minutes. The solution is to assume a uniform distribution, and distribute the found data as shown.*

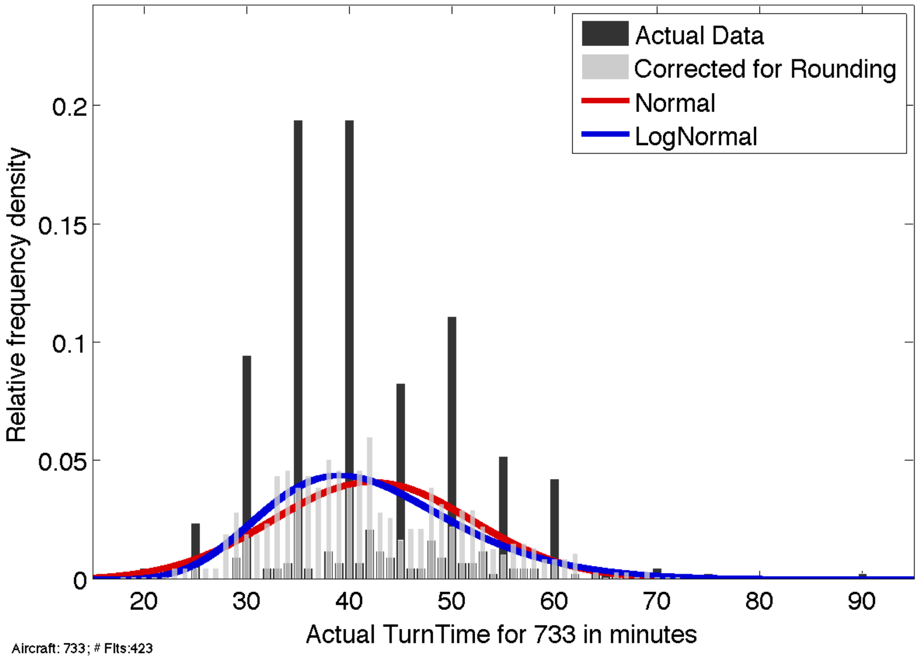

Figure B.4. Example of probability fit of smoothened data. *When the data is correctly smoothened, an accurate data fit can be applied. The example given is for a Block-time approximation outbound to Johannesburg for a Boeing 737-800.*

B.2 Schedule data

Schedule data is retrieved from Netline, a Lufthansa schedule management system. Two files are retrieved namely the schedule information and the possible flight connections. The output for the data processing of the schedule data is as follows:

Flight Schedule: Flight number, Date, Aircraft Type ,Departure Airport, Arrival Airport, STA, STD. Onward Flight Number, Onward STD, Onward Date

Possible Flight Connections: Hub, Inbound Flight Number, Inbound Departure Airport, Inbound STA, Inbound STA date, Outbound Flight Number, Outbound Arrival Airport, Outbound STD, PCT,

The Flight Schedule file contains all scheduled flight time data and is used to create an array of flight objects. Schedules are currently made on a 7 day rotation cycle. As such, the simulation will also assume a 7 day rotation cycle. No provision can be made as to reduce it to a daily cycle as this would exclude twice-daily flights.

The Possible Flight Connections file contains all the possible passenger connections for transfers in Nairobi and is used in combination with the booking data to populate flight connections.

From the Flight Schedule, an array of flight objects is created which forms a direct input for the stochastic simulation of delay propagation.

The input for this algorithm is a schedule file from Netline and the processed block time data from Sabre. The challenge is that the Schedule file does not contain any tail information. This is because Netline optimizes flight rotations to minimize the required sub-fleet on anonymous tail basis. This is defined as an aircraft assignment based on aircraft type instead of a maintenance optimized tail assignment[1].

The work around required to assign flights to anonymous tails is described in figure B.5. First, the flight list is sorted on the scheduled time of departure. The first flight is used as the start of the anonymous tail rotation, and as such an aircraft is created. The flight rotation of an anonymous tail is chronologically followed. Each flight requires (1) retrieving the flight data; (2) creating the flight and (3) removing the flight from the list. By the last schedule day, the rotation is finished and the creation of a new tail rotation can be started.

The result is an array of flight objects, each linked to an aircraft object. The next step is to populate the flights, and interconnect the flights for passenger connectivity.

B.3 Passenger booking data

Passenger booking data is extracted from Delorean, a passenger booking analysis tool. The data contains the expected transfer passenger load on a Origin and Destination level, and the output of the processing stage is defined as follows:

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[1] Discussed in more detail by Bazargan (2010).

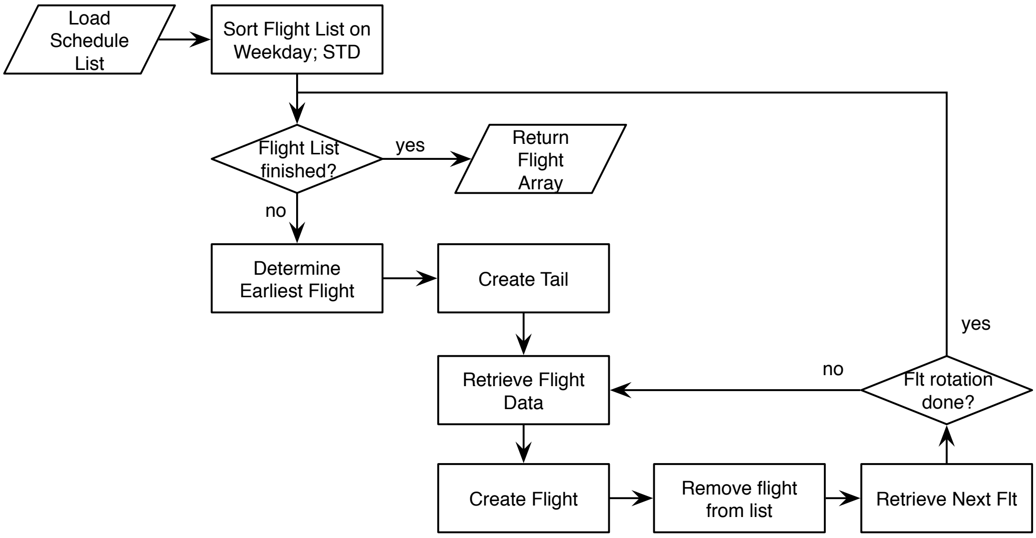

Figure B.5. ***Specification of processing flight schedule.*** *The flowchart shows how the flight schedule data is used to create an array of flight objects.*

Origin and Destination Demand: Flight Leg Departure Airport, Flight Leg Arrival Airport, Passenger CityPair, Season, Number of Passengers

The average demand can be found on a Origin and Destination level. The conceptualization of passenger flows is described in chapter 4. Using this logic, an algorithm is created that can translate the origin and destination booking data from Delorean into flight leg connections from the Possible Flight Connections file imported from Netline.

The input for this algorithm is a possible passenger connections file from Netline and a processed passenger demand file from Delorean. What the algorithm does is to 'populate' all the possible flight connections found at JKIA with demand.

The algorithm to populate the schedule with passenger demand consists of three iteration cycles as is shown in figure B.6. The first cycle is to iterate through the array of flight objects. Then, there is an iteration through all possible passenger connections. The third iteration cycle is a work around that provides for flight rotations that connect multiple destinations before returning to Nairobi. The connecting flight number is assigned one or multiple destinations, depending on whether it is a circular flight, that can be used to fill expected demand on an origin and destination level.

There is also a provision is for infeasible connections, as when there is no demand[2] the flight connection is removed.

The result of this algorithm is a flight array with upstream connecting flights and downstream connecting flights. Each connecting flight contains the expected number of passenger. This finalizes the pre-processing stage, after which the flight array is ready for the simulation.

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[2] An example is the flight KQ0117 from Amsterdam (AMS) that connects to the flight KQ0102 to London (LHR). There is, historically speaking, no demand for this connections as passengers prefer to fly direct.

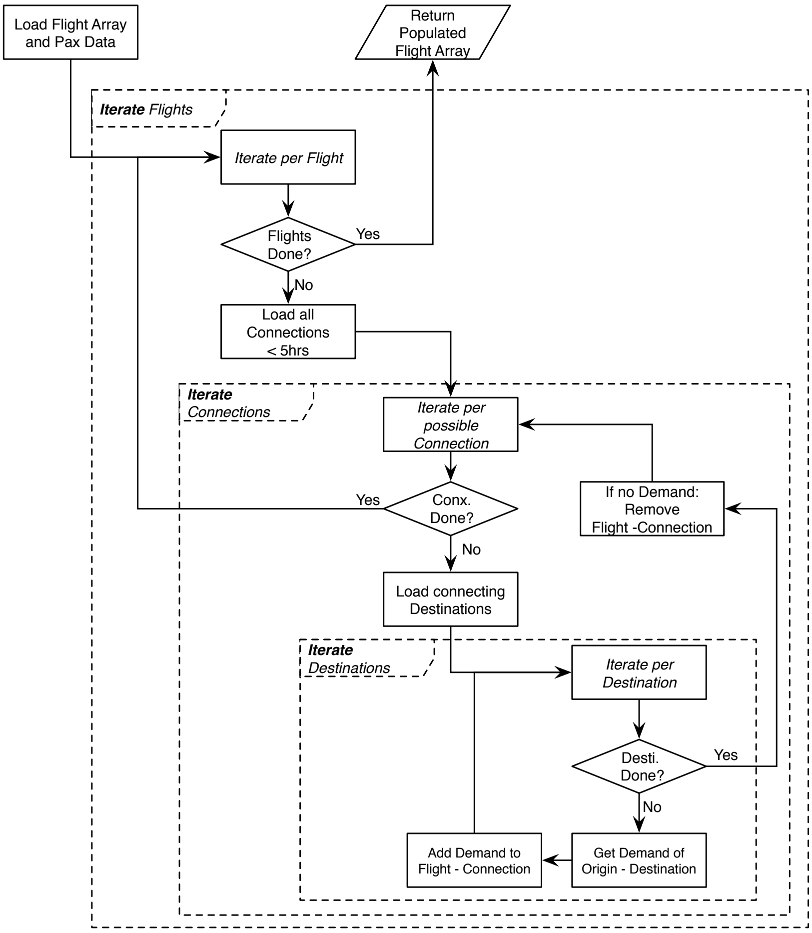


Figure B.6. Specification of population of flight array. *The array of flight objects can interconnected with transfer passenger data, accounting for circular flights that have two destinations.*

C. Determining the required simulation run-length

Using the Central Limit Theory, a theoretical required number of simulation runs can be calculated to ensure trust in the Monte-Carlo simulation. The basis is that the simulation iterates until a threshold run-length is reached.

A standard simulation run-length procedure is used to determine the required simulation run-length. The basis is to setup a pilot simulation run of the flight schedule to determine the variance in the simulation findings, and compute a theoretical required simulation run-length based on a 95% confidence interval calculation.

A derivation of the theoretical required simulation run-length follows, and is adapted from Kraaikamp and Meester (2005). The simulation delivers an expected delay severity, $\hat{\zeta}$, which is the average delay severity from n runs:

$$\hat{\zeta} = \frac{\sum_{i=1}^{n} Xi}{n} \tag{C.1}$$

The purpose of the simulation run is to determine the delay severity, actual number of affected flights ζ, of a primary delay stowed upon a flight. The absolute error is the difference between the actual and expected delay severity:

$$E = |\hat{\zeta} - \zeta| \tag{C.2}$$

The purpose is then to choose n as to to satisfy the error requirement that there should be a 95% confidence, $1-\alpha$, that the simulated error E is less than 1 flight, ε. As such, the following should be upheld:

$$P(E < \varepsilon) = 1 - \alpha \tag{C.3}$$

$$P\left(|\hat{\zeta} - \zeta| < \varepsilon\right) = 1 - \alpha \tag{C.4}$$

As indicated, the run-length calculation uses the confidence interval. The probability that ζ satisfies the confidence interval of $1-\alpha$:

$$P\left(c_l < \zeta < c_u\right) = 1 - \alpha \tag{C.5}$$

$$P\left(z_{1/2\alpha} < \zeta < z_{1-1/2\alpha}\right) = 1 - \alpha \tag{C.6}$$

With $z_{1/2\alpha}$ and $z_{1-1/2\alpha}$ being the percentile lower and upper limit points of the confidence level.

The Central Limit Theory states if we simulate a sample $X_1 ... X_n$ from the distribution $N(\zeta, \sigma^2)$, then our simulated delay severity, $\hat{\zeta}$, is from a distribution $N(\zeta, \sigma^2/n)$. As such we can approximate ζ by the Central Limit Theory, and place that into the confidence level interval:

$$P\Big(z_{1/2\alpha} < \frac{(\hat{\zeta}-\zeta)\sqrt{(n)}}{\sigma} < z_{1-1/2\alpha}\Big) \approx 1-\alpha \tag{C.7}$$

$$P\big(z_{1/2\alpha}\sigma n^{-1/2} < \hat{\zeta}-\zeta < z_{1-1/2\alpha}\sigma n^{-1/2}\big) \approx 1-\alpha \tag{C.8}$$

Under the assumption that the underlying distribution is normal and symmetric, the following upholds:

$$P\Big(\big|\hat{\zeta}-\zeta\big| < z_{1-1/2\alpha}\sigma n^{-1/2}\Big) \approx 1-\alpha \tag{C.9}$$

It is seen that equations C.4 and C.9 are congruent, and as such:

$$\varepsilon = z_{1-1/2\alpha}\sigma n^{-1/2} \tag{C.10}$$

$$n = \frac{\sigma^2 z^2_{1-1/2\alpha}}{\varepsilon^2} \tag{C.11}$$

Concluding, a theoretical required simulation run-length, n_{theor}, can be calculated based on the upper bound percentile, $z_{1-1/2\alpha}$, and the variance, σ^2, of the underlying distribution. However, this is precisely what the simulation is set out to simulate. A work around is necessary, and the proposed is to use a pilot simulation to study the outcome variance, $\hat{\sigma}^2$, and percentile point, $\hat{z}_{1-1/2\alpha}$, to determine the theoretical required simulation runs, n_{theor}. As such:

$$n_{theor} = \frac{\hat{\sigma}^2 \hat{z}^2_{1-1/2\alpha}}{\varepsilon^2} \tag{C.12}$$

A sequential method is used to verify if the simulation run satisfies the theoretical requires run-length. The reason for this is apparent after a pilot simulation run is created. During this pilot all flights with a 30 minute primary delay in 500 simulation runs. The variance, σ^2, indicates a minimum required simulation runs. However, as is shown in figure C.1, the challenge in choosing a required simulation run as it is related to the experimental delay severity, $\hat{\zeta}$.

As such a sequential method is chosen where each 1,000 simulation cycles a new theoretical run-length is calculated. Due computing power, a threshold of three times the theoretical required run-length is specified. If the current simulation satisfied this threshold, the simulation is stopped.

The simulation can be verified to see if the outcome is stable. Figure C.2 shows the outcome of 10 simulation series where flight 533 is given a 30 minute delay. Each simulation is performed with 5000 cycles, the expected delay severity is plotted on the latitudinal axis. With a σ^2 of approximately 10.8, the theoretical run-length is approximately 1,600. A trade-off between simulation accuracy and computing power has to be made. Iteratively, a required threshold run-length of over 3 times the theoretical run-length is chosen. Considering the stability in the solutions presented in figure C.2 this is found sufficient, as such:

$$n_{req} = 3 \cdot n_{theor} \tag{C.13}$$

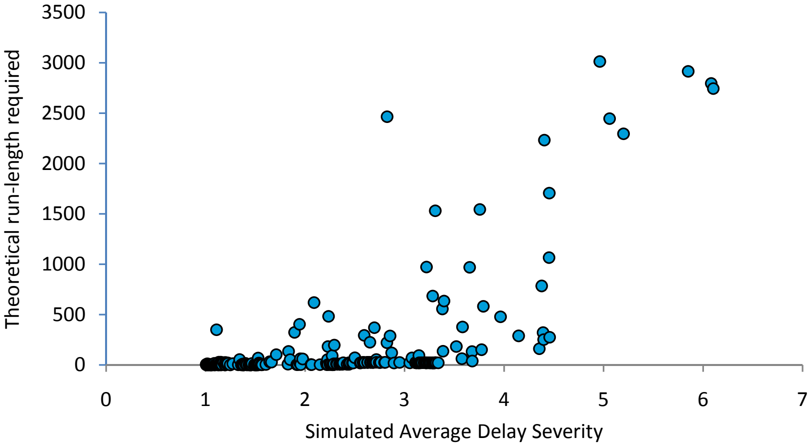


Figure C.1. Theoretical required simulation runs

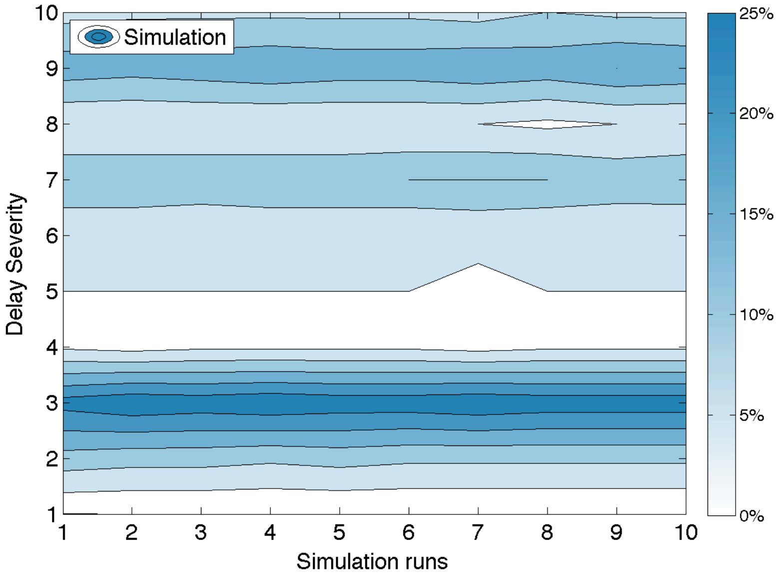


Figure C.2. Validating the run-length of the simulation *The simulation of a 30 minute delay on flight 533 is performed 10 times with 5,000 simulation cycles. The theoretical required run-length is approximately 1,600. The outcome is stable, and as such a high confidence is achieved.*

D. Schedule retiming proposals

This appendix presents an overview of several alternative flight timings made using the delay severity simulation to improve schedule stability. The purpose of this appendix is to show what has been achieved and what can be achieved with the simulation and the methodology as to improve schedule stability.

The improvements have been spread over four cases. First, a set of timings on routes correcting the block-time for aircraft and season, implemented per september 2011. Then, a set of low-impact timings which do not inflict any changes on preceding or subsequent flights. Thereafter, two alternative flight timings are discussed that do require the consideration of protecting passenger connectivity. These proposals are implemented as September 2011. The last case discussed is on the circular flight to Khartoum (KRT) and Cairo (CAI), which has an impact on a large number of feeding flights.

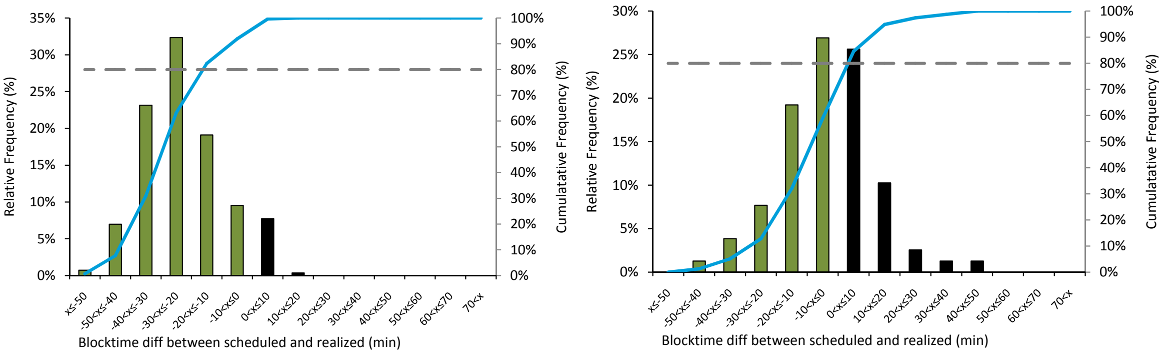
D.1 Proposals on routes correcting block-time for aircraft and season

The first section on improving block-time confidence will analyze routes correcting for aircraft and season. Two examples are discussed, implemented from the Winter 2011 season onwards and shown in table D.1.

The first example is the flight rotation to Amsterdam, flown in high season by a Boeing 777 and in low season by a Boeing 767-300. Analysis of the Block-time confidence shows a large difference between the performance due cruise velocity. The analysis of the outbound flight to Amsterdam has been done for flights between September 2010 and September 2011 and shown in figure D.1. 78 flights were flown with a Boeing 767-300, with a confidence of 59%. However, 272 flights were flown with a Boeing 777, with a 92% confidence.

The second aspect of this section is to consider seasonality on routes where seasons are impacted. The main routes impacted are the long-haul Asian routes, such as the example discussed of the flight inbound from Bangkok (BKK). Figure D.2 shows how the average ABT with respect to the SBT. As can be seen, the ABT varies monthly due to seasonal winds. During the winter period the winds are strongest and run from East to West. Thus decreasing the required block time inbound from Bangkok. As such, the confidence level during the winter and summer season differs, as is shown in figure D.3. During the summer the inbound flight from Bangkok is tight, whilst the SBT is over-scheduled during the winter period.

In conclusion, studying the historical flight performance on an aircraft and season level can impact the Block-time confidence level. Using the Block-time confidence tool, several flights have been re-timed. The routes that have been re-timed per October 2011 are shown in table D.1.



(a) Flying 772 **(b)** Flying 767

Figure D.1. Blocktime influence of aircraft type. *There is a difference in flight performance between the Boeing 772 and 767 due to the cruise velocity. As such, the flight from Nairobi (NBO) to Amsterdam (AMS) has a difference Block-time confidence level depending on the aircraft type flown.*

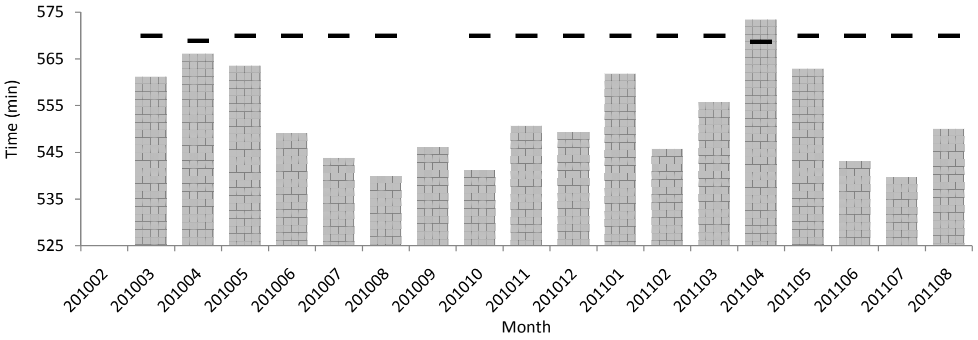
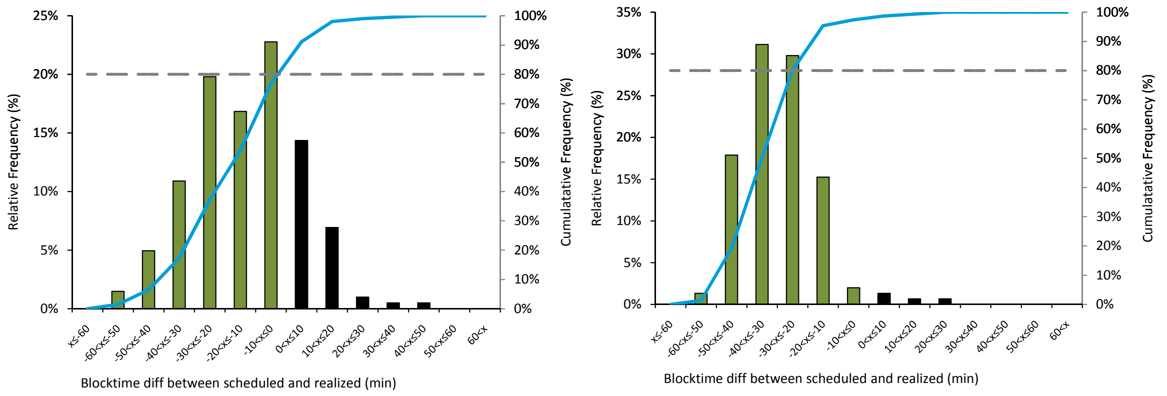


Figure D.2. Seasonal block time variation inbound flight from Bangkok. *Monthly average Actual Block Time and Scheduled Block Time for the flight inbound from Bangkok on a Boeing 767. The monthly average ABT is shown in grey bars, the black markers indicate the monthly SBT.*



(a) Summer **(b)** Winter

Figure D.3. Block time confidence analysis of Bangkok. *The differences between Scheduled and Actual Block Times per season, for the flight inbound form Bangkok. (Data on Boeing 767, from September 2010 to September 2011)*

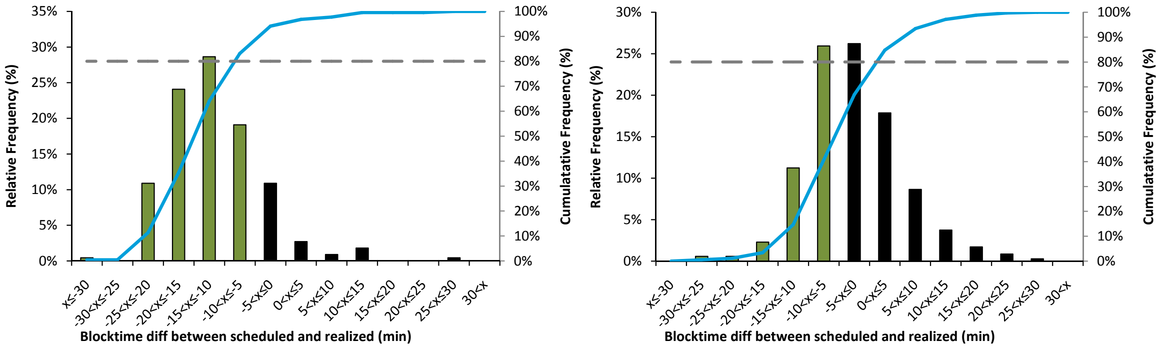
Table D.1. BlockTime improvements considering aircraft and season. These routes have been retimed as per September 2011 to achieve a higher Block-time confidence level.

FltNum	DepAp	ArrAp	Days	∆SBT	∆STD	∆STA	AcType	Season
KQ0120	NBO	FCO	..3.5.7	+5	-5	0	737	
KQ0121	FCO	NBO	1..4.6.	+25	0	+25	737	
KQ0886	NBO	BKK	12.4..7	-20	+20	0	767	Winter
KQ0886	BKK	CAN	123.5..	+10	0	+10	767	Winter
KQ0887	CAN	BKK	123.5..	+5	-5	0	767	Winter
KQ0887	BKK	NBO	123.5..	0	0	0	767	Winter
KQ0860	NBO	BKK	..3.56.	-20	+20	0	767	Winter
KQ0860	BKK	HKG	…4.67	+10	0	+10	767	Winter
KQ0861	HGK	BKK	…4.67	+5	+5	0	767	Winter
KQ0861	BKK	NBO	…4.67	0	0	0	767	Winter

D.2 Low-impact improvements on flight rotations

This section will discuss several flight rotations where the re-allocation of the slack-time during the rotation can result in an overall increase of punctuality.

Flight KQ0406 and KQ0408 are circular flights to ADD and JIB. The main change is to re-allocate slack from the outbound flight to ADD with the flight from ADD to JIB. Figure D.4 shows a high confidence on the first, a low on the second. The airports are not slot-restricted, as such a retiming can be done without changing the departure time from and arrival time to Nairobi. By re-allocating block time this circular flight can be optimized for a higher aircraft arrival punctuality without impacting the rest of the schedule.



(a) NBO-ADD: 91%

(b) ADD-JIB: 53%

Figure D.4. Example achieved block time confidence for circular flights.

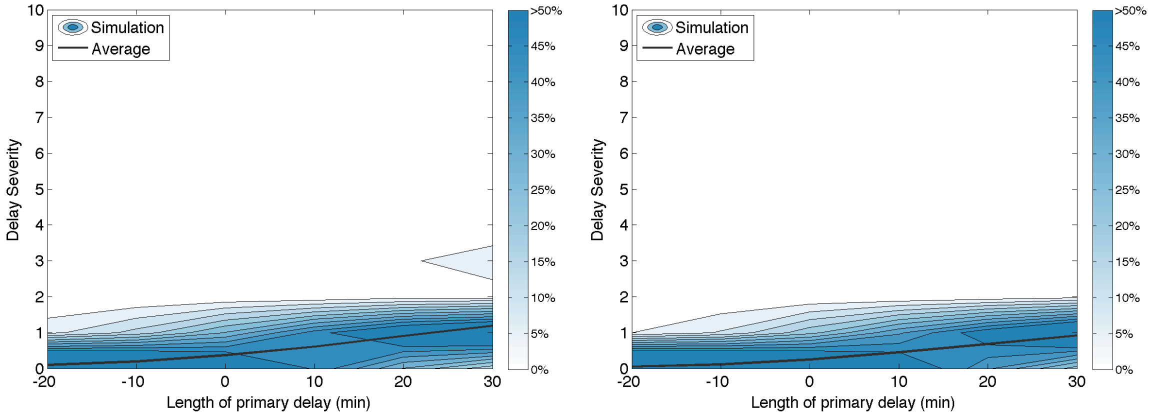
Other such example are flight KQ0550 and KQ0452. An overview of the low impact Block-time improvements are shown in table D.2, and are implemented as per September 2011.

The alternative flight timing of are shown in table D.2 and improve the overall schedule stability. To illustrate, the example of how the retiming of flight KQ0554 to Kinshasa (FIH) can lead to a more robust flight as the probability of the flight arriving on-time is higher. Figure D.5a shows the current situation, with the improvement shown in figure D.5b. By adding 5 minutes to the SBT this flight is less likely to

Table D.2. Low impact Block-time improvements. *These routes have been retimed as per September 2011 to re-allocate the slack-time throughout the rotation without impacting preceding or subsequent flights due to passenger connectivity.*

FltNum	DepAp	ArrAp	Days	∆SBT	∆STD	∆STA
KQ0550	NBO	BZV	.2.4.6.	+5	0	+5
KQ0550	BZV	FIH	.2.4.6.	0	+5	+5
KQ0550	FIH	NBO	.2.4.6.	0	+5	+5
KQ0406	NBO	ADD	…4.67	-5	0	-5
KQ0406	ADD	JIB	…4.67	+5	-5	0
KQ0406	JIB	NBO	1…5.7	0	0	0
KQ0408	NBO	JIB	..3.5..	0	0	0
KQ0408	JIB	ADD	..3.5..	0	0	0
KQ0408	ADD	NBO	…4.6.	+5	0	+5
KQ0452	NBO	DZA	.2.4…	+5	0	+5
KQ0452	DZA	HAH	.2.4…	-5	+5	0
KQ0452	HAH	NBO	.2.4…	0	0	0

disrupt the inbound flight, KQ0555.



(a) Base, $\bar{\zeta}$=0.35 **(b)** Improvement, $\bar{\zeta}$=0.23

Figure D.5. Improvement robustness flight outbound to FIH.

D.3 Analysis on flight rotations considering passenger connections

Changing block-time results in changing departure or arrival time. This can impact the flight rotation and the passenger connectivity. This section will discuss an example of how changing a SBT will require the retiming of subsequent flights. As discussed in chapter 4 the guideline to sell a transfer connection is a MCT of 50 minutes.

The first example is flight KQ0542, identified as a sensitive flight due low inbound Block-time confidence from Cotonou (COO). To increase the Block-time confidence, an addition of 10 minutes would require re-timing flight KQ0402 and KQ0403 to ensure for transfer passengers. An overview is given in figure D.3 of the retiming decisions made in the improvement proposal. The implementation was per September 2011.

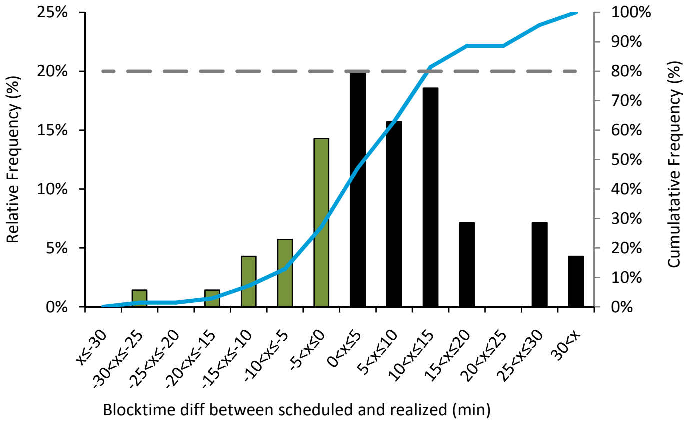


Figure D.6. Block-time confidence for Flight KQ0542 inbound from COO. *(Data from Boeing 737-700, between September 2010 and September 2011)*

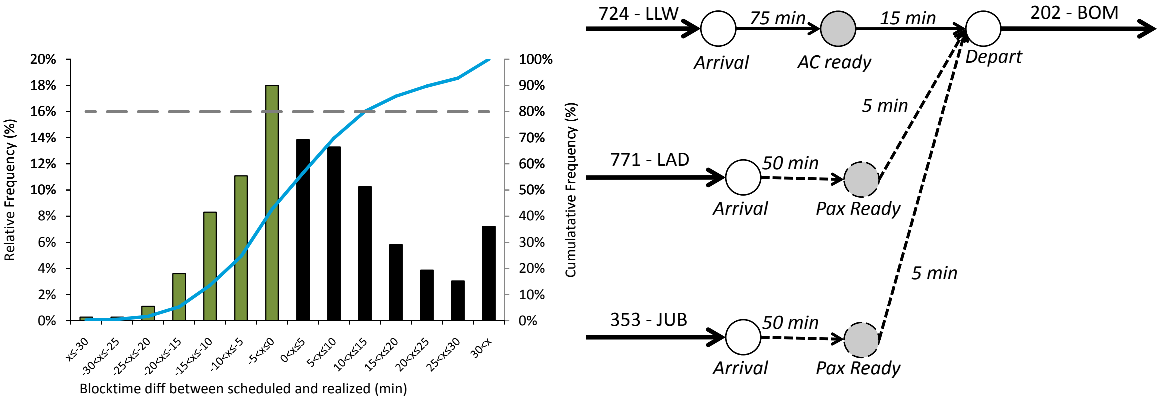
Table D.3. The alternative flight plan proposed for the circular flight to Lagos and Cotonou. *Implemented in September 2011. The flight KQ0452 impacts passenger connectivity downstream and, as such, flights KQ0402 and KQ0403 have to be delayed.*

FltNum	DepAp	ArrAp	Days	∆SBT	∆STD	∆STA
KQ0542	NBO	LOS	.2.4.6.	+10	0	+10
KQ0542	LOS	COO	.2.4.6.	0	+10	+10
KQ0542	COO	NBO	.2.4.6.	+10	+10	+20
KQ0402	NBO	ADD	123.5..	-5	+15	+10
KQ0402	ADD	JIB	123.5..	+5	+10	+15
KQ0403	JIB	ADD	123.5..	-5	+15	+10
KQ0403	ADD	NBO	123.5..	-5	+10	+5

A second study was done on the flights to Bombay (BOM). On a Boeing 767 the Block-time confidence is low as is seen in figure D.7a. Retiming is only possible by advancing flight KQ0202 due slot restrictions in Bombay (BOM). As such, the connectivity feeding onto the flight has to be considered. Shown in figure D.7b, two flights have to be advanced to feed into a retimed KQ0202 flight.

The result is retiming the rotations prior to the flight, in this instance the flight rotations to Jubba (JUB) and Luanda (LAD). Furthermore, the SBT for the flights inbound and outbound from Luanda (LAD) are increased to ensure a higher Block-time confidence.

The improvement on schedule stability of retiming the outbound flight to Bombay (BOM) is shown in figure D.8. Currently, the flight has a large probability of delaying a significant number of downstream de-feeding flights, as is shown in figure D.8a. The direct effect of adding 20 minutes on the whole rotation is that the severe delays on all de-feeder flights is pushed back.



(a) NBO-BOM: Block-time confidence 43%

(b) Schedule effects of advancing BOM

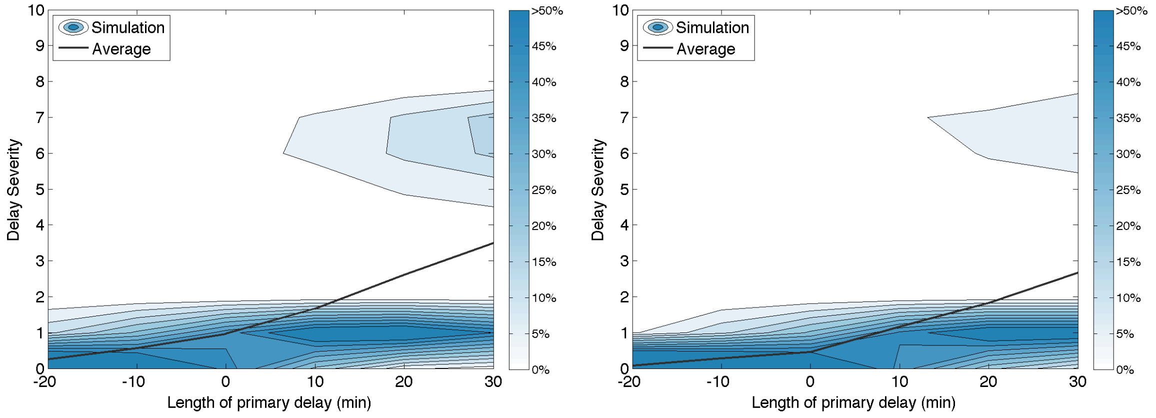
Figure D.7. Block time confidence for outbound flight to Bombay. *An increase in a 43% block time confidence level for the outbound flight to Bombay is required. The choice to advance to rotation as to increase the SBT is influenced by the impact onto the schedule. In particular the feeding flights that have to be advanced as to adhere to the Minimum passenger Connecting-Time of 50 minutes.*

Table D.4. The alternative flight plan proposed for the circular flight to Bombay. *The alternative flight plan for the rotation to Bombay, implemented as per October 2011. The impact of the alternative flight plan requires advancing several feeder flights.*

FltNum	DepAp	ArrAp	Days	∆SBT	∆STD	∆STA
KQ0202	NBO	BOM	1234567	+10	-10	0
KQ0203	BOM	NBO	1234567	+10	0	+10
KQ0350	NBO	JUB	1234567	0	-10	-10
KQ0351	JUB	NBO	1234567	0	-10	-10
KQ0352	NBO	JUB	1234567	0	-10	-10
KQ0353	JUB	NBO	1234567	0	-10	-10
KQ0770	NBO	LAD	.2..5..	+10	-30	-20
KQ0771	LAD	NBO	.2..5..	+15	-20	-5

The disadvantage of advancing the rotation to Bombay is that some feeder flights get a tighter connection. For example, flight KQ0550 as shown figure D.9. In the base scenario, a lengthly delay will only affect the inbound flight and the flight to Bombay. However, as the PCT is shorter in the proposal the probability of delaying the Bombay flight increases for smaller delays.

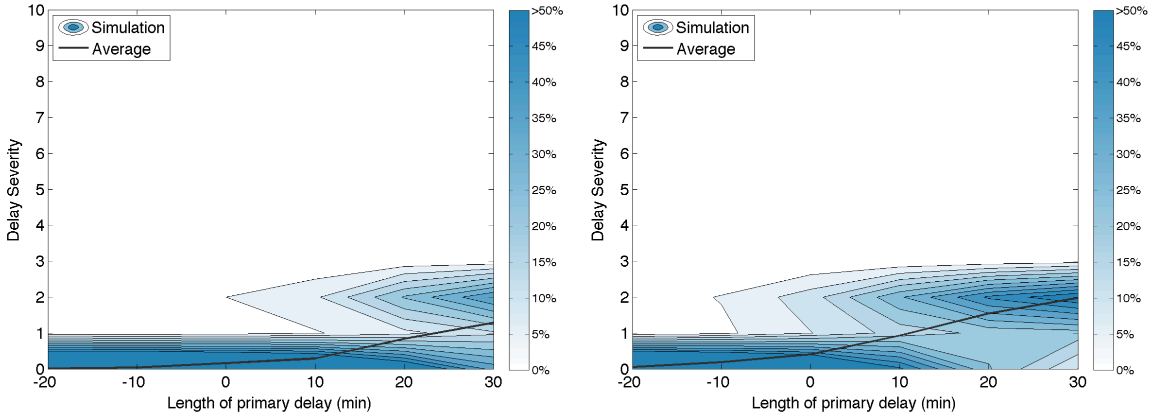
In conclusion to the alternative flight plan for KQ0202, even though some feeder flights increase their expected delay severity due a shorter PCT, the overall picture is that re-timing the Bombay flight increase schedule stability.



(a) Base, $\bar{\zeta}$=0.96

(b) Improvement, $\bar{\zeta}$=0.52

Figure D.8. Improvement robustness flight outbound to BOM.



(a) Base, $\bar{\zeta}$=0.16

(b) Improvement, $\bar{\zeta}$=0.36

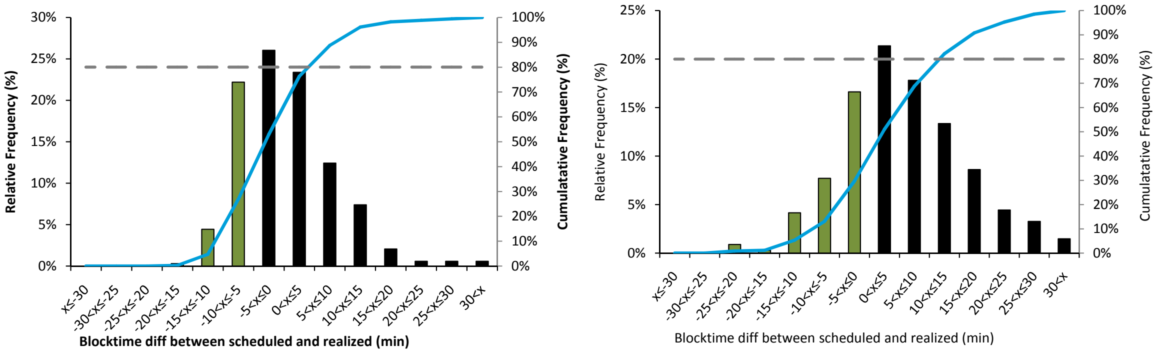
Figure D.9. Improvement robustness flight outbound to FIH.

D.4 Improvement of Khartoum and Cairo rotation

This section will discuss how a Block-time improvement on the flight rotations require advancing the departure of flight KQ0320, and with that 18 other flights to ensure for sufficient connectivity.

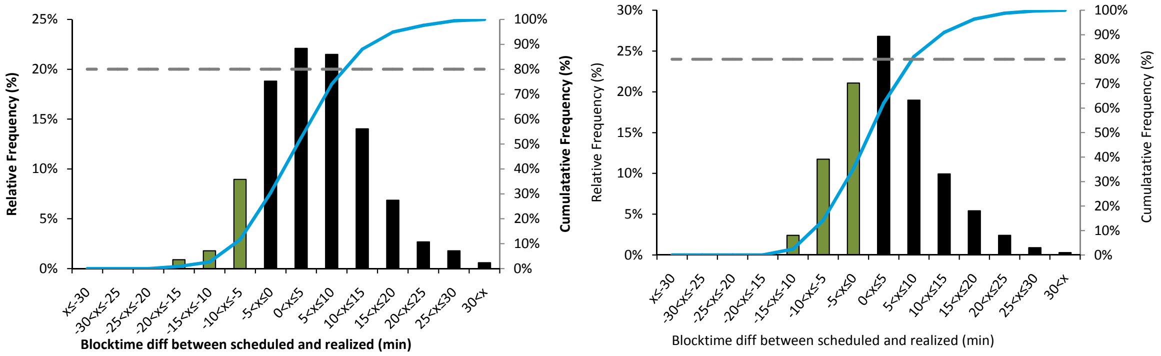
D.4.1 Block-time analysis on Khartoum and Cairo

Figure D.10 shows the current Block-time analysis, from which it follows that there is a low Block-time confidence throughout the rotations. As can be seen, this rotation is planned in with negative slack-time. The current arrival punctuality into Nairobi is 48%. From this analysis it follows that the Scheduled Block-time should increase over all flight legs.



(a) NBO-KRT: 53%

(b) KRT-CAI: 29%



(c) CAI-KRT: 30%

(d) KRT-NBO: 35%

Figure D.10. Block-time confidence CAI KRT. requires +5 throughout, minimum (335 Flights, data from September 2010 to September 2011)

D.4.2 Passenger connectivity onto the flight to Khartoum

In a similar fashion to retiming the Lagos flight, see chapter 6, the effects on passenger connectivity is analyzed for retiming the Khartoum and Cairo flight.

Table D.5 shows the connections onto flight KQ0320. In first place it shows there is no place to move without breaking passenger connections. When looking into the flights one level further, the connections can advance except for the flight KQ0710/1.

The choice has to be made to de-link the flight from flight KQ0710/1 to Gaborone (GBE). This flight is started in May 2011, and was timed such to link with the Khartoum and Cairo flight. Flight KQ0710/711 is starting up, and has collected over 2,700 passengers at a 59% load factor. The choice to de link the flight with the Khartoum and Cairo flight is that there where only 17 passengers connected in the time flight KQ0710/1 flew.

In conclusion to the passenger connectivity, there is room to advance flight KQ0320 to create more Scheduled Block-time if a de-link with flight KQ0711 from Gaborone is realized.

Table D.5. Overview passenger connectivity feeding into flight KQ0320. All connections onto flight KQ0320 with connections of 60 minutes or less. (Schedule 22 august to 28 august 2011)

FltNum In	**WkDy Pattern**	**DepAp**	**Via**	**STA**	**PCT**	**FltNum Out**	**ArrAp**	**nPax**
KQ0702	1….6.	LUN	NBO	1330	50	KQ0320	KRT	8
KQ0586	1234567	NLA	NBO	1325	55	KQ0320	KRT	5
KQ0711	…45.7	GBE	NBO	1325	55	KQ0320	KRT	2
KQ0722	..3.5..	LUN	NBO	1325	55	KQ0320	KRT	8
KQ0724	.2….7	LLW	NBO	1325	55	KQ0320	KRT	6
KQ0451	.2.4..7	SEZ	NBO	1320	60	KQ0320	KRT	3
KQ0555	1.3.5.7	FIH	NBO	1320	60	KQ0320	KRT	4
KQ0761	1234567	JNB	NBO	1320	60	KQ0320	KRT	5

D.4.3 Impact of alternative timing

Overall, table D.6 shows the proposed alternative flight timing of the Khartoum Cairo flight and the effects on the feeding flights. The basis for the change to increase the block-time throughout the rotation is to advance the departure of flight KQ0320. To ensure for legal passenger connections, 10 flights (or 18 flight legs) have to be advanced.

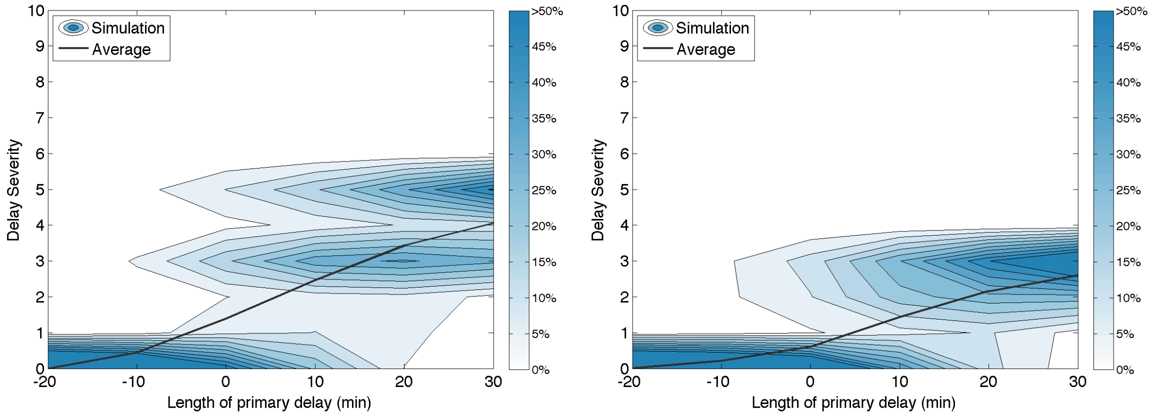
Table D.6. The alternative flight timing for the circular flight to Khartoum and Cairo. The alternative flight timing is still in the proposal phase due to extra stress it could place onto the morning wave.

FltNum	**DepAp**	**ArrAp**	**Days**	**∆SBT**	**∆STD**	**∆STA**
KQ0320	NBO	KRT	1234567	+5	-20	-15
KQ0320	KRT	CAI	1234567	+5	-15	-10
KQ0321	CAI	KRT	1234567	+5	-10	-5
KQ0321	KRT	NBO	1234567	+5	-5	0
KQ0702	NBO	HRE	1…..6.	0	-40	-40
KQ0702	HRE	LUN	1…..6.	+10	-35	-25
KQ0702	LUN	NBO	1…..6.	0	-20	-20
KQ0586	NBO	FBM	1234567	-5	+5	0
KQ0586	FBM	NLA	1234567	+5	0	+5
KQ0586	NLA	NBO	1234567	-15	+5	-10
KQ0722	NBO	LLW	..3.5..	+5	-20	-15
KQ0722	LLW	LUN	..3.5..	0	-15	-15
KQ0722	LUN	NBO	..3.5..	0	-15	-15
KQ0724	NBO	LUN	.2.4..7	+5	-20	-15
KQ0724	LUN	LLW	.2.4..7	0	-15	-15
KQ0724	LLW	NBO	.2.4..7	0	-15	-15
KQ0450	NBO	SEZ	.2.4..7	0	-10	-10
KQ0451	SEZ	NBO	.2.4..7	0	-10	-10
KQ0760	NBO	JNB	1234567	0	-10	-10
KQ0761	JNB	NBO	1234567	0	-10	-10
KQ0554	NBO	FIH	1.3.5.7	+5	-20	-15
KQ0555	FIH	NBO	1.3.5.7	+5	-15	-10

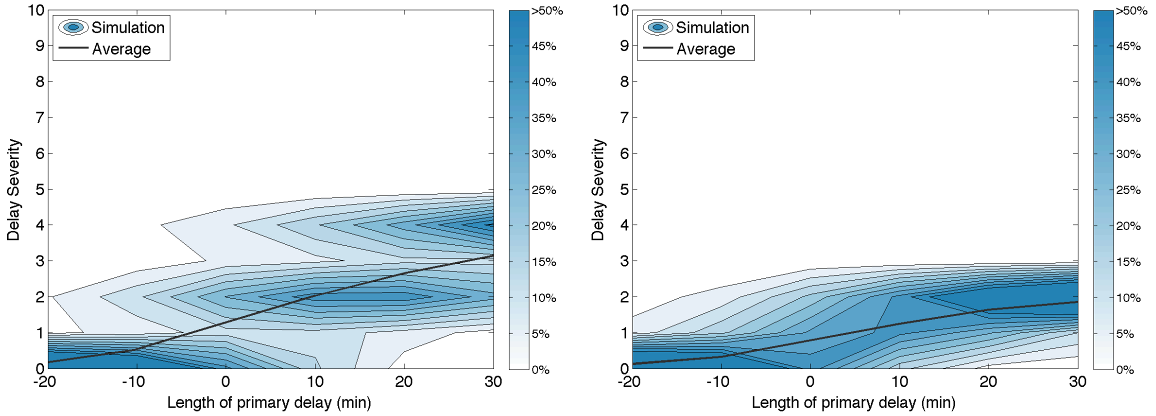
The impact of the alternative flight timing for the flights to Khartoum and Cairo is analyzed on schedule stability and ground operations. Figure D.11 shows specific improves on the circular flight rotation to Khartoum (KRT) and Cairo (CAI) in the flight delay severity simulation. In comparison to other flights, these flights remain critical yet feasible. Figure D.11a and D.11b shows the difference between the first leg, KQ0321 outbound to Khartoum (KRT), to decrease the severity. The two bands of delay severity seen in the base scenario are due to the 3 subsequent flights legs and due to passenger connectivity. By allocating extra Block-time, the probability of the first leg disrupting all subsequent legs reduces.

However, the impact on the busy morning wave of advancing the feeder flights is large. Currently, the policy is to investigate purposes as to reduce the peak in the morning wave. By advancing these flights, the overall impact in the morning wave could be a reason as to not implement this recommendation. However, the positive impact is that the de-feeding flights could be more punctual and not disrupt the morning wave the day after.

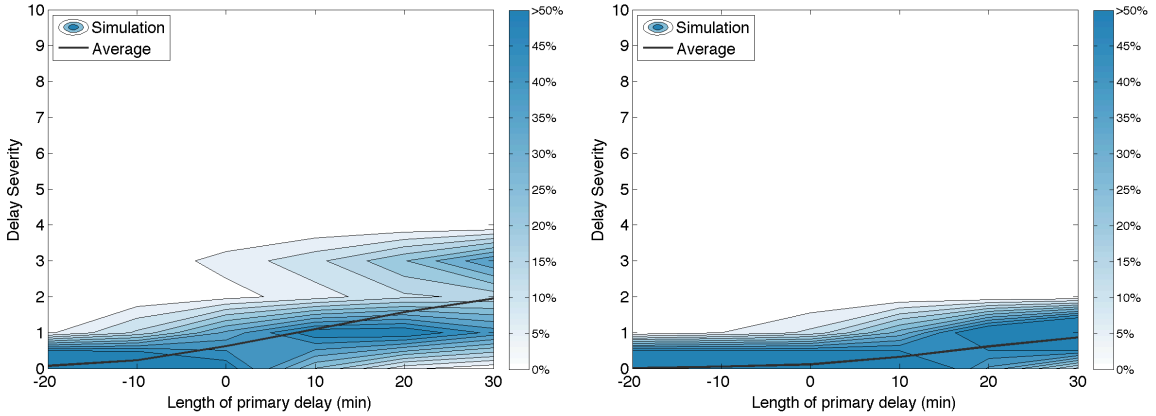
In conclusion, it is possible to stabilize the circular flight rotation to Khartoum (KRT) and Cairo (CAI). The current proposal decreases expected delay severity significantly, however a further investigation into the peak of the morning wave is necessary.



(a) KQ0320 to KRT, Base, $\bar{\zeta}$=1.2 **(b)** KQ0320 to KRT, Improvement, $\bar{\zeta}$=0.7



(c) KQ0320 to CAI, Base, $\bar{\zeta}$=1.1 **(d)** KQ0320 to CAI, Improvement, $\bar{\zeta}$=0.6



(e) KQ0321 to KRT, Base, $\bar{\zeta}$=1.4 **(f)** KQ0321 to KRT, Improvement, $\bar{\zeta}$=0.45

Figure D.11. Robustness Increase CAI KRT.