MASTER

Robust airline operations

minimizing disruptions on the day of operations through robust scheduling

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Robust Airline Operations:
Minimizing Disruptions on the Day of Operations through Robust Scheduling

by

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in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

KLM Operations Control

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‘Cause I'm leavin' on a jet plane,
Don't know when I'll be back again’
- John Denver

ABSTRACT

This report discusses robust airline operations at KLM through an analysis of the scheduling process in a distributed decision making framework. This resulted in the development of an anticipation function taking into consideration the impact of technical – and scheduling restrictions. A data structure was presented which establishes the link between a defect and KPIs. This data enables the implementation of an anticipation function that shows the added value of flexibility or the cost of limited flexibility through a time-cost trade-off.

ACKNOWLEGEMENT

This report is a result of a Master thesis project conducted at KLM Operations Control and a closure of my study career. It has been a great experience to study in Eindhoven these last 3 years. I met great new people, got the opportunity to go to Hong Kong and finally this thesis project at KLM. So I will be the last to complain and would like to take this opportunity to thank a few people for making all this possible.

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Last but not least my family and friends who have supported me through my entire study career. My dad who struggled through my thesis again, giving insightful comments. Linda, who came up with the great idea to study in Eindhoven and showed me around. And everyone who has made my study career unforgettable thanks a million!

Nana Looise
Eindhoven, May 2008

MANAGEMENT SUMMARY

This report is written as part of the thesis project for the Master of Science in ‘Operations Management and Logistics’ which is provided by the University of Technology in Eindhoven. This project is conducted at KLM Operations Control and took place from September 2007 until May 2008.

Problem description

KLM indicated that there were problems with their aircraft availability process resulting in not achieving their punctuality objectives, especially for their intercontinental (ICA) flights. Due to the high dependence on transfer passengers and – cargo, punctuality is essential for KLM. KLM suggested that this is due to an increase in technical restrictions, i.e. technical defects on an aircraft which limit the destinations it can fly. The poor performance in 2007 initiated this project to investigate whether the technical restrictions effect the performance. The aircraft availability process is responsible for the availability of an aircraft at the gate fit for the intended flight prior to an ICA departure. To enable this, the schedule should incorporate sufficient flexibility to deal with the disruptions that occur at the day of operations (DoO), i.e., the day when scheduled flights are actually executed. In order to improve the operational performance a robust schedule is required. The development of a robust schedule requires an anticipation function on the flexibility in the operational schedule. This results in the following project assignment:

> *Design an anticipation function to optimize the flexibility in the decision variables for the front office at the DoO which will minimize the effect of disruptions.*

In order to come to a solution a theoretical and practical analysis is conducted. The theoretical analysis discusses literature on airline scheduling and distributed decision making to provide a theoretical background. The practical analysis involved an analysis of the scheduling process at KLM and the flexibility and restrictions in the schedule. The analysis resulted in requirements for the design phase, which involves the development of a data structure and anticipation function. The focus will be on the ICA fleet and the aspects related to the aircraft availability process.

Analysis

The analysis has resulted in various requirements for the design phase from both a theoretical and practical background. The analysis at KLM indicated that an increase in non-performance is a result of insufficient flexibility in the schedule to deal with the disruptions at the DoO. The focus will be on technical defects and operational control as these cause the major disruptions. These disruptions can be translated into technical – and scheduling restrictions that effect the flexibility in the schedule. The effect of these restrictions on flexibility needs to be determined, which requires additional data. In order to improve performance either more flexibility in the schedule is required, i.e., diminishing scheduling restrictions, or technical restrictions need to be limited through e.g. a reduction in repair lead-time.

The literature review has shown that the scheduling process at KLM fits the distributed decision making (DDM) structure (fig. 1) of Schneeweis (1995). This indicates that an improved anticipation function is required that links the DoO with Network and enables Network to anticipate on the required flexibility in the schedule. In order to improve performance a robust schedule is required. A robust schedule involves both flexibility and stability within the schedule. Flexibility indicates the different recovery options, whereas stability is related to limiting the propagation of disruptions in the schedule (Burke, 2007). Therefore, the propagation of disruptions and the use of decision variables is a requirement for the anticipation function. The propagation of the disruption can be expedited through the use of decision variables, this is however at a certain cost. Therefore a trade-off needs to be made between time – and cost impact of disruptions and flexibility. A similar trade-off is made in the new product development where the ability to expeditiously develop and market products is critical. Time-cost trade-offs are extensively discussed in the project scheduling literature where activities can be shortened at additional costs (Roemer et al., 2000).

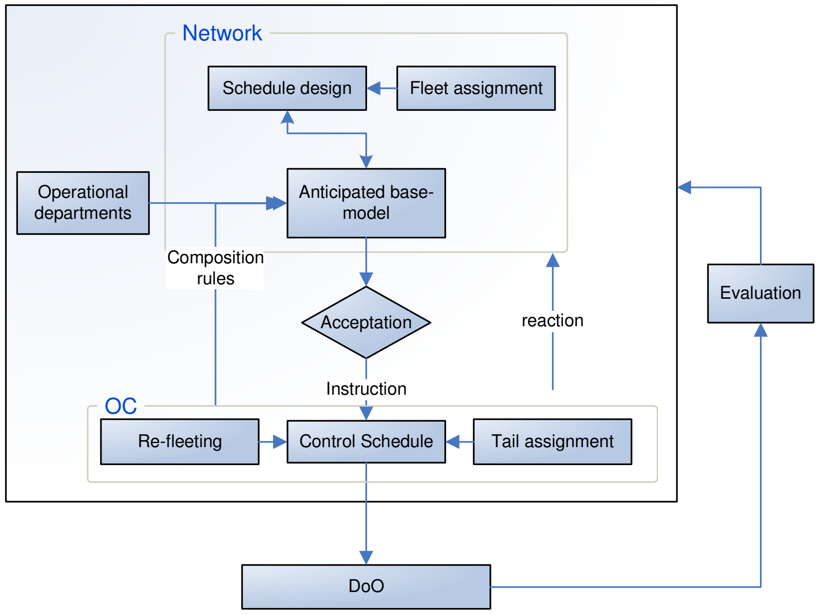

Figure 1. Scheduling process at KLM in a DDM framework

These requirements resulted in the design of a data structure with the required data to determine the effect of technical restrictions in the operation. In addition, an anticipation function is presented that considers the lead-time of a disruption with the associated costs. This indicates the effect of additional flexibility or, the other way around, the effect of restricted flexibility.

Design

The design involves both 1) a data structure to establish the link between a defect and KPIs and 2) a cost function which shows the added value of flexibility or the cost of limited flexibility.

The data-structure categorizes the defects with their restrictions and relates their repair lead-time to the available ground time to determine whether a defect results in a disruption with operational consequences. These disruptions arrive at the senior operation contoller (SOC), which was to resolve the disruption with the decision variables available. By indicating to what extend their options are restricted and linking the chosen option to the KPIs, the effect of technical restrictions can be quantified. In addition, the data enables to elaborate on the suggested anticipation function.

The anticipation function considers the amount of flexibility in the schedule and assumes a disruption on an aircraft, i.e., either late arrival, no-go defect or deferred defect. It determines the cost of the different available decision variables with the associated lead-time, i.e., the time it takes to get back on schedule. The point of reference (or base line) is the cost and leadtime for ‘doing nothing’, i.e., delaying the flight and consecutive flights. A trade-off can be made between the cost and leadtime of the different decision variables. Robust scheduling does not involve being able to deal with all disruptions. Based on a flexibility budget it can be determined which disruptions can be dealt with in the schedule and which disruption will result in cancellations.

Conclusions and recommendations

The project assignment involved the development of an anticipation function to optimize the flexibility at the DoO and minimize the effect of disruptions. The anticipation function establishes a link between the top – and base level of the distributed decision making framework for airline scheduling. The designed model anticipates upon the required flexibility in the schedule to deal with the restrictions at hand. On the other hand, the choice can be made to reduce these restrictions on the DoO to keep the schedule operational feasible. The implementation of the model enables to indicate the major restrictions in the schedule, which can be acted upon. This provides an optimization in flexibility, which minimizes the effect of disruptions.

Recommendations regarding the implementation for the data structure involve a test phase to validate and elaborate upon the suggested data structure. Therefore, the data structure should be recorded for several weeks to validate the structure. In addition, the costs and benefits should be determined and the appropriate way to record the data structure. The anticipation function requires further validation and elaboration before implementation. Various limitations are mentioned such as the effect of a combination of disruptions on flexibility and the modeling of limited swap options in case of a deferred defect.

Furthermore, the data structure and anticipation function are suggested from an aircraft availability point of view, i.e., taking into consideration the operational impact of technical – and scheduling restrictions. Both the data structure and anticipation function can be extended in further research by including crew and ground services. In addition, the impact on E&M regarding the possibility of repair lead-time reduction can be considered in further research.

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1. Introduction

This chapter will discuss the scope of the thesis project starting with the field of research in § 1.1 followed by a brief description of the company in § 1.2. Subsequently, § 1.3 discusses the problem at hand with the resulting problem definition. Finally, in § 1.4 the methodology and report structure will be presented.

1.1 Field of research

The field of research in this project is the airline scheduling process, as the airline industry has been very advanced in applying operations research models. Since the privatization of the airline industry in the US during the 70's, competition has intensified. This required cost savings through the optimization of their operational processes. A major operational process for an airline is the scheduling process, which includes the development of the flight schedule, the aircraft assignment and crew scheduling. The size and the complexity of the scheduling problem make it a challenging topic in the operations research field. Although major cost savings have been achieved through the implementation of operational models; there are still many challenges and opportunities for further research.

This project will analyze the coordination process in airline scheduling and schedule disruptions at KLM, the Royal Dutch Airlines, based on the distributed decision making theory. More specifically, an analysis will be made of the problems that occur around the day of operations (DoO), i.e., the day when the scheduled flight is actually executed, and the tail assignment, i.e., the assignment of the actual aircraft to the flight, in the inter continental (ICA) flights. This project will investigate the source of the problems and provide an anticipation function to improve the robustness of the schedule. The contribution of this project is to link distributed decision making and robust airline operations.

1.2 Company description

1.2.1 KLM Royal Dutch Airlines

KLM Royal Dutch Airlines (KLM) forms the heart of the KLM Group, which also includes KLM Cityhopper and Transavia.com. KLM is together with Air France part of Europe's leading airline group with Schiphol as one of the hubs in their hub-and-spoke strategy. Due to the small Dutch market, KLM is very dependent on transfer traffic (70 percent transfer passengers). KLM daily operates 638 flights to 125 destinations in 67 countries. KLM has three core businesses: passenger transportation (Passenger Business), cargo transportation (KLM Cargo), and aircraft maintenance (KLM Engineering & Maintenance). The organizational structure is provided in appendix B and key facts and figures in table 1.

KLM's mission statement:
"*By striving to attain excellence as an airline and by participating in the world's most successful airline alliance, KLM intends to generate value for its customers, employees and shareholders."*

Table 1. Facts and figures 2006/2007

Operation Revenues	7,201 mln Euro
Net Result	276 mln Euro
Number of staff	31.778
Fleet	190
Number of passengers	More than 22 mln
Number of cargo	Over 619.888 ton

In order to create value, KLM focuses on further improvement of their operational processes to enhance efficiency and reliability enabling KLM to achieve their motto of becoming "the reliable airline".

1.2.2 KLM Operations Control Centre

KLM Operations Control Centre (OCC) performs a matchmaking role between commercial demand and operational feasibility. They are responsible for the control of the operational schedule from two months before the start of the operational schedule until the DoO. Their objective is to obtain operational integrity through the improvement of process management. This enhances the punctuality of the schedule and enables solving disruptions as pro-actively as possible. KLM OCC is divided into the back office, which is responsible for the control of the operational schedule until the DoO, and the front office, which is responsible for the control of the operational schedule at the DoO. In the front office, experts of the different operational departments are grouped together, who are responsible for a part of the operational process at the DoO. This brings the different processes closer together and facilitates communication among departments.

KLM OCC is responsible for:

- *The acceptation of the operational schedule:* The operational schedule is handed over to OCC two months before the start of the operational schedule. During the acceptation phase, the operational schedule is tested in a simulation tool, OPiuM (§ 3.3.2). Based on the forecast performance of the operational schedule in OPiuM, the operational schedule is accepted or adjusted to make it operationally feasible.
- *Monitoring and controlling of the network operations:* From two months prior to the start of the operation schedule until the day of operations, the OCC controls the operational schedule. This involves e.g. optimizing fleet assignment based on demand, implementing commercial requests for changes in the schedule and solve disruptions due to decrease in airport capacity.
- *Support of network operations in exceptional situations:* Resolve disruptions in the network operations and try to get back on schedule as soon as possible. Disruptions can have various causes, such as severe weather conditions, lack of capacity, political, technical limitations, air traffic control, crew, volcanic eruptions, strikes etc.
- *Evaluation of network performance:* The network performance is evaluated based on key performance indicators (KPI), which are the arrival punctuality, departure punctuality (+15 minutes), completion rate and no-connection rate. The KPI are indicated in table 2. The arrival punctuality and departure punctuality are the percentage of flights that have arrived at scheduled arrival time or departed within 15 minutes of scheduled departure. Completion rate indicates the number of executed flights and the no-connection rate is the percentage of passengers that missed their connecting flight.

Table 2. Key performance indicators

KPI		Target
Arrival punctuality	EUR	70%
	ICA	70%
Departure punctuality (+15 minutes)	EUR	81 %
	ICA	68%
Completion rate	EUR	98.9%
	ICA	99.6%
No connection rate		2.5 %

1.2.3 Operational process at KLM

This section discusses the control structure of the operational process at KLM, which operates in a matrix structure. Figure 2 provides an overview of the operational process for an individual plane, which is divided into three sub processes, which obtain their resources from the resource suppliers.

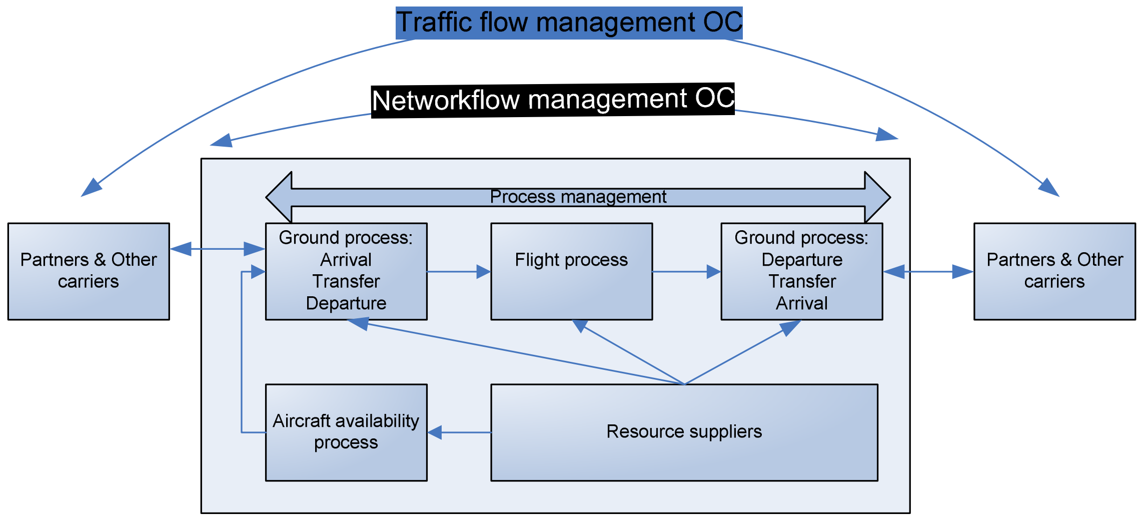


Figure 2. Network and process control

The operational process is divided into the following three processes:

- *Ground process*

The ground process involves all activities required to make the aircraft ready for take off between opening the door of the arrived aircraft until the closing of the door of the departing aircraft. The ground process is divided in the ground process arrival and ground process departure. These processes involve e.g. unload and load of luggage and cargo, cleaning, refueling, boarding passenger, security and crew transport.

- *Flight process*

The flight process involves all activities between closing the door of the departing aircraft and opening the door of the arriving aircraft. This process involves e.g. pushback, flying, in-flight service and catering, flight technical, flight planning, crew planning.

- *Aircraft availability process*

The aircraft availability process is responsible for providing an aircraft fit for the intended flight on time before the start of the departure ground process. The aircraft availability is required to enable the availability of an aircraft prior to a flight and to provide flexibility in order to restore disruptions in the schedule. This process involves e.g. towing, maintenance, spare aircraft and crew.

The operational process is controlled at two levels:

- *Network flow management*

The operational manager is responsible for controlling the network process, i.e., the overall process of ground, flight and aircraft availability at the day of operations, while taking into account the KPI.

- *Traffic flow management*

Traffic flow management considers the entire flight process of the KLM and connecting flights from partners or other carriers as passenger satisfaction is based on the performance of the entire flight. Currently, a traffic flow management (TFM) tool is operational at KLM, which takes into account the cost/benefits of delaying a flight, cancelling a flight and what to do in extreme conditions. The costs of delaying or cancelling a flight are known as non-performance costs. The non-performance costs of delaying a flight are based on similar aspects as discussed in Jarrah et al. (1993). It takes into consideration the number of no-connections at departure and on arrival, the additional cost of high speed flying to catch up on delay and the cost of lost customers due to no-connections. The cancellation tool considers alternative flights and availability to minimize delay for the passenger, the cost to accommodate passengers and crew due to cancellation, the cost of lost customers due to dissatisfaction. The "what if" tool considers what to do in extreme conditions such as severe weather resulting in limited capacity. The tool suggests which flights could be cancelled or delayed while minimizing disruptions in the schedule with the associated cost.

1.3 Problem description

KLM indicated that there were problems with their aircraft availability process resulting in not achieving their punctuality objectives, especially for their intercontinental (ICA) flights. Due to the high dependence on transfer passengers and – cargo, punctuality is essential for KLM. Poor punctuality leads to dissatisfaction among customers and an increase in non performance costs. Table 3 provides an overview of the performance over the past years. This shows that the performance has decreased over the past couple of years indicating that there is a structural problem. KLM suggests that this is due to an increase in technical restrictions, i.e., technical defects on an aircraft which limit the destinations it can fly. The poor performance in 2007 initiated this project to investigate whether the technical restrictions effect the performance.

Table 3. Key performance indicators 2007

KLM ICA	**2003-2004**	**2004-2005**	**2005-2006**	**2006-2007**	**2007-2008**
Number of flights	14510	15673	16490	16471	17047
Departure Punctuality Schiphol 15'	65	**64.8**	69.8	69.2	**67.3**
target	65	68	68	68	68
Arrival Punctuality Schiphol 0'	68.3	72.1	75.3	**69.5**	**68.3**
target	70	70	70	70	70
Arrival Punctuality Schiphol 15'	85.9	87	87.7	**84.8**	**84.7**
target			87	87	87
Completion factor worldwide (3 days)	99.8	99.6	99.5	99.6	**99.3**
target	99.6	99.6	99.6	99.6	99.6
No connections at arrival Schiphol	1.9	2.1	2.1	2.2	2.3

The aircraft availability (AA) process is responsible for the availability of an aircraft at the gate fit for the intended flight prior to an ICA departure, providing sufficient time for the execution of the ground process based on norms. To enable the AA, the schedule should incorporate sufficient flexibility to deal with the disruptions that occur at the DoO, e.g. weather conditions, maintenance delays or defects on the aircraft.

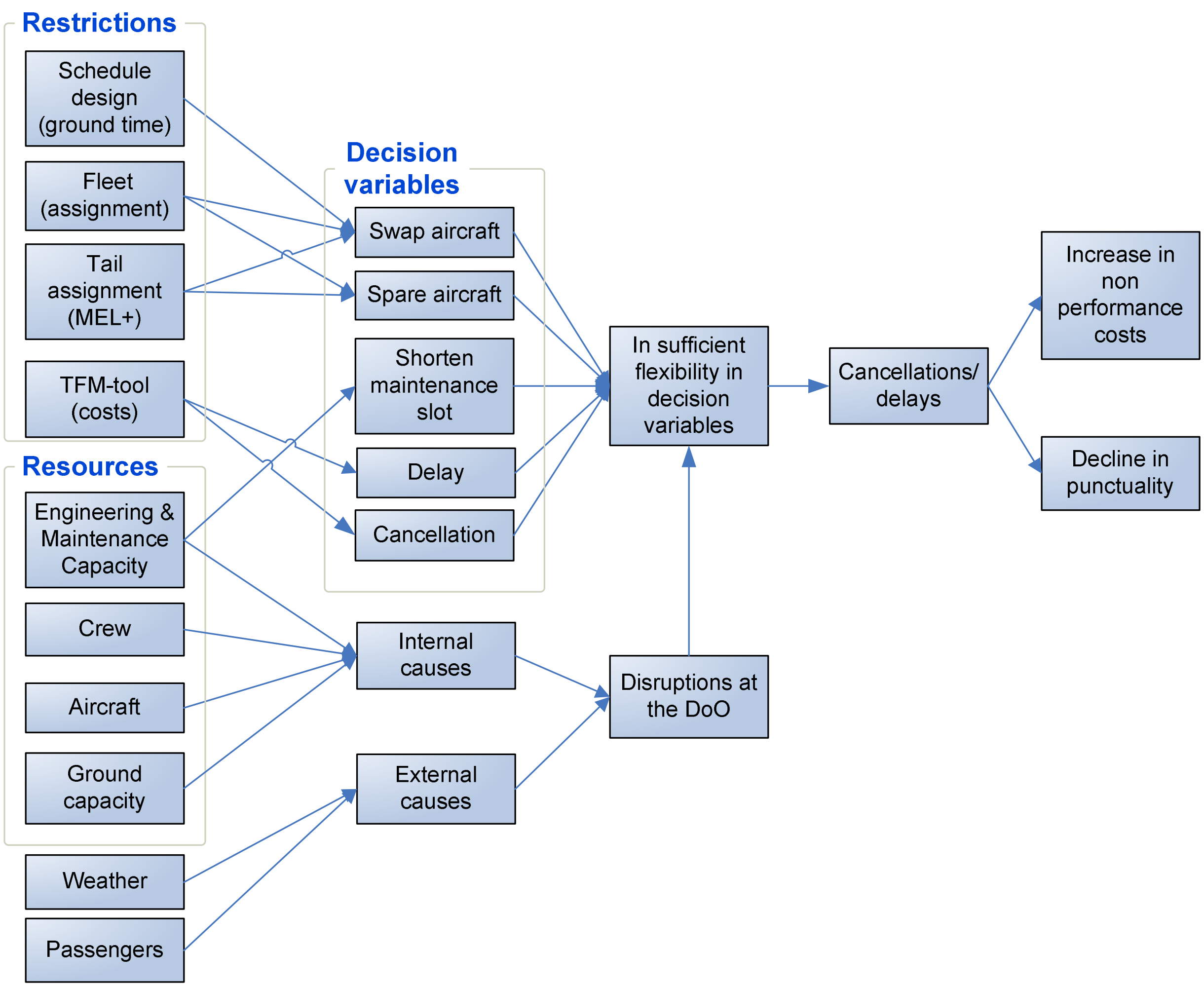


Figure 3. Preliminary cause and effect tree

Figure 3 (and appendix C) shows that the poor performance in punctuality is a result of an increase in delays and cancellations. The increase in non-performance indicates that there is not sufficient flexibility in the schedule to deal with the disruptions at the DoO. In order to improve the operational performance a robust schedule is required. A robust schedule is less sensitive to the stochastic influence of the operational environment and provides sufficient flexibility for recovery actions in case of a disruption (Burke et al., 2007). In addition, a robust schedule should enhance punctuality and reduce non-performance cost. The development of a robust schedule requires an anticipation function on the flexibility in the operational schedule. To facilitate the development of an anticipation function an analysis of the flexibility in the schedule is required and how the flexibility is restricted. This anticipation function contributes to current practice as it illustrates the propagation of disruptions and the effect of technical restrictions on flexibility. This results in the following project assignment:

> *Design an anticipation function to optimize the flexibility in the decision variables for the front office at the DoO which will minimize the effect of disruptions.*

In order to come to this solution the following aspects need to be considered:

- *What are the causes of the disruptions at the DoO? To what extent do AA related causes contribute to the disruptions at the DoO?* (§ 3)

- *What are the decision variables of the operations management at the DoO and how are they restricted? What are the effects of technical restrictions on the decision variables?* (§ 4)
- *What are the requirement for an anticipation function for the development of a robust schedule design including (re-)fleeting, and tail assignment?* (§ 5)

1.3.1 Scope of this project

This project will focus on the ICA fleet and disruptions that effect AA resulting in delays and cancellations. In other words, only disruptions that cause shortages in the fleet will be considered while shortages related to e.g. crew will be out of scope for this project. In addition, disruptions are taken as a given, while the focus will be on solving these disruptions through enlarging the flexibility in decision variables. A solution will be achieved through the development of an anticipation function, which coordinates the information flow between OC and the Network department, where the schedule is developed. The anticipation function enables the trade-off between non-performance and flexibility in terms of time and cost. A conceptual framework for the anticipation function is suggested as the implementation is out of scope for this project. In addition a data structure with the required data for implementation is presented. This will provide an answer to the project assignment which will provide guidelines for the improvement of the scheduling process that could concern tail assignment, (re)fleeting and schedule design.

1.4 Project design and Report structure

In order to structure the remainder of the project, a conceptual project design is developed which is presented in fig. 4 and appendix D. A conceptual project design provides an overview of the different steps that need to be taken to develop a solution for the problem (Verschuren & Doorewaard, 2003).

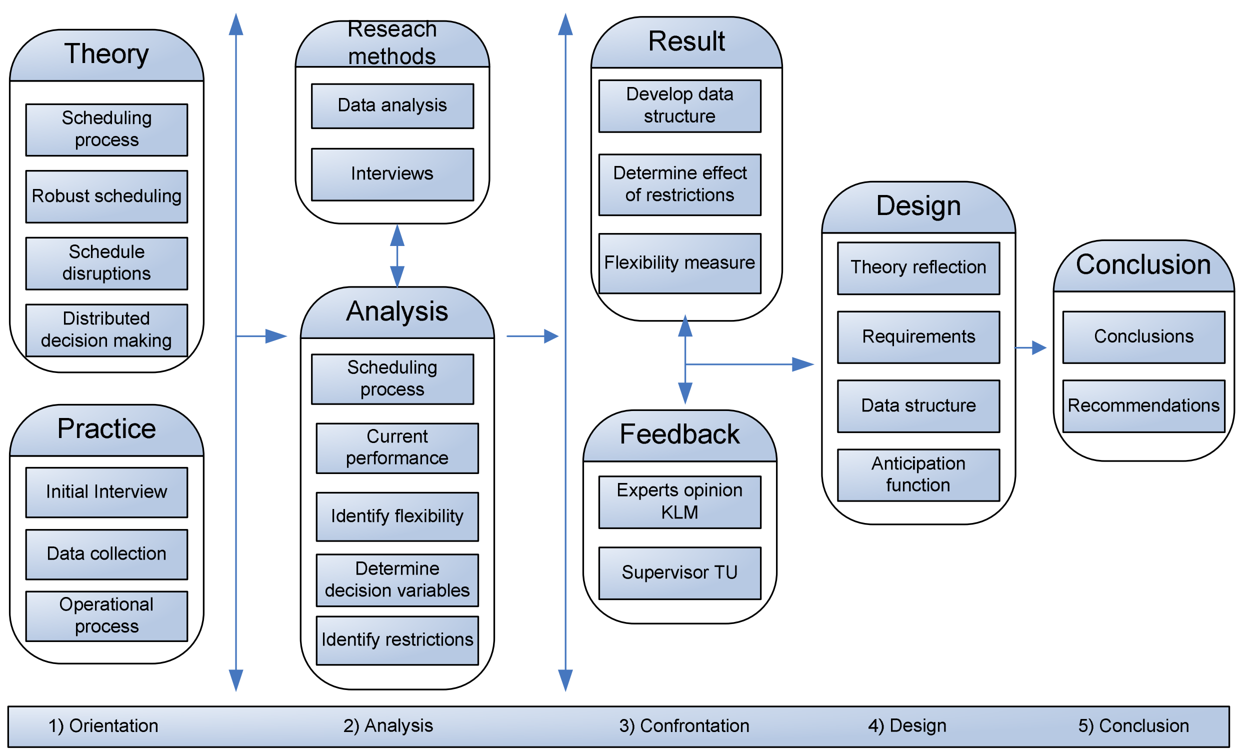


Figure 4. Conceptual project design

This project (fig. 4) is divided into five phases: 1) orientation phase, 2) analysis phase, 3) confrontation, 4) design phase and 5) conclusion. The orientation phase is represented by the left side of the diagram, which provides the theoretical and practical background of the project with the associated problem description. This chapter (§ 1) has discussed the organizational context of the project with the problem description and § 2 will discuss the theoretical background of airline operations. In the analysis phase, a closer look is taken at the scheduling process and the current performance in § 3, which identifies the major disruptions at the DoO. Subsequently, the flexibility and restrictions in the schedule are discussed in § 4. The confrontation took place during the intermediate presentation, where the results of the analysis phase were presented. This resulted in the requirements for the design phase, i.e., the development of a data structure and anticipation function discussed in § 5. Finally in § 6, conclusions and recommendation are presented.

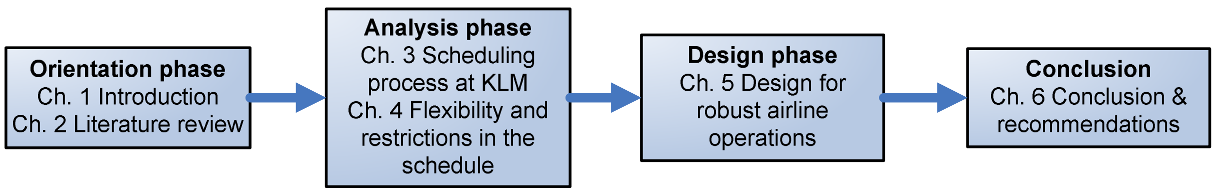


Figure 5. Report structure

2. Literature review

This chapter will provide a literature review on airline scheduling and schedule disruptions to get familiar with the topics, models and terms in this field of research. First, distributed decision making will be discussed to provide the organizational context in airline scheduling. Second, the overall scheduling process is presented to provide a better understanding of the theoretical background of the problem, followed by a detailed description of the different elements in the scheduling process. Third, an overview will be provided of the literature regarding schedule disruptions.

2.1 Distributed decision making (DDM)

In order to manage the complexity of organizations, planning and decision making is often decomposed in smaller mutually dependent subsystems. Decision making is often done sequentially and hierarchically resulting into an a-symmetric interdependence between the different subsystems making one system more important than the other. Schneeweiss (1995) developed a general framework for this distributed decision making (DDM), which can be characterized as the design and coordination of connected decisions. DDM ranges from purely intellectual segregation and subsequent coordination to decisions distributed over a variety of decision makers, all of them participating in some problem of mutual interest (Schneeweiss, 2003). The size and complexity of airline scheduling requires a decomposition of the scheduling process, which results in DDM where schedule design is developed at the top level with a higher level of aggregation compared to day of operations at the base level with more detailed information and a shorter reaction time (Schneeweiss, 1995).

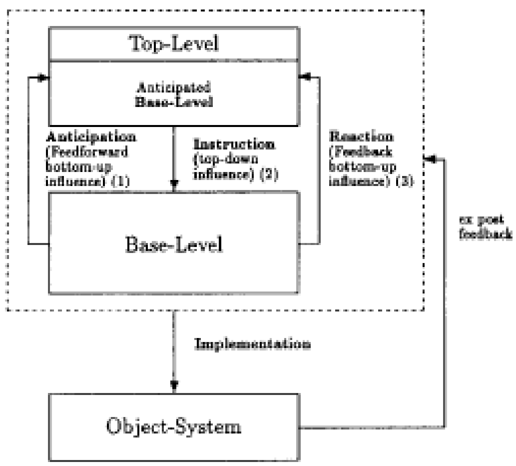


Figure 6. Interdependencies between hierarchical levels (Schneeweiss, 1995)

Schneeweiss (1995) developed a general framework for hierarchical interdependencies within an organization (fig. 6) which represents DDM. Schneeweiss (1995) considers three stages in this framework: 1) anticipation, 2) instruction and 3) reaction. Anticipation is the bottom-up influence of the base-level on the top-level, which results in the anticipated base-level. Top-decisions are based on the anticipated base level which basically is an aggregation of the base-level. Then having anticipated the base-level, the top-level makes a decision which influences the base-level which is an instruction. An instruction is the influence of the top-level on the base-level. A reaction is then the response of the base level on the top-level's instruction. The 'final' decision is implemented in the object-system, which is the system controlled by the top-level and base-level. All decisions prior to the implementation of the 'final' decision are called ex ante and after implementation ex post. The object-system can influence top- and base-level through ex post feedback. In airline scheduling, the top-level designs the schedule based on aggregated information of the different operational resources at the base-level (Schneeweiss, 2003). In the development phase of the schedule design anticipation, instruction and reaction results in a flight schedule for the day of operations. The execution of the flight schedule at the day of operations can be considered at the object system. An evaluation of the day of operations should provide feedback for the top – and base-level and further improve the anticipation function. The improved anticipation function allows for improved coordination between top – and base-level and therefore should enhance performance at the DoO of subsequent schedule design. The following sections will discuss the theoretical background of airline scheduling and scheduling disruptions.

2.2 Scheduling overall process

One of the major topics in airline operations research is airline schedule planning, this involves designing future airline schedules and maximizing airline profitability. The abundance in variables and constraints make the airline scheduling process very challenging resulting in a wide range of literature on the topic. Barnhart and Cohn (2004) provide an overview on the optimization approaches for airline schedule planning. Due to the wide range of constraints, it is impossible to construct a single optimization model for the scheduling process. Therefore, they suggest a decomposition approach in four core problems (fig. 7): schedule design, fleet assignment, aircraft maintenance routing and crew scheduling. Schedule design involves deciding upon which destinations to fly, at what frequency and how to schedule those flights to meet that frequency. Then, fleet assignment assigns the aircraft type to the different flights in the schedule. Subsequently, aircraft maintenance routing ensures the satisfaction of maintenance constraints, while routing the aircraft. Finally, crew is assigned to each flight, while minimizing costs and considering aircraft type (Barnhart & Cohn, 2004). These core problems are solved sequentially and are still of considerable size providing significant challenges in the operations research as discussed by Barnhart and Cohn (2004). Klabjan (2005) provides an overview of the large-scale models in the airline industry related to schedule design and fleeting, aircraft routing, crew scheduling and disruption recovery. He focuses on large-scale linear programs mixed integer models and the underlying solution methods. According to Klabjan (2005) a large improvement has been the introduction of column generation, where a model is given implicitly and is dynamically updated in order to improve the incumbent solution. Both Klabjan (2005) and Barnhart and Cohn (2004) indicate that schedule design is mainly done manually as little optimization is possible due to the size and complexity of the problem.

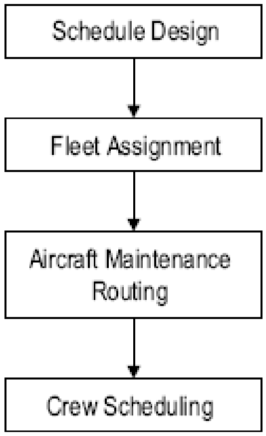


Figure 7. Airline scheduling process

2.2.1 Fleet assignment

Sherali et al. (2006) provides an overview on the fleet assignment literature, which discusses the assignment of an aircraft type to a flight. The main challenge in the fleet assignment problem (FAP) is the optimization in capacity as a small aircraft on a high demand flight could result in *spilled* customers due to insufficient capacity, while a larger aircraft could result in *spoiled* seats and higher operational costs. Sherali et al. (2006) first presents the basic fleet assignment model, distinguishing between a connection network (Abara, 1989) and time-space network structure (Hane, 1995). In the connection network, the arcs represent the connections and the nodes the point in time when the flights arrive or depart. The objective function of the resulting mathematical program maximizes the expected revenue minus the operating cost along with the penalties from the relaxed constraints. A disadvantage of the model is that all feasible connections need to be specified, resulting in a model with unmanageable size. The time-space network structure (fig. 8) focuses on representing flight legs, i.e., a leg spans the journey from the time an aircraft takes off until it lands, and leaves it to the model to decide on the connections, as long as these are feasible to the time and space considerations. Hane et al. (1995) present the multi-commodity flow problem with side constraints defined on a time-space network for the fleet assignment problem. It describes a basic daily, domestic fleet assignment problem and then presents chronologically the steps taken to solve it. This model provides greater freedom for establishing connections with less decision variables. On the other hand, this model does not assign aircraft to

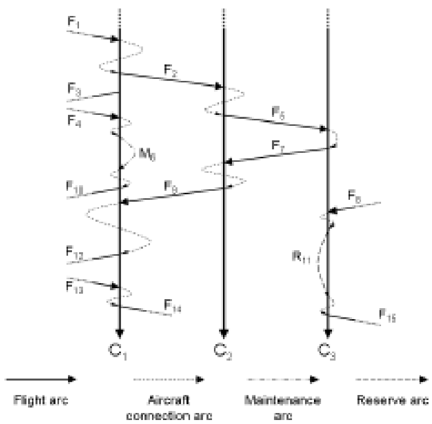


Figure 8. Time space network (Burke et al., 2007)

flights but aircraft types to flights, making it inappropriate for aircraft routing. Both basic FAP models have shown to be beneficial in the airline industry, e.g. at American Airlines and US Airways. Especially, the methods of Hane et al. (1995) have been widely applied and resulted in major cost benefits. This in turn provided the incentive for elaborating on the FAP through integrated fleet assignment models as discussed by Sherali et al. (2006) with schedule design, maintenance routing, crew scheduling, passenger considerations, weekly fleeting model, through-fleet assignment and re-fleeting based on demand.

Integrating fleet assignment and scheduling resulted in an extension of Abara's (1989) connection network with additional constraints. Furthermore, Lohatepanont and Barnhart (2004) presented an extension of the time-space network model while integrating leg selection and fleet assignment model. The model enabled to determine the set of optional legs to offer, while considering the revenue changes due to the deletion of paths. Several studies discuss fleet assignment with maintenance routing like Clarke et al. (1996), which extend the time-space network model to include maintenance constraints. More studies in this field are discussed in the following paragraph. Another consideration is passenger revenue, which can be taken into account when assigning aircraft types to optimize both capacity and revenue. Barnhart et al. (2002) integrated the time-space network model with the path-based decision model to optimize fleet assignment and passenger revenue together. Lohatepanont and Barnhart (2004) extended the model through the inclusion of the leg selection. Furthermore, Yan and Tseng (2002) incorporated scheduling, fleet assignment and passenger demand consideration in one model. This model is based on the time-space network and consists of two networks. The first network considers the fleet-flow network and the second the passenger flow network.

To further optimize passenger revenue, re-fleeting should be considered based on updated demand. Berge and Hopperstad (1993) propose a variation of the time-space network to incorporate demand driven dispatch, i.e., demand driven re-fleeting approach. The model is a multi commodity network flow problem with the aircraft types representing commodities. Instead of solving an integer program to optimality, they propose two heuristics, the sequential minimum cost flow method and the delta profit method, to find re-fleeting solutions in significantly shorter time. Jarrah et al. (2000) develops a more elaborate re-fleeting model, based on a time-space network that can be used in conjunction with five different fleet assignment models in order to use the re-fleeting model in different fleeting assignment setting. A model is developed based on the multi-commodity integer flow network of Hane et al. (1995) with side constraints for maintenance, crew availability and noise restrictions. The five fleeting assignment models are discussed and a solution scheme to find the best solution for re-fleeting. On the other hand, Powell (2003) discusses various dynamic programming models for transportation operations, which consider dynamic information processes. Due to the complexity of the resources, i.e., aircrafts, the aircraft fleet assignment is considered as a heterogeneous resource allocation problem. Compared to the multi commodity problem, the attribute vector of a resource is far more complex in a heterogeneous resource allocation problem. Powell (2003) discusses a stochastic algorithm to deal with the resulting large-scale dynamic programming model. Bish et al. (2004) considers another aspect of re-fleeting, which is the timing and the frequency of swapping, i.e., how often the swapping decision should be revised. The fleet assignment problem has been studied in various settings in line with real life situations. Although significant progress has been made in the fleet assignment literature, various challenges are still ahead.

2.2.2 Aircraft routing

Aircraft routing is, given an assignment of flights to fleets, a sequence of flights, or routes, to be flown by individual aircraft such that assigned flights are included in exactly one route, and each aircraft visits maintenance stations at regular intervals. Desaulniers et al. (1997) studies the daily aircraft routing and scheduling problem, which consists of finding a fleet schedule that maximizes profits given a heterogeneous fleet of aircraft, a set of operational flight legs over a one-day horizon, departure time windows, durations and profits according to the aircraft type for each flight. They ignore however maintenance constraints. They have formulated this problem by means of the multi commodity network flow formulation and a set partitioning type formulation. The network structure of the subproblem is described when a column generation technique is applied to solve the linear relaxation of the first model and a Dantzig-Wolfe decomposition approach is used to solve the linear relaxation of the second model.

Barnhart et al. (1998) elaborate on Desaulniers et al. (1997) by incorporating maintenance constraints, while solving the fleet assignment and aircraft routing simultaneously. They discuss a string-based model and branch-and-price solution approach to solve the fleet assignment problem based on the connection network, which guarantees satisfaction of maintenance requirements and also includes through-revenues. They assume a rolling time horizon, where they only check what has to be done periodically and assume that the period is shorter than the time horizon. A string is a sequence of connected flights that begins and ends at maintenance stations, satisfies flow balance and is maintenance feasible. They solve the string based fleeting and routing model for both long – and short haul flights.

Sarac et al. (2006) develop a branch-and-price approach for solving an operational aircraft routing problem that focuses on operational view rather than a long-term view. It incorporates resource availability constraints and maintenance constraints. The daily aircraft maintenance routing is a problem in which the objective is to minimize the total daily maintenance costs without violating legal remaining flying hours of each aircraft, subject to the resource constraints of the maintenance stations. The model is based on the connection network and a set partitioning based formulation in which decision variables represent feasible routes for aircraft. Having considered the aircraft routing, aircrafts need to be assigned to the flights, which will be discussed in the following section.

2.2.3 Tail assignment

Tail assignment is the assignment of actual aircrafts (registrations) to the different flights two days in advance of the day of operations (DoO). According to Klabjan (2005), models related to the day-of-operations are either multi commodity models or set partitioning models where the solution methodology is either a local search technique or an integer programming based heuristic.

Paoletti et al. (2000) discusses two models that deal with aircraft rotation and aircraft assignment at Alitalia sequentially. The aircraft rotation model (ARM) builds the weekly scheme of fleet employment that is an aircraft rotation, in which the legs are assigned to generic aircraft. This model optimizes all the objectives that are independent from the specific characteristics and requirement of individual aircraft guaranteeing in any case the possibility of preserving the aircraft plan in the daily execution of activities. The ARM problem is formalized as a minimum-cost flow problem in a multi commodity network. The problem is solved as an assignment problem, where maintenance requirements are not considered. They maximize the through value, i.e., the amount of flight legs that are executed subsequently by the same aircraft, and the aircraft turn times. The aircraft assignment model (AAM) builds the daily aircraft routing the day before the activity is to be carried out. This model assigns the legs to the specific aircraft in accordance with the aircraft's functional and technical limitations, optimizing the objectives of regularity and punctuality of operations and, at the same time, following as much as possible the plan provided by the ARM. The AAM model is formalized using an integer-programming model. The problem has been approached and reformulated as a constrained resource problem. It tries to follow the solution from the ARM problem as much as possible. Their model is string based but it has several additional operational constraints. They employ a constraint programming approach.

Grönkvist (2003) considers the fleet assignment and the tail assignment problem simultaneously by creating routes for a set of individual aircrafts and covering a set of flights in a timetable, such that various operational constraints are satisfied, while minimizing the cost function. For the optimization criteria, Grönkvist (2003) focuses on the robustness or quality of the solution, rather than real monetary costs. In addition, he considers multiple fleets for tail assignment. Grönkvist (2005) discusses how constraint programming can improve the performance of a column generation solution process for the tail assignment problem in aircraft scheduling. Grönkvist (2005) uses the connection network to model the basic constraints in the tail assignment problem. Constraint programming focuses on constraint satisfaction and therefore on feasibility rather than optimization. In general, column generation is stronger in optimization rather than feasibility. Therefore integrating a constraint-programming model in column generation allows for shorter run times and higher solution quality.

2.3 Schedule Disruptions

Having discussed the theoretical background in scheduling process, disruptions in the schedule need to be taken into consideration. Schedule disruptions can be dealt with in two ways, through schedule recovery and robust scheduling. Schedule recovery involves re-optimizing the schedule after a disruption occurs, while robust scheduling is a more pro-active approach, which builds robustness into the schedule to prevent disruption (Lan et al., 2006).

Schedule recovery is normally done in stages: 1) new aircraft routings are created by rerouting aircraft and delaying/cancelling flight legs, 2) cockpit and cabin crew are reassigned, 3) passengers are re-accommodated (Lan et al., 2006). Jarrah et al. (1993) propose two network models which will provide solutions in the form of a set of flight delays or a set of flight cancellations, while considering swapping aircrafts among flights and using spare aircrafts. The cost of a delay or cancellation is quantified based on the following factors; the number of passengers on the flight, number of passengers connecting when the flight arrives, possible delay at arrival, possible cancellations resulted from the delayed flight, lost crew time and disruption of aircraft maintenance. Both the delay and cancellation model are minimum-cost network models. Bard et al. (2001) presents the time-band optimization model for reconstructing aircraft routings in response to groundings and delays experienced over the course of the day. A time-band model is a network positioned on a two-dimensional plane in which one axis represents time and the other space or station location and is similar to a time-space network where the arcs represent the flight legs. The resulting mathematical model is an integral minimum cost network flow problem, which is solved as a linear program. The objective function of the mathematical formulation minimizes the delay costs of flights in aircraft routes and cancellation costs for cancelled flights. Rosenberger et al. (2003) present a model that additionally considers crew and passengers. The model optimizes the rescheduling of flight legs and rerouting of aircrafts while minimizing rerouting and cancellation costs. An integer program is presented for the aircraft recovery, which is revised to incorporate the minimization of disrupted crew and passengers.

The literature on robust scheduling studies the development of schedules that have an improved performance in operation. The robustness of a schedule is influenced by its sensitivity to stochastic events, the flexibility within the schedule and its stability. The flexibility is related to the number of recovery options available to moderate the effects of a disruption, whereas the stability of the schedule is a measure for the probability of a delay to spread through the schedule and the availability of recovery strategies with a limited impact on the rest of the schedule (Burke et al., 2007). Manipulating the robustness objectives in the schedule can influence the robustness of a schedule. The robustness objective considered by Rosenberger et al. (2004) is hub isolation and short cancellation cycles. They show that a robust fleet assignment model and aircraft rotation with many short cycles is often less sensitive to a flight cancellation than one with only a few short cycles. They propose a model based on the Barnhart (1998) string model and show that fleet assignment models with many short cycles and reduced hub connectivity are more robust and perform better than those that minimize planned operational cost and passenger spill. Lan et al. (2006) present two approaches to minimize passenger disruptions and achieve robust airline schedule plans. The first approach is an integer-programming problem, which reduces delay propagation by intelligently routing aircraft and therefore improving punctuality and minimizing the number of disrupted passengers. The second approach focuses on minimizing the number of no-connection passengers due to insufficient connection time. An algorithmic solution approach is developed which reschedules the departure times of flight legs within a small time window enabling a reduction of the number of no-connections without a significant increase in operational costs. Burke et al. (2007) present a time window approach for incremental and integrated multi objective improvement of robustness objectives in airline schedules. Burke et al. (2007) argue that the construction of robust airline schedules should be a multi objective optimization problem that generates schedules with a good balance between the individual robustness objectives, i.e., schedule reliability and schedule flexibility, which maximize the operational performance of the schedule. A large-scale simulation is conducted with a sensitivity analysis to evaluate the operational performance of the individual trade-off schedules, which enabled a better understanding of the interaction between the different robustness objectives and their relationship with schedules' operational performance.

2.4 Conclusion

This chapter has provided the theoretical background on airline scheduling and scheduling disruptions. This discussion indicated the complexity of airline scheduling problems resulting in huge mathematical models with numerous variables and constraints. The design of such a model will be out of scope for this project. Therefore the focus will be on the coordination of decision making in the scheduling process in terms of DDM. Thus far this project will be the first in relating DDM to airline scheduling in scholarly literature. An analysis will be made of the decision making processes in airline scheduling and the applicability of the DDM in this respect in § 3. On the other hand, scheduling disruptions indicated the stochastic nature of airline operations at the DoO and the necessity for robust scheduling. The discussion on current performance in § 3 illustrates the stochastic nature of airline operations at KLM and indicates the major disruptions. This project defines a robust schedule as one that involves both flexibility and stability within the schedule, where flexibility indicates the different recovery options and stability is related to limiting the propagation of disruptions in the schedule (Burke, 2007). Therefore the flexibility in the schedule is discussed in § 4 and to what extend it is restricted at the DoO. Based on DDM theory the specification of an anticipation function that takes into account robust scheduling, allows for the development of a proper anticipation base-level. This in turn enables the top-level to design a robust schedule.

3. Scheduling process at KLM

This chapter analyses the scheduling process (§ 3.1) and the current performance of the operational schedule (§ 3.2). This should provide an answer to the causes of the disruptions and to what extent these disruptions are associated with the aircraft availability process.

3.1 Scheduling process

In line with Barnhart and Cohn (2004), the KLM decomposes the scheduling process and develops their schedule sequentially as is modeled in figure 9. The scheduling process involves: 1) schedule design with fleet assignment, 2) accepting and testing the schedule, 3) controlling the schedule which involves re-fleeting and tail assignment, 4) the DoO and 5) the evaluation. Figure 9 shows that the scheduling process at KLM can be framed as a distributed decision model of Schneeweiss (1995), where OC is the base-level with the DoO as the object system, while the top-level is represented by the Network department for the schedule design. The different elements in the scheduling process will be discussed in the subsequent sections.

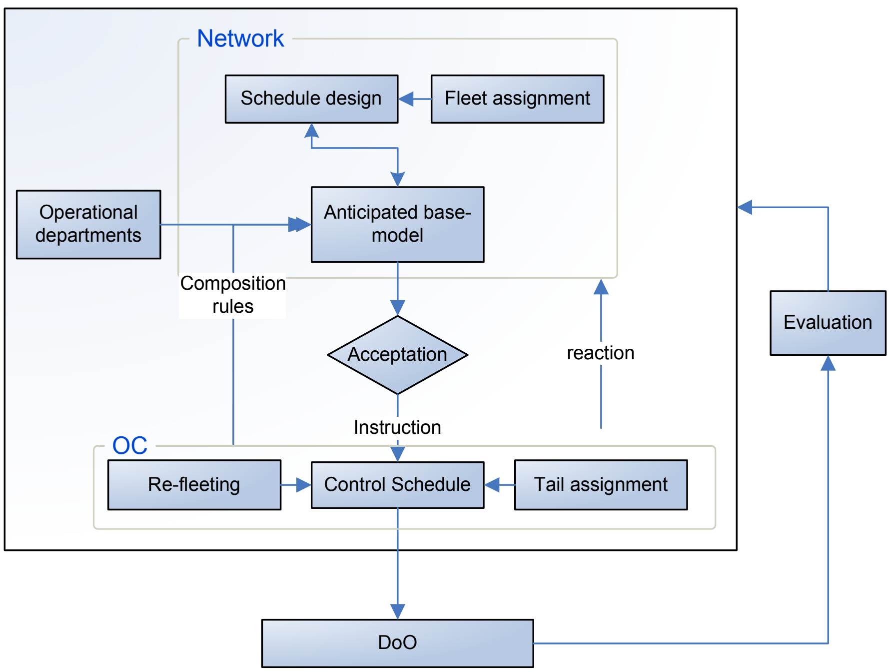


Figure 9. Scheduling process at KLM in a DDM framework

KLM divides a year in four operational plans. The scheduling process is executed for each operational plan in a chronological order as shown in figure 10. The transfer represents the acceptation phase of the scheduling process.

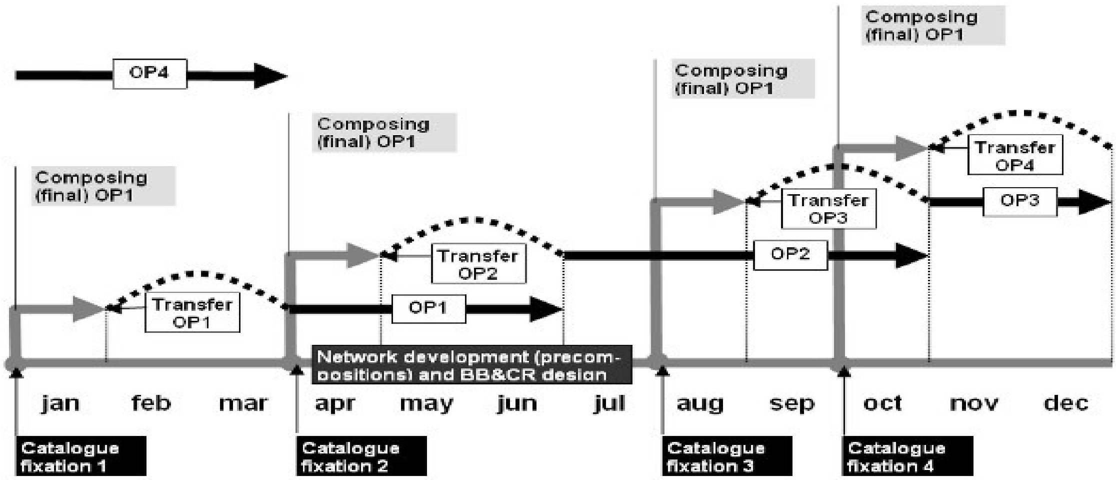


Figure 10. Schedule of the operational plans during the year

3.1.1 Schedule Design

The network department is responsible for the development of the flight schedule based on the commercial demand and the constraints given by the operational departments to make the schedule operationally feasible. The network department is divided into a commercial unit and a scheduling unit. The commercial unit starts the development of the schedule by forecasting the demand regarding destinations and flight frequency. Having decided upon the destinations, the scheduling unit determines the block times of the flight legs during a meeting with all the different operations departments, i.e., operations control (OC), ground services and flight services. In terms of the distributed decision making, this step involves the development of the anticipated base-level which indicates the amount of resources available. KLM has a hub-and-spoke network with Schiphol as their main hub. All flights depart from the hub and fly to a spoke city to return back to the hub airport. The main advantage is the connecting opportunities at the hub, allowing to consolidate demand from several markets onto each flight (Lohatepanont & Barnhart, 2004). Most aircrafts fly back and forth between a spoke city and the hub. There are some circle – and tail flights which stop at more than one station before flying back to Schip-hol. Circle flights stop at a number of destinations and fly in a circle back to Schiphol. A tail flight flies to a destination, makes an additional stop, and flies back on the same destination to Schiphol. When the block times are set, a schedule is made and slots are requested at the different airports. The schedule is developed in the software package *Flash*. The development of the schedule requires a trade-off between commercial demand and operational constraints, in other words a trade off between financial performance and operational performance. Having obtained the required slots, an operational check is done by fulfilling all the composition rules, i.e., operational constraints in the catalogues. Each operational department (OC, ground, flight, technical services) has a catalogue. Catalogues provide data based on previous performance indicating their capabilities. These catalogues function as the anticipated base model, which link the operational departments with the schedule design at Network. After the operational check, the schedule is handed over to OC, which is responsible for the schedule until the DoO, i.e., the instruction step in the distributed decision model (see fig. 9).

Table 4. Fleet at KLM

EUR fleet		ICA fleet	
B737-300	14	B747-400 passenger	5
B737-400	13	B747-400 combi	17
B737-800	17	B747-400 full freighter	3
B737-900	5	MD-11	10
		A330-200	10
		B777-200	15
		B777-300	1

Table 4 provides an overview of the current fleet at KLM. The current utilization of the ICA fleet is about 65 percent including the spare aircrafts while excluding maintenance and repair, i.e., the ICA aircrafts fly on average about 15 to 16 hours a day. Network schedules a continuous line for the maintenance and it is up to the technical services at the OCC to determine which aircraft (type) will use this maintenance slot. In addition, repair slots are scheduled for a fleet type. The problem is however to exchange the repair slots among fleet types to get the right type back to Schiphol for repair. Network may schedule sufficient maintenance slots for the right aircraft type, however as fleet types are swapped in the controlling phase these maintenance slots might go lost. Furthermore, spare aircrafts are scheduled as a backup for disruptions at the day of operations. For the EUR fleet there are always two spare B737 scheduled and for the ICA fleet there is always a spare B747 scheduled, six days a week an MD-11 or A330 and two days a week a B777.

3.1.2 Acceptation

Two months before the start of the operational schedule the schedule design is checked on feasibility with OPiuM, a simulation tool that forecasts the performance of the schedule design (Jacobs et al., 2005). The simulation tool allows to test the feasibility of the entire schedule and not specific flights or routes. Disturbances in OPiuM are the result of the difference between a value drawn from a statistical distribution and a scheduled process time. The statistical distributions used in OPiuM are based on the service time distributions, provided by the department responsible for their sub process. Whenever there is a disturbance in the simulated schedule, OPiuM optimizes the remainder of the schedule by evaluating a number of potential measures. Penalties, awarded to all these measures, are used to evaluate the remainder of the schedule (Jacobs et al., 2005). The robustness of the schedule is determined based on the number of measures that had to be taken during the simulation. The measures implemented in OPiuM are in line with the measures the senior operation controller (SOC) can take to optimize the remainder of the schedule at the DoO, which are:

- *Swapping two fleet lines*: A fleet line is the sequence of flights scheduled during the scheduled period to be performed by one aircraft. Swapping fleetlines implies that the scheduled flights for a particular plane for the remainder of the rotation are swapped with those scheduled for an alternative plane. A rotation is the sequence of flights from Schiphol to destination and back.
- *Using a spare aircraft:* A spare aircraft is kept idle for a longer period of time that can be scheduled whenever a problem in the schedule occurs.
- *Reducing maintenance time:* Maintenance can be cut by approximately 15 percent of the scheduled maintenance time by increasing the amount of assigned resources, i.e., engineering staff and equipment.
- *Cancelling or delaying a flight:* A cancel-measure implies that an entire rotation is cancelled, i.e., it will not be executed. A delay-measure implies that a flight leg is delayed often resulting in the delay of the entire rotation.

In terms of the DDM framework the acceptation is the instruction phase, which is the top-down influence, where Network hands over the schedule to Operations Control (OC). OPiuM is used during the acceptation as a reaction function of OC to determine whether the operational feasibility based on which the operational schedule is approved or not. OPiuM considers the probability of the disruption with the associated cost. In addition, it does not consider the propagation of disruptions. Currently, the technical restrictions are not considered in OPiuM.

3.1.3 Control Schedule

OC is responsible for controlling the schedule from two months before the start of the operational schedule until 17.00 the day before DoO. During this period they optimize the fleeting assignment based on updated demand as suggested by Berge and Hopperstad (1993), which is done based on a re-fleeting tool in Flash. Apart from this re-fleeting, they implement additional flights due to commercial demand, swap, delay or cancel flights caused by disruptions; e.g. political turmoil resulting in airport closure, announced strikes, restrictions in capacity or additional maintenance requirements issued by an aircraft manufacturer like Boeing. Four weeks before the DoO, the cockpit and cabin crew is assigned to the different flights, which restricts the possibilities of further re-fleeting as especially cockpit crew is only allowed to fly certain types of aircrafts. Therefore, crew needs to be considered in swapping between aircraft types for the remainder of the process. Although the fleet assignment has been done, assigning a registration to a flight is done about two days in advance.

3.1.4 Tail assignment

About three days before the DoO, the technical service planner assigns registrations to the different flights, which is called tail assignment. This is done based on the (technical, operational, etc.) restrictions of the different aircrafts. The tail router is used to assign registrations to the different flights. The tail router is an optimization tool that takes into account the fuel consumption, optimizes ground time, Schengen connections, and technical restrictions.

- *Fuel consumption:* The fuel consumption is different for each registration and could differ about 5 percent among the different registrations. It is therefore preferable to use registrations with minimum fuel consumption on long flights and payload critical flights.
- *Ground time:* The tail router optimizes the ground time available. The norm ground time indicates the minimum time the registration needs to turn. This is a hard constraint in the tail router, which is optimized to guarantee the robustness of the schedule.
- *Schengen connection & Gate constraints:* The tail router tries to connect Schengen flights to Schengen flights. This enables the assignment to certain gates that separate Schengen passengers and therefore making passenger flow on the ground more efficient. On the other hand, the tail router single out flights to Tel Aviv, which require additional security checks which is only done at a certain gate, where Schengen flights can not arrive.
- *Technical restrictions:* The tail router takes the current state of the registration into consideration and aligns it with the restrictions on the flight legs which are stated in the route matrix. A maintenance update is done three times a day, which is converted to a dataset of restrictions for the tail router. Each technical complaint related to a registration is translated into constraints on destinations with a valuation. A valuation can be positive, i.e., flying with that registration to that destination is preferable, or negative, i.e., flying with that registration to that destination is not recommended. In the tail router the different constraints are listed per destination. In addition, the tail router makes sure that a certain registration is back on time for a maintenance slot.

For the narrow body, i.e., EUR fleet, the tail router takes into account how many hours a registration can still fly before it needs to go into maintenance. This enables assignment to shorter flights enabling it to be back on time. Furthermore, the constraints related to a maintenance complaint are clearly defined for narrow body. For wide body (ICA fleet) however, these two aspects are not or hardly taken into account, i.e., the route matrix currently operational is outdated and does not consider all the technical restrictions for the different destinations. For both narrow – and wide body, the tail router does not consider the actual weather conditions but historical averages. Most constraints related to maintenance complaints are however based on weather conditions. It is difficult to integrate the actual weather conditions in the tail router, especially for wide body, where the tail router plans three days ahead. The tail router is based on the demand driven dispatch model of Berge and Hopperstad (1993) and solved with the Delta Profit Method (DELPRO), which operates in Flash. The tail router is run daily with a time horizon of a couple of days (time span dependent on narrow – or wide body) to optimize the tail assignment on current maintenance conditions, which are recorded in Flash.

3.1.5 Day of Operations (DoO)

At the DoO, the actual schedule is executed. A day before the DoO, the registrations are assigned to the different scheduled flights. At the DoO, changes can be made manually in the tail assignment, e.g. due to delays. At the DoO, KLM is currently using PlanBoard, which presents the flights schedule, Incra to make changes in the schedule and TFM tool to calculate the costs and benefits of delaying or cancelling a flight and what to do in case of limited runway capacity due to e.g. severe weather conditions. The OCC front office is responsible for resolving any disruption in the operation taking into account the flight – and crew safety, non-performance costs and operational integrity. The operations controller and senior operations controller (SOC) are responsible for the operation of the Europe and ICA schedule respectively. Their objective is to go back to the published schedule as soon as possible in case disruptions occur. Their decision variables are similar to the measures used in OPiuM and the TFM tool can guide them in their decisions. Each delay or cancellation is logged with the reason for delay or cancellation and the number of minutes in case of delay. Every morning, all managers in charge of the operational departments on that day meet to evaluate yesterday's performance and discuss today's situation regarding disruptions, weather conditions and resource availability.

3.1.6 Monitoring

The data department, SQ, is responsible for monitoring and evaluating the processes and performance through data collection and analysis.

3.2 Current performance

The performance is measured based on the KPI as discussed in § 1.2.2, which are effected by the number of cancellations and delays. This section will discuss the major sources of disruption that lead to the use of the decision variables cancellations and delay and their relation with aircraft availability.

3.2.1 Cancellations

For each of the cancellations, a reason code is registered which are listed is appendix F. Table 5 and figure 11 provide an overview of the causes for cancellation. This shows that most cancellations are caused by TI, i.e., no aircraft available due to technical reasons. Second in line is CI, i.e., as a consequence of no aircraft available due to technical reasons. It can therefore be concluded that technical defects have a major impact on the performance of the operation. The number of cancellations directly effects the completion factor KPI.

Table 5. Reason codes for cancellations ICA (25-3-07 until 8-1-08)

Count of cancellations	Type of aircraft						
Reason code	**332**	**744**	**772**	**73W**	**74E**	**M11**	**Grand Total**
CC Cockpit	11					6	**17**
CI Technical	4	1	4		23	2	**34**
CS Damage		3			4	4	**11**
CU Technical	8				6	2	**16**
CW Weather	1				2		**3**
TI Technical	21	4	4	4	28	15	**76**
TU Technical					2	2	**4**
VP Weather						3	**3**
WE Weather	6				4	1	**11**
Grand Total	**51**	**8**	**8**	**4**	**69**	**35**	**175**

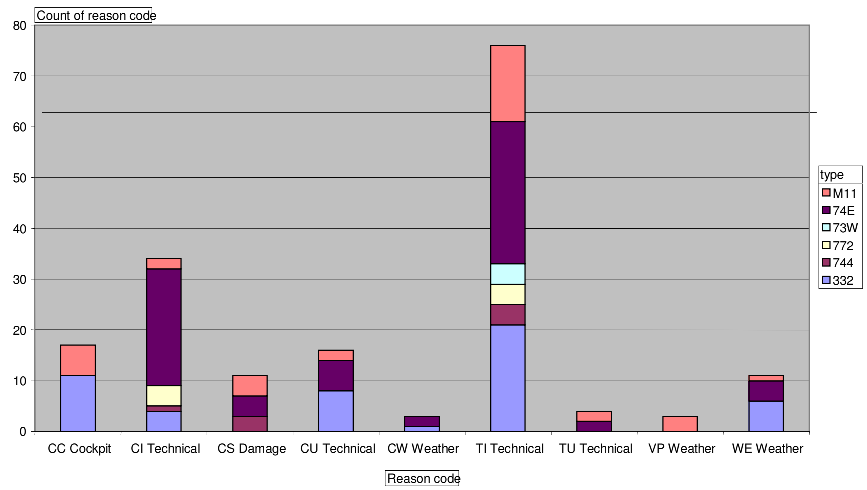


Figure 11. Reason codes for cancellations ICA (25-3-07 until 8-1-08)

3.2.2 Delays

The punctuality KPI is directly effected by the delays. Figure 12 shows that the different causes for the delay. Most delays are caused by passage handling, which includes everything related to passenger such as missing checked-in passenger, over bookings and excessive hand luggage at the gate. This is however not related to the aircraft availability process and therefore out of scope for this project. Second and third in line are technical services and operation control. Both the aspects effect aircraft availability, i.e., whether the aircraft is available on time and in good condition. Technical Services involve aircraft defects, urgent repairs, late release of scheduled maintenance, non scheduled maintenance, aircraft change for technical reasons. Operation control involves too little ground time scheduled between flights, late incoming aircraft (AC). Therefore further analysis is required on the technical and operational control delays.

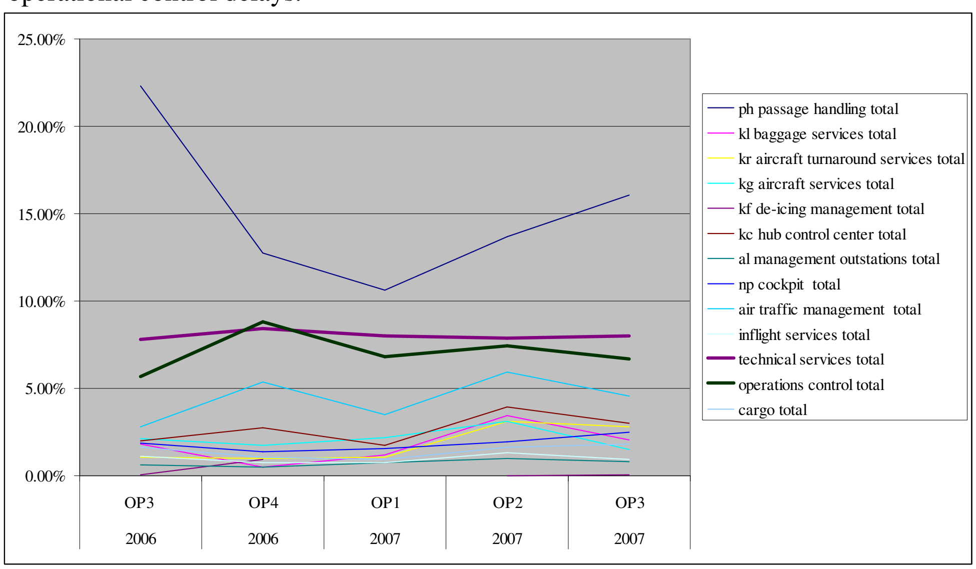


Figure 12. Reason codes for delays

Figure 13 and 14 show which aspects within the technical and operations delays cause the most delays. Technical delays involve the following:

- ***41 Aircraft defects:*** Urgent repairs required.
- ***42 Scheduled maintenance:*** Aircraft late release from scheduled maintenance

- ***43 Non-scheduled maintenance:*** Special checks and/or additional works beyond normal maintenance schedule
- ***44 Spares and maintenance equipment:*** Aircraft awaiting spares for repairs from the maintenance department
- ***45 AOG spares:*** Aircraft on ground awaiting spares for urgent repairs for another flight
- ***46 Aircraft change:*** Aircraft change for technical reasons
- ***48 Scheduled cabin adjustments:*** Aircraft cabin configuration change causing extension of the scheduled ground time.

Most technical delays are caused by aircraft defects or urgent repairs, which are a result of a defect incoming aircraft that needs to be fixed in order to take off again or a defect aircraft that has reached its deadline. Second in line are the aircraft swaps for technical reasons, which is required when the repair of an aircraft will take too long or the defect aircraft cannot fly to the scheduled destination due to technical restrictions (§ 4.2.2).Both these delay codes are a result of unscheduled repair.

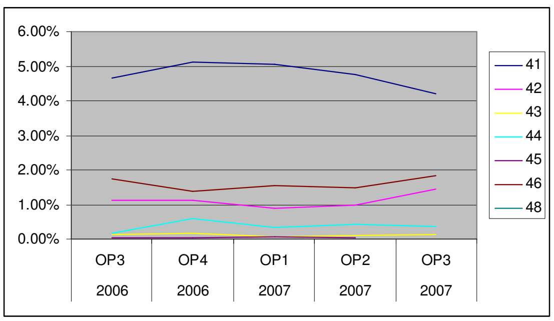


Figure 13. The different technical delays

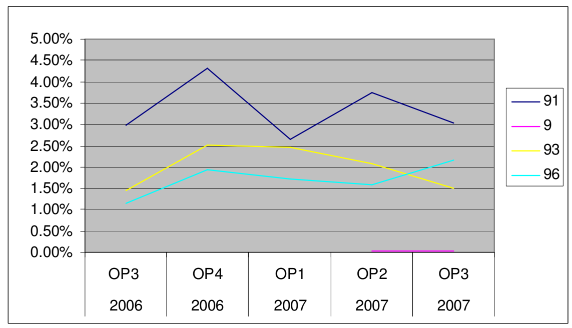


Figure 14. The different operations control delays

Operations control delay involves:

- ***91 Load connection:*** Waiting for passengers, cargo or mail from another flight.
- ***9 Schedule ground time:*** The schedule ground time is less than declared minimum ground time
- ***93 Aircraft rotation:*** Late arrival of incoming aircraft from another flight or previous sector.
- ***96 Operations control:*** Re-routing or diversion of flight.

Figure 14 indicates that most delays are caused by transfer passengers and – cargo from a late incoming flight. Due to the large amount of transfer passengers, it can be beneficial to delay the flight and wait for connecting passengers to prevent dissatisfied passengers. This is however not directly related to aircraft availability. Second in line is the late incoming aircraft which is late for the scheduled departure. Due to the high aircraft utilization often minimum ground time is scheduled between flights. Therefore a departure delay results in an arrival delay causing a snowball effect and resulting in poor performance of the aircraft availability (AA) process.

3.3 Conclusion

As § 1 indicated the operational performance, based on the KPIs, is a combination of the operational schedule with its inherent flexibility and the disruptions that occur at and around the DoO. This chapter discussed the scheduling process and the operational performance resulting in an overview of the major disruptions. Section 3.1 has provided an understanding on the development of the operational schedule and the different elements in this process. Based on this analysis, the conclusion can be made that the KLM scheduling process fits the distributed decision framework of Schneeweiss (2003). Furthermore, it has shown the importance of the anticipated base model that functions as a link between the operational departments, among which the OC, and the Network department.

Subsequently in § 3.2 the disruptions that effect the operational performance were discussed. This analysis shows that technical defects and operation control have a major impact on the operational performance. Both these aspects are part of the aircraft availability process and therefore the remainder of the project will focus on these two aspects. Although the disruptions are taken as a given, it is important to determine the effect of these disruptions on the flexibility in the schedule. The following chapter will discuss the flexibility in the schedule and to what extent this is restricted. This allows for further improving the anticipated base model which in turn results in a better anticipation of the DoO at the Network level to enhance the development of a robust schedule.

4. Flexibility and restrictions in the schedule

Having discussed the scheduling process and the disruptions at the DoO, this section will analyze the flexibility provided in the schedule. The literature review has shown the size of the airline scheduling problem, making re-scheduling after a disruption impossible. Therefore flexibility is provided by the number of recovery options, i.e., decision variables, in the schedules. The decision variables at the DoO and how they are used will be discussed in § 4.1 followed by a discussion of the restrictions § 4.2, i.e., scheduling restriction and technical restrictions. Subsequently, the data analysis on these restrictions is presented in § 4.3.

4.1 Decision variables at the DoO

This section will discuss the flexibility in the schedule in order to deal with the disruptions at the DoO. Disruptions in a planned schedule have their impact on the availability of aircrafts for future flights. Therefore, one flight delay can have a cascading down line disrupting impact over time and space unless appropriate recovery actions are taken (Abdelghany et al.,2008). Decision variables are recovery actions that can be taken in case of a disruption. As suggested in § 1.3, the poor performance in punctuality and non performance cost is a result of the lack in flexibility in the decision variables to deal with the disruptions that occur at the DoO as is graphically represented in appendix C. The different decision variables available for the DoO are as follows:

1. *Swapping an aircraft*

This involves swapping the flights of a scheduled aircraft with the flights of a later scheduled aircraft. This creates more time in case of a late incoming aircraft or prevents a cancellation when the scheduled aircraft is technically restricted to fly to its scheduled destination (§ 4.3.2). This is often only possible for the same aircraft type due to the operational – and capacity capabilities of the aircraft.

2. *Shorten/ cancel maintenance slot*

In order to create more time for the delayed aircraft or newly assigned resources, the option to shorten or cancel a maintenance slot is considered. Depending on the maintenance done during that slot, it is considered whether the slot can be shortened or the maintenance delayed to create time and resources in the schedule.

3. *Spare aircraft*

As mentioned in § 2.1.1, there are spare aircrafts scheduled among the different aircraft types. In case of a disruption, the spare aircraft can be used to replace the scheduled aircraft for the flight. It should however be taken into consideration whether there is crew available and whether the aircraft type is capable of flying to that destination with the booked number of passengers and amount of cargo. Therefore, a spare aircraft can often only be used for a flight of the same aircraft type as originally scheduled.

4. *Delay flight*

A flight can be delayed to create ground time in case of a disruption such as a late incoming aircraft or delayed maintenance. This is what happens when the SOC decides to do nothing in case of a disruption. The subsequent flight will be delayed until sufficient slack is provided in the schedule to get back on schedule. There are however costs involved in delaying a flight, which can be found in the TFM-tool as discussed in § 1.2.3. In addition, it decreases punctuality which is one of the KPIs.

5. *Cancel flight*

If none of the above recovery actions is possible, the only other option is to cancel a flight and rebook passengers to the next flights or other airlines. Due to the high costs of cancellations, it is a last resort measure.

The decision variables are listed in the way they are considered in case of a disruption, which is in line with the costs incurred for the use of a decision variable. The decision variables are similar to the measures used in OPiuM as discussed in § 3.1.2. When a disruption occurs which cannot be resolved within the slack provided by the schedule, the operation controller considers the different decision variables for recovery. As they operate in a time-critical environment, they have limited capability to anticipate all disruptions and explore all possible solutions for their recovery. Therefore, the quality of the recovery plan often depends on the level of experience of the operation controller who is handling the projected system disruptions (Abdelghany et al., 2008). When considering the different decision variables several aspects are taken into account:

1. To enhance punctuality in the flight operation
2. To minimize non-performance costs:
   a. Transfer all passengers and cargo
   b. Consider connecting passengers and cargo in case of delay
3. Aircraft type capabilities
4. Prevent or limit propagation to following flights
5. Minimum required quota of airport slots, i.e., if a flight to a certain airport is cancelled too often KLM will lose the slot for that airport

The aircraft availability catalogue states requirements regarding the amount of spare aircraft and spare maintenance slots to incorporate flexibility in the schedule. The amount of spare aircrafts or maintenance slots is based on previous experience. For the swaps however no requirements are made.

The ‘cash impact, future value’ of the decision variables delay and cancellation are considered in the TFM-tool. The TFM-tool shows the non-performance costs and the re-book options for passengers per flight. This indicates which flights are most or least costly to delay or cancel in case the use of these decision variables is required. In addition, it considers the no-connecting passengers as a result of a delayed flight. In other words, it takes into account the delay propagation of a disrupted flight, i.e., the effect this delay has on subsequent flights with the associated costs. Propagated delay is a result of a previous delay or disruption causing the scheduled aircraft to arrive late for its flight leg. According to Lan et al. (2006), this accounts for 20 to 30 percent of the total delay.

Currently, there are no tools operational at the DoO for the ‘costs’ incurred when swapping an aircraft or using a spare aircraft. In OPiuM on the other hand, a penalty is assigned to swapping an aircraft as it is a recovery measure with additional handlings and costs. Although swapping an aircraft or using a spare aircraft does not directly result in non-performance costs, it does limit the remaining capacity in the schedule and requires additional handlings, such as the towing of an aircraft. By using the spare aircraft, an amount of spare capacity is used which cannot be used again in case of a disruption. The same goes for swapping an aircraft to create more time in case of a disruption, which reduces the remaining slack in the schedule. In some cases it might be more beneficial to incur the costs of a delay instead of limiting the capacity in a schedule through a swap or use of a spare aircraft.

4.2 Restrictions in flexibility

The decision variables at the DoO can be restricted by the following three aspects related to aircraft availability:

- Scheduling restriction (Lack in free ground time): A tight schedule where everything is scheduled according to anticipated norm times provides no room for disruptions. As shown by Ramdas and Williams (2007), high aircraft utilization and therefore limited free ground time result in more delays and cancellations as there is no slack to resolve the disruptions. Apart from that, it limits swap options as there is no time to swap. Furthermore, a tight schedule leaves little room to schedule (urgent) repairs.
- Maintenance: Planned maintenance is required which can restrict decision variables as a certain aircraft is to be scheduled for a maintenance slot. This restricts swap options in previous flights to make sure that specific registration arrives at that maintenance slot on time.
- Technical restrictions: Technical restrictions are caused by defects on an aircraft. Defects can result in various restrictions. This can range from a no-go for all destinations or a selection of destinations to a deadline for repair between 3 and 120 days.

For the development of the anticipation function, the effect of these three aspects on the operations at the DoO needs to be determined. The following section will elaborate on these scheduling – and technical restrictions.

4.2.1 Scheduling restrictions

Scheduling restrictions are a result of the schedule design. Ramdas and Williams (2007) study the effect of capacity utilization and capacity flexibility on airline flight delay by comparing these two aspects among different airlines. The aircraft utilization is the fraction of time that the aircraft is actually flying, out of the available time during which it could be flying. The aircraft utilization at KLM is rather high (§ 3.1.1) compared to its peers, which increases the chances of delay (Ramdas & Williams, 2007). This can however be compensated by capacity flexibility, i.e., if there are many flights using the same type of aircraft that are scheduled to depart close in time to any particular flight, capacity flexibility is greater. Capacity flexibility enhances possibility for swap options and therefore minimizes delay (Ramdas & Williams, 2007).

Another scheduling restriction is the scheduled maintenance slots for an aircraft registration. During the tail assignment phase, three days ahead of the DoO, the registration is scheduled in such a way that it will be back on time for the scheduled maintenance slot. This limits the swap options as the specific registration needs to be back on time for that maintenance slot.

4.2.2 Technical restrictions

Technical restrictions are a result of the Minimum Equipment List (MEL) indicating the minimum requirements for an aircraft allowing it to fly. The KLM MEL is developed based on the Master Minimum Equipment List (MMEL) provided by the producers, i.e., Boeing and Airbus. The MMEL describes the minimum requirements for an aircraft to fly and the restrictions when an element is defect. A defect is either 1) a routine job during the available ground time, 2) a no-go which keeps the aircraft on the ground or 3) a deferred defect with which the aircraft can continue to fly under certain restrictions. The MMEL indicates whether a defect is a no-go or a deferred defect and lists the associated restrictions category of complaint depending on the lead-time for repair. This implies that aircrafts can continue to fly for 3-10 days while they are not fully operational as they cannot fly to restricted destinations. An example of this is a defect on the auxiliary power unit (APU), which provides electricity to enable air conditioning while the aircraft is on the ground. For destinations like Amsterdam, air-conditioning is not required, however when flying to Africa air-conditioning on the ground would be preferable. So in case an aircraft has a broken APU, very warm or cold destinations are no-go destinations apart from those airports that can provide electricity on the ground. According to the MEL, an aircraft can continue to fly with a broken APU for 10 days as it does not effect flight safety. However it is very restrictive in the operation as the aircraft can only be scheduled to fly to a limited number of destinations. Apart from the MEL there is a Configuration Deviation List (CDL) which indicates the limitations when small elements are defect. The aircraft can continue to fly but with higher costs, e.g. increased fuel costs. These defects do however not result in no-go's and therefore will be out of scope for this project.

Based on the MMEL, the KLM MEL is developed as each airline needs to make the MMEL operator applicable taking into account the law, i.e., the JAR MEL and the Technical Condition of the fleet (TSV- Technische Staat Vloot). A few years ago the KLM MEL was renewed with the introduction of the Basic Operating Philosophy (BOP) bringing the KLM MEL back to basic as it was overloaded with restrictions. The BOP contains 6 values Flight Technical has taken into consideration in the development of the KLM MEL, which are:

1. Flight Safety
2. Operation Integration: Eg. ETOPS, extended twin operations allowing an aircraft to cross the ocean. A non-ETOPS plane can not cross the ocean directly but needs to stay close to an airport and therefore needs to fly past Iceland, Greenland etc. to go to the US in stead of straight ahead with the associated extra flying time and costs.
3. Economy of operations: These are restrictions which e.g. cause increased fuel costs but are categorized as CAT D allowing to fly with this defect for 120 days, while incurring extra costs.
4. People: This aspect focuses mainly on guaranteeing safe work and rest conditions of the cockpit and cabin crew, which is closely related to flight safety and passenger.

5. Passenger: Very service oriented like in-flight services, temperature, in-flight entertainment systems, stairs etc.
6. Environment: Environmental conditions like extra fuel usage.

The basic KLM MEL however resulted in a poor condition of the fleet, which required the development of the MEL+. Figure 15 gives a graphical representation of the development of the MEL+. The MEL+ is a combination of the KLM MEL, the Service Level Agreement (SLA) and the route matrix. The KLM MEL is a law document, therefore defects have a repair lead-time as stated in the MEL. A recent change in law states that upgrading a restriction to a CAT B in the KLM MEL in stead of a CAT C as indicated by the MMEL, KLM is required to solve it in three days and is not allowed to fall back on the CAT C description of the MMEL. Therefore, it is not wise to upgrade all restrictions to a category with a shorter leadtime to speed up the repair as it will become illegal to fly the plane as soon as it crosses the deadline for repair. Therefore, additional specifications are required by contract or in SLA, i.e., service level agreement which discusses the CAT X complaints, i.e., service oriented complaints. The SLA describes the preferred deadline for repair. So the KLM MEL and the SLA discuss all the restrictions on the fleet, which is translated into restrictions per destination in the route matrix.

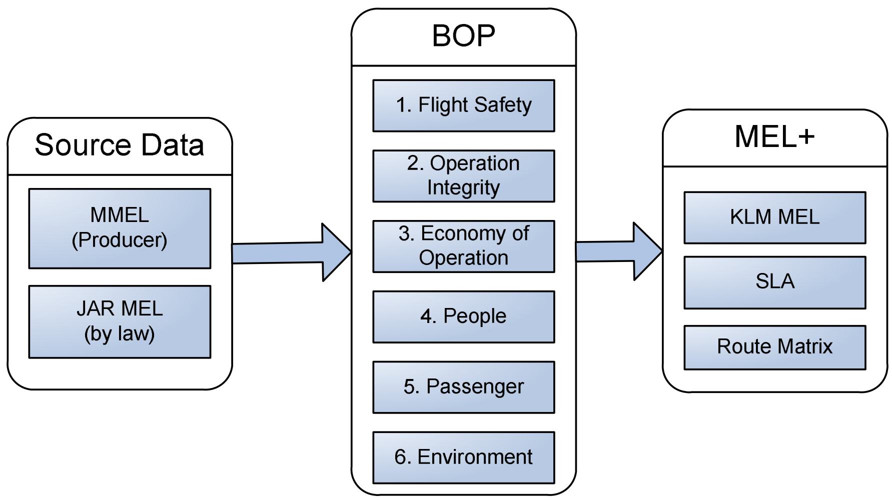


Figure 15. Development MEL+

The route matrix provides a cross reference table that shows the relation between the different destinations and the related technical restrictions on that route. In addition, it indicates the priorities for the scheduling of planes in the tail assignment phase as is shown in table 6. The route matrix for the narrow body is far more elaborated compared to the wide body. Hardly any technical restrictions are implemented in the route matrix for wide body and therefore in the tail router, as the MEL+ is still in development and no clear cross reference table is available.

The following aspects make the tail assignment for wide body significantly more difficult compared to narrow body:

- The number of aircrafts with deferred defects that result in route restrictions is significantly higher
- The amount of restrictions per destination is a lot higher
- The scheduling is more difficult due to longer flight legs.
- The Asia tails[1] need to be taken into consideration with the scheduling of the 747-400.

[1] Asia tails are aircrafts where the crown in the KLM logo is replaced by 'Asia'. These aircrafts are used to fly to Taiwan as China does not accept the same carrier to fly to both Chinese and Taiwanese destinations. Through the adjustments on the aircraft it is KLM Asia that flies to Taiwan and KLM Royal Dutch Airlines that flies to different destinations in China.

Table 6. Priority in tail assignment

Priority	Category	Reason
High priority	Hard repair- and maintenance urgency	Assure short term availability
	Spare aircraft	Assure a spare aircraft for the following day
	Routing, taking into account ETOPS (777, 330, 767), Asia/non-Asia 74E and route matrix requirements	Assure availability for the operation and assign the fleet.
	Repair urgency cat C complaint	Assure availability of specification on short term
	Replace loan parts	Costs
	Repair urgencies Service Deficiencies, cat X complaint.	Address specific wishes
Low priority	Requirements considering fuel use.	

In the tail assignment phase, technical services (TD) indicates it is very difficult to schedule the 747 combi and the 777. It is currently impossible to schedule the aircrafts while fulfilling all requests. It is only possible to satisfy the no-go's (the hard constraints) by neglecting restrictions on other legs.

The current discussion and development on the MEL+ involves Flight Technical, Fleet Services, E&M and OC. Although it would be preferable to solve all defects at once, the capacity at E&M needs to be taken into consideration. The capacity at E&M is limited by: 1) materials on stock, 2) manpower, 3) available ground time to repair. Therefore, an agreement needs to be made between the capacity at E&M, the BOP values of Flight Technical and the operational aspects for OC. In addition, these departments daily meet in a Collaborative Decision Making (CDM) meeting to discuss the state in the fleet and how to solve the current issues. The results of these meetings is stored in a database and provided to the front office at the DoO. The MEL+ restrictions are stored in a database which is able to provide all the operational restrictions related to each defect. The defects resulting in a no-go have an immediate effect on the operation, while the deferred defects that have a no-go on certain destinations limit the flexibility in the operation as is illustrated in fig. 16. As the MEL+ is still in development for the ICA fleet, there is no accurate data on the MEL-items resulting in a no-go.

4.3 Data analysis restrictions

Figure 16 provides a graphical overview of how the decision variables (DV) are restricted through technical – and scheduling restrictions and provides an indication of the required data to determine this effect. It starts with a disruption on the aircraft in the fleet as is represented on the left side. The disruption can be a defect or another disruption resulting in the late arrival of the aircraft. In case of a defect, the distinction is made in what kind of defect it is and which route restrictions it will result in. This in turn has effect on the decision variables as it limits e.g. the options to swap and therefore limits the available flexibility in the schedule. Subsequently, possible solutions are suggested to overcome these restrictions in flexibility. On the other hand, flexibility can be restricted by scheduling restrictions such as limited ground time or swap options available in the schedule at hand. Possible solutions are suggested to overcome these restrictions on flexibility. This figure shows improved flexibility can be found by limiting technical restrictions or enhancing slack/flexibility in the schedule design.

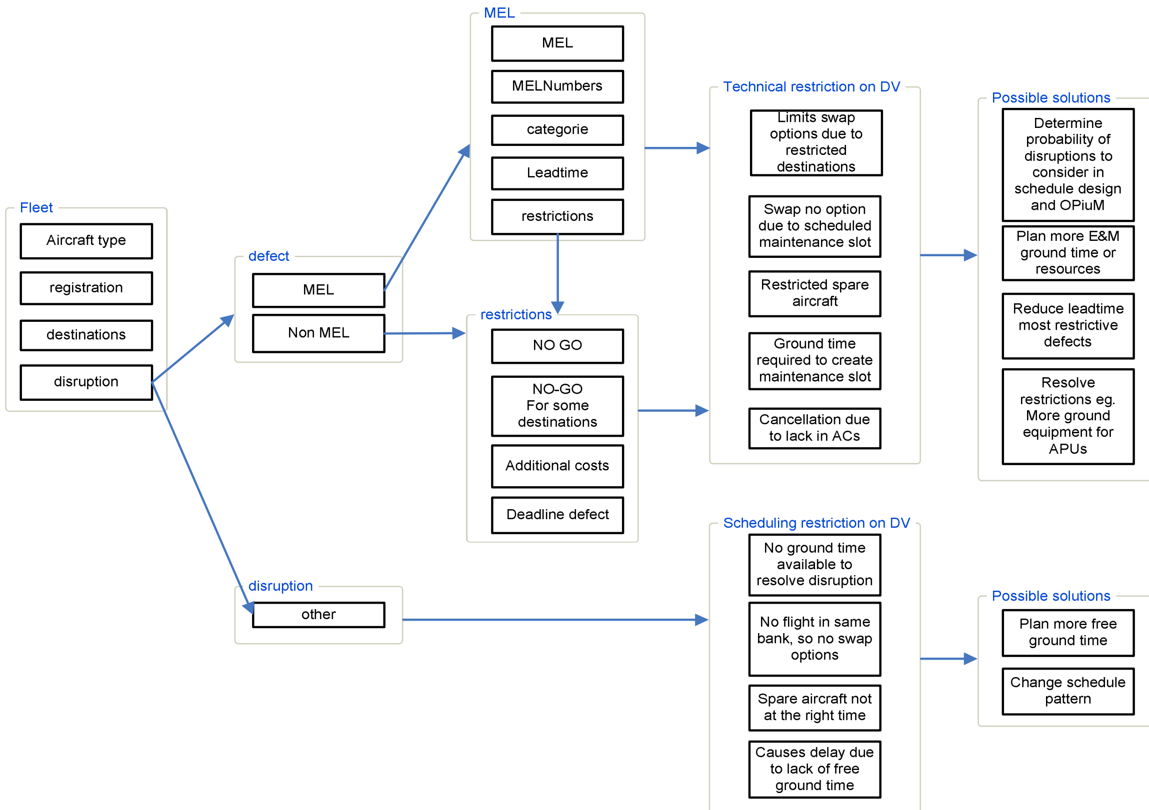


Figure 16. The restrictions on decision variables
Note: DV = decision variable, AC=aircraft, APU= auxiliary power unit

In order to determine which of the possible solutions is recommended, the effect of the technical restriction needs to be determined. This can be done by establishing a link between the defects that result in a no-go and the delay or cancellation caused by it. In the ICA fleet, consisting of 61 aircrafts, on average 500 defects occur of which 50 result in deferred defects, with an associated deadline. This indicates that the remaining 450 defects are solved straight away. Among these 450 defects are the no-go's, most of which will be resolved in the planned ground time. When however the defect cannot be fixed within the planned ground time it will result in a disruption. This is however not recorded as the focus is on repairing the defects straight away and making the aircraft operational again as soon as possible. The repair lead-time of deferred defects is recorded; it is however not recorded e.g. how often swap cannot be executed due to a deferred defect on the aircraft. This should indicate how often an operation controller runs into a situation with restricted flexibility due to technical restrictions and to what extend the MEL-deadlines are operationally feasible.

As the MEL-data are still in development and the data on no-go's is not recorded, it is very difficult to determine the effect of technical restrictions on flexibility in the schedule. The possible solutions indicated on the right side of fig. 16 show the possible actions, which can be taken when the effect of the technical restrictions is determined. In addition, it shows the most restrictive defects on the operation, which could be anticipated upon at E&M. On the other hand, data on available ground time is required to determine the effect of scheduling restrictions. It was suggested that the amount of free ground time compared to the norm has diminished over the years as the capacity utilization has increased. There are however no accurate data on the free ground time in the schedule as not every action is recorded in Planboard during the DoO. This makes it difficult to determine the effect of restrictions on the decision variables, i.e., the flexibility in the schedule. During the intermediate presentation general consensus was reached that a data structure was required to determine the effect of the restrictions on flexibility. The following chapter will elaborate on which data is required to determine the effect of restrictions on the flexibility in the schedule.

Furthermore the intermediate presentation indicated that the general perception is that the number of restrictions has increased over the years on both the scheduling and technical side. The mindset in front office is to keep on flying and limit delays and cancellations as much as possible. With the increase in restrictions they have became more 'creative' in overcoming disruptions and restrictions. For example, an aircraft with a broken APU is scheduled for a no-go destination as the ground power unit is not always operational. If the choice is between cancelling the flight or flying to that destination, they will check the situation of the ground power unit and let the aircraft fly. Therefore the increase in restrictions has not resulted in poor performance straight away. There are however limits to this 'creativity' which should be indicated. The 'creativity' should not be required. Therefore it should be more transparent how many restrictions the front office has to deal with and to what extent there is sufficient flexibility in the schedule to cope with these restrictions. Therefore, during the intermediate presentation was decided that an anticipation function is required that determines the added value of flexibility.

4.4 Conclusion

This chapter discussed the flexibility in the schedule in terms of decision variables, i.e., which recovery actions can be taken in case of a disruption. While the use of the decision variables delay and cancellation is guided by the TFM-tool, the costs of swapping an aircraft or using a spare aircraft is not quantified in terms of capacity and/or costs. Doing so would allow for better insight in the propagation of disruptions at the DoO and enhance the anticipation of future events, while improving proactive behavior. Robustness is currently provided by stating the amount of spare aircrafts and spare maintenance slots in the schedule, which is based on previous experience. An improved anticipation function that takes into account flexibility and stability, i.e., the recovery options and their propagation, provides better insight in the required spare aircrafts and maintenance slots.

Subsequently, the restrictions in flexibility were described, which are divided in scheduling and technical restrictions. This provided the solution direction for the design phase as enhanced flexibility can be created through either minimizing technical restrictions in terms of repair lead-time or providing more flexibility in the schedule design. In addition, it was shown that currently insufficient or inaccurate data is available in order to determine the effect of these restrictions. In order to determine the effect of restrictions on flexibility in the schedule, a data structure is required that enables the quantification of the effect of these restrictions. Once the required data is available the consequence of limited flexibility on performance needs to be identified through an anticipation function. These aspects will be considered in the design phase.

5. Design of robust airline operations

This chapter will provide suggestions on robust airline operations given technical restrictions. First, an overview of the requirements in the design will be discussed in § 5.1. Second, a method to record the required data to measure the effect of technical restrictions is presented in § 5.2. Third, the recorded data can be implemented in the anticipation function presented in § 5.3. This anticipation function quantifies the effect of technical restrictions and indicates a solution direction in terms of enhanced flexibility in the schedule or diminishing the lead-time of technical restrictions.

5.1 Specification of design

The prior chapters have resulted in various requirements for the design phase from both a theoretical and practical background. The analysis at KLM resulted in the following requirements:

- Flexibility in the schedule is identified as the different decision variables in the schedule.
- The flexibility is restricted by technical restrictions and scheduling restrictions.
- Data structure to determine the effect of restrictions on performance, i.e., KPIs.
- Transparency in the amount of flexibility and restrictions at the DoO.
- Enable a trade-off between the added value of flexibility or a reduction in technical restrictions.

The literature review provided the following requirements:

- The DDM framework indicated the need for an improved anticipation function.
- The size of the airline scheduling problem results in huge mathematical programs, therefore rescheduling is impossible when disruptions occur. Therefore flexibility is limited to a number of recovery options.
- The stochastic nature of airline operations requires a robust schedule.
- Robustness involves flexibility, i.e., the different recovery options, and stability, i.e., limiting propagation of disruptions.
- Limiting the propagation of disruptions can be done through the use of decision variables with the associated costs resulting in a time-cost trade-off.
- Similar time-cost trade-offs are made in project scheduling where activities can be shortened at additional cost.

These requirements resulted in the design of a data structure with the required data to determine the effect of technical restrictions in the operation. In addition, an anticipation function is presented that considers the lead-time of a disruption with the associated costs. A comparison is made between the costs of 'doing nothing' compared to the cost of the different recovery actions. This indicates the effect of additional flexibility or, the other way around, the effect of restricted flexibility.

5.2 The effect of technical restrictions

The following method to measure the effect of scheduling – and technical restrictions is suggested to provide an indication of the effect of restrictions on the flexibility.

1. Based on the operational schedule at the DoO, the capacity flexibility will be determined in terms of the amount of swap options assuming a perfect condition of the fleet. The swap options can be restricted by the schedule design and the scheduled maintenance slots on registration. This should result in a probability for the effect of scheduling restrictions, e.g. if there are 8 swap options of the 16 flights at hand the scheduling restriction is 50 percent.
2. Subsequently the current state of the fleet will be taken into consideration and compared with the technical restrictions as stated in the MEL+ to see if this further limits the swap options. This information is daily obtained for the Supervisor Dispatch and the Senior Operations Controller (SOC). This should determine the effect of technical restrictions, e.g. of the 8 available swap options in the schedule 4 cannot be executed due to technical restrictions.

3. The effect of the restrictions will be compared with the performance of the schedule. It is expected that when the effect of the restrictions is higher the performance of the schedule is lower.

This method provides an indication of the effect of restrictions on the possibilities to swap. It results in a probability for the scheduling restrictions and the technical restrictions. Multiplying these provides an indication of the capacity flexibility in terms of the decision variable “swapping an aircraft”. This method is recorded for a couple of weeks and the results are presented table 8.

Table 8 shows for each of the different aircraft types what the probability was to swap based on the scheduling – and technical restrictions that day. This illustrates that the effect of scheduling restrictions is more restrictive compared to the effect of technical restrictions. Based on the results of this method the effect of technical restrictions seems only quite limited, which suggests that there might be another aspect more restrictive for the operations. It does however show that the aircraft types 747 combi and 777 are the most restrictive aircraft types as suggested by the TD in § 4.2.2. Furthermore, the overall probability seems to be rather the same over the days. This makes it difficult to relate this to the performance. The limitations of this method should however be taken into account, which are mentioned in § 5.2.1.

Table 7. The effect of restrictions in terms of probability for the ICA fleet

Aircraft	744			747 combi			M11			777			330					
Date	Ps	Pt	**P**	Ps	Pt	**P**	Ps	Pt	**P**	Ps	Pt	**P**	Ps	Pt	**P**	**Average P**	**Departure punctuality**	**Completion rate**
17-1	0.45	1.00	**0.45**	0.11	0.94	**0.09**	0.47	0.98	**0.46**	0.19	1.00	**0.19**	0.56	0.89	**0.50**	**0.28**	**73.9**	**98.1**
18-1	0.20	1.00	**0.20**	0.09	0.82	**0.08**	0.47	1.00	**0.47**	0.20	1.00	**0.20**	0.52	1.00	**0.52**	**0.24**	**71.1**	**98.1**
21-1	0.20	1.00	**0.20**	0.25	0.88	**0.23**	0.27	1.00	**0.27**	0.16	0.93	**0.14**	0.68	0.89	**0.60**	**0.24**	**46.7**	**95.3**
22-1	0.47	0.90	**0.40**	0.10	1.00	**0.10**	0.27	1.00	**0.27**	0.19	0.97	**0.19**	0.30	1.00	**0.30**	**0.21**	**84.1**	**100**
23-1	0.20	1.00	**0.20**	0.19	0.94	**0.17**	0.58	1.00	**0.58**	0.21	0.98	**0.20**	0.51	1.00	**0.51**	**0.28**	**84.1**	**100**
24-1	0.40	1.00	**0.40**	0.17	0.94	**0.14**	0.11	0.95	**0.10**	0.21	1.00	**0.21**	0.49	0.83	**0.46**	**0.22**	**89.1**	**100**
25-1	0.35	1.00	**0.35**	0.26	0.97	**0.24**	0.16	1.00	**0.16**	0.25	1.00	**0.25**	0.49	0.89	**0.46**	**0.24**	**73.9**	**99.1**
29-1	0.20	1.00	**0.20**	0.11	0.97	**0.10**	0.49	0.87	**0.40**	0.32	1.00	**0.32**	0.25	1.00	**0.25**	**0.21**	**95.3**	**99**
30-1	0.33	1.00	**0.33**	0.08	0.88	**0.07**	0.34	1.00	**0.34**	0.23	1.00	**0.23**	0.24	1.00	**0.24**	**0.20**	**84.4**	**99**
31-1	0.47	0.90	**0.40**	0.14	0.96	**0.13**	0.55	0.98	**0.54**	0.12	1.00	**0.12**	0.67	0.89	**0.56**	**0.29**	**68.8**	**100**
1-2	0.48	0.90	**0.44**	0.15	0.99	**0.15**	0.24	0.90	**0.22**	0.24	0.98	**0.23**	0.21	1.00	**0.21**	**0.21**	**52.2**	**100**
5-2	0.30	1.00	**0.30**	0.15	0.97	**0.14**	0.27	1.00	**0.27**	0.33	0.98	**0.32**	0.36	1.00	**0.36**	**0.23**	**88.9**	**100**
6-2	0.35	0.90	**0.30**	0.11	0.97	**0.10**	0.50	1.00	**0.50**	0.36	1.00	**0.36**	0.57	1.00	**0.57**	**0.31**	**75**	**100**
Average	**0.31**	**0.97**	**0.30**	**0.14**	**0.94**	**0.12**	**0.34**	**0.98**	**0.33**	**0.21**	**0.99**	**0.21**	**0.46**	**0.96**	**0.44**	**0.23**	**74.66**	**99.05**

Note: Ps= the effect of scheduling restrictions, Pt= the effect of technical restrictions, P= Ps*Pt= the probability to swap taking into account scheduling and technical restrictions.

5.2.1 Limitations

This analysis provides an indication of the effect of scheduling – and technical restrictions. Several limitations should however be taken into account.

- *Human factor:* Every night the dispatch and SOC receive a list with the technical defects in the fleet. The DMM decides which defects appear on the list, i.e., the defects that could effect the operation. Then again, each of the dispatchers and SOC can interpret the 'seriousness' of technical restrictions differently making this measurement rather subjective.
- *Filter technical defects:* Associated with the limitation mentioned above is that different operational parties consider a different list of technical restrictions. The MEL+ is developed at flight technical, which considers a list different from the one at the TD for the tail assignment, while the SOC and dispatch at the DoO consider yet another list with operational restrictions. Therefore conducting the same analysis with data from flight technical could result in a different conclusion, e.g. making technical restrictions far more restrictive.
- *Focus on one decision variable (swapping an aircraft):* This measurement focuses on one decision variable, i.e., swapping an aircraft. This method needs to be elaborated upon to include the other decision variables such as spare aircraft, delay and cancellation. In § 4.3, it is briefly mentioned which data is required. This will be elaborated upon in the remainder of the project.
- *Time span:* The data collection was only done for thirteen days, which is insufficient to assume that technical restrictions have no effect.

This measure needs to be elaborated upon to determine the actual effect of the technical restrictions. The quantification of the effect of technical restrictions enables to determine whether flexibility is mainly limited by schedule design or technical restrictions. This indicates whether flexibility in the schedule design needs to be enhanced or the repair time of technical restrictions needs to be shorter.

- The effect of the technical restrictions on the DoO could be implemented in OPiuM to further improve this simulation, providing better insight in the operational feasibility of the schedule.
- It will provide insight into the most restrictive defects, which can be acted upon in terms of e.g. reducing the deadline in the MEL. On the other hand, the restriction can be resolved for example by providing ground equipment at out-stations to overcome the restriction of an APU.
- In addition, it gains insight in the required distribution of the spare maintenance (TO)-slots, whether there is more demand for many short TO-slots or a few long TO-slots.

In § 5.2.2, a measure is suggested to minimize the effect of these limitations and provide a proper indication of the effect of technical restrictions.

5.2.2 Measure to determine the effect of technical restrictions

To determine the effect of technical restrictions on the DoO, additional data is required from both the technical specialists where the defects are detected and the SOC where the defects that result in a disruption need to be solved. This should link the defects with the delays/cancellation and therefore with the KPIs. Figure 17 (and appendix G) provides the sequential process for the measurement of technical restrictions.

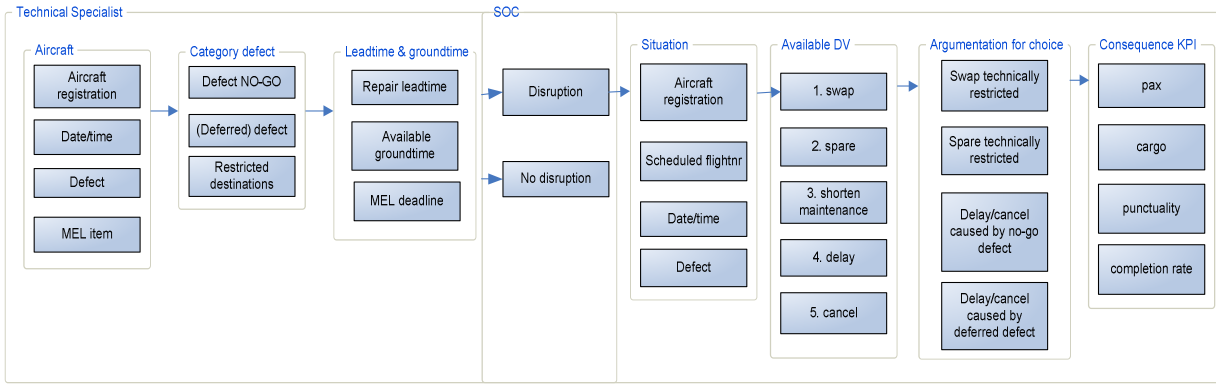


Figure 17. Structure for technical restrictions measure

This measure establishes a link between defects with the associated technical restrictions and delays and cancellations that effects the non-performance costs. The measure is divided in 1) *the technical aspect* that determines whether a defect results in a disruption and 2) *the operational aspect* that determines whether the disruption effects the operation and the KPI. A disruption in this case is a situation where the SOC needs to take action to minimize the consequences of the disruption. This results in a decision tree for technical specialists and the SOC, which are provided in figure 18 and 19 (appendix H and I). The decision tree for technical services makes the distinction in defects between the no-go defects and deferred defects. Although all defects are currently recorded there is not a clear distinction between the no-go defects and the deferred defects. The subsequent step records the repair lead-time for the defects to compare this with the available ground time or the deadline set for the deferred defect. This data is recorded for the deferred defects to check whether they are repaired within the deadline. Recording the repair lead-time for the no-go defects enables to relate this to the available ground time and determines whether it will result in a disruption. The deferred defects that cause route restrictions are considered as a disruption as the SOC needs to take this into consideration. So in addition to the current dataset a categorization of the defects is required. Furthermore their repair lead-time needs to be recorded and whether it resulted in a disruption, i.e., the cases when the SOC needs to be notified on the defect.

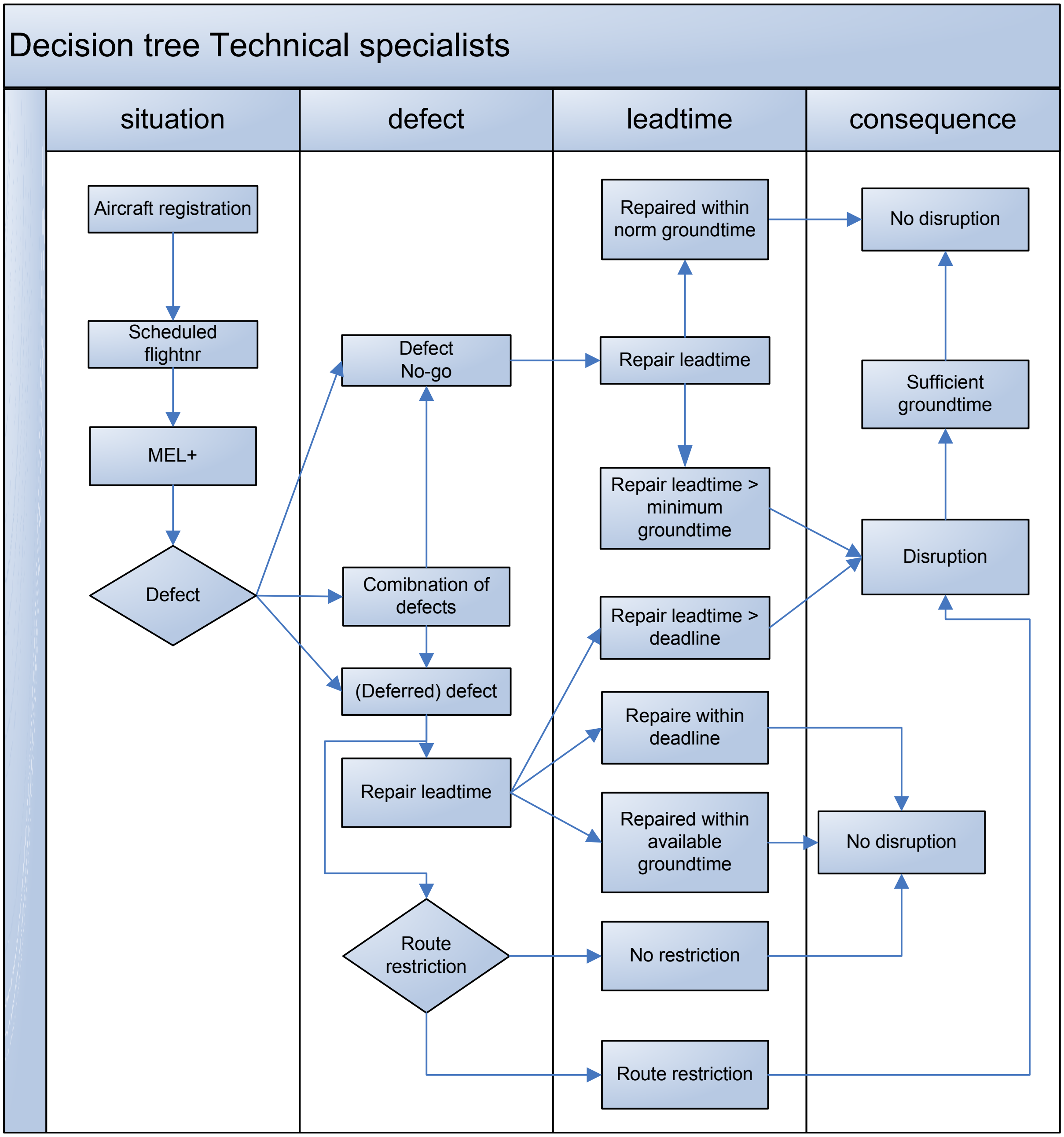


Figure 18. Decision tree Technical services

The SOC is then notified on the disruption and needs to take action in order to minimize the consequences on the KPI. The decision tree indicates the different options, i.e., decision variables, the SOC has in case of a disruption. The availability of each of the decision variables should be indicated and based on the situation at hand he determines the most suitable option. To determine the effect of technical restrictions and especially route restrictions, data is required on how often a swap cannot be executed due to a restriction or a swap had to be executed due to a restriction. For each of the decision variables argumentation is provided why that one is chosen or not. This is finally related to the KPIs on which data is available. Through this structure the link between a defect, with the related technical restrictions, and the KPIs can be established.

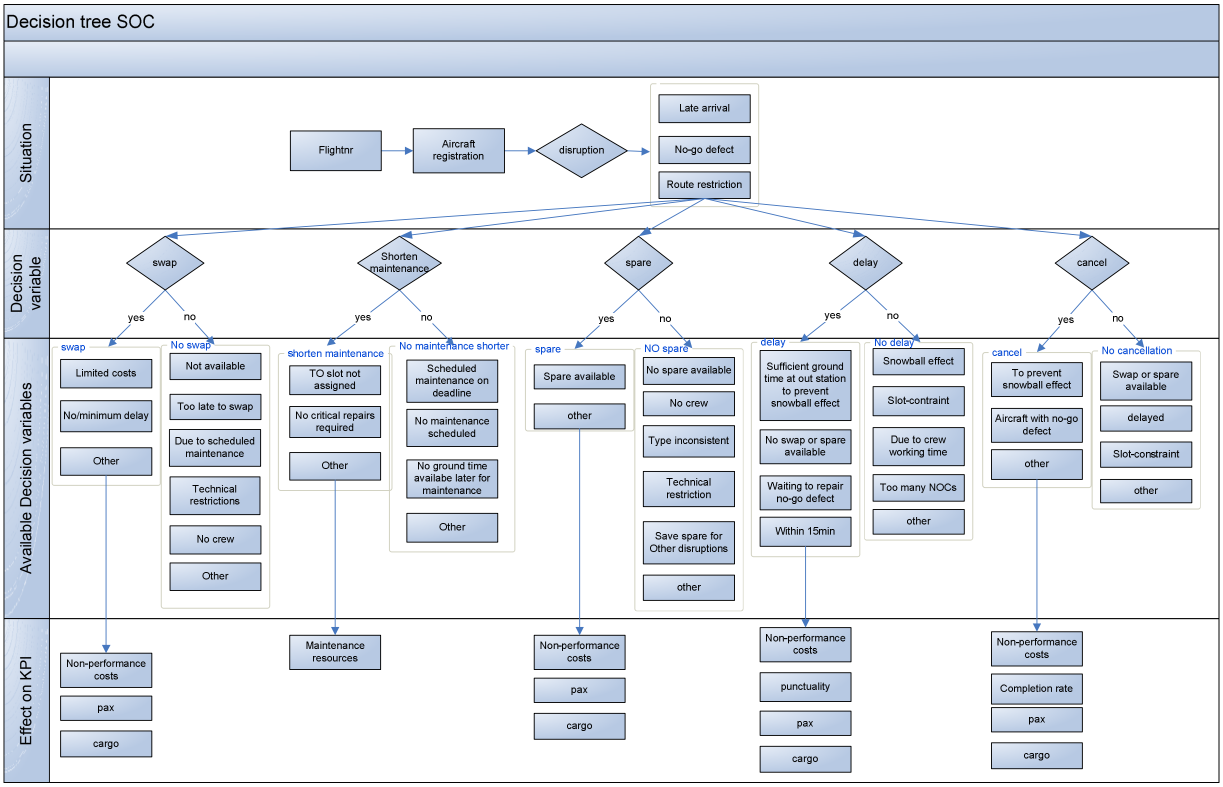


Figure 19. Decision tree to measure technical restrictions

The result of this data structure should indicate whether the focus should be on minimizing technical restrictions through reduction of repair lead-time or enhancing flexibility in the schedule design. It should enable a trade-off between the cost of operating with technical restrictions and the cost of reducing repair lead-time at E&M. The following section § 5.3 will suggest a cost function to enable this trade-off.

5.3 Measure for flexibility

Flexibility in the schedule is expressed in the available decision variables: swap, spare aircraft, shorten maintenance, delay and cancellation. Flexibility in the schedule costs money as it takes time of resources. This section presents an anticipation function for flexibility that considers the lead-time of a disruption with the associated costs. The lead-time of a disruption is the time it takes to get back on schedule. A comparison is made between the costs of 'doing nothing', i.e., delaying the flight and consecutive flights, and the cost of the different decision variables which results in a reduction of the lead-time of a disruption. This illustrates the effect of additional flexibility or, the other way around, the effect of restricted flexibility and enables a trade-off between time and cost. Similar trade-offs are made in the product development projects where shortening activities (crashing) in the project reduces the lead-time at additional costs (Roemer et al., 2000; Ahmadi et al., 2001).

Large development processes can require the coordination of thousands of individual design activities with complex information dependencies and couplings between them (Ahmadi et al., 2001). Therefore project scheduling, like airline scheduling, is considered computational challenging. The success of the product development process depends largely on its performance along three different dimensions: 1) product quality, 2) development lead-time and 3) development costs. In terms of airline operations, this involves 1) achieving the key performance indicators, 2) limiting the propagation of the disruption, 3) the costs for the use of decision variables. The ability to expeditiously develop and market new products is one of the crucial success factors in product development. Whereas projects used to be executed sequentially, now various ways exist to reduce the development lead-time of the project such as: 1) overlapping of activities, 2) concurrent exploration of alternatives and 3) shortening activities, i.e., crashing activities (Roemer et al., 2000). Crashing in project scheduling has an analogy with the use of decision variables in airline operations. Crashing can be done through e.g. hiring additional resources to shorten the activities, which could be compared to using a spare aircraft. Another form of crashing involves cancelling activities in the project effecting the product quality but cut the development lead-time like cancelling a flight. In project scheduling a manager minimizes the sum of two costs: 1) the opportunity cost of entering a market too late, and 2) the project development cost (Graves, 1989). In case of a disruption in airline operations a manager minimizes the sum of two costs 1) the non-performance cost for the propagation of the disruption, and 2) the cost for the decision variables.

This anticipation functions considers the available flexibility on flight level and at what cost it can deal with disruptions. When flexibility budget is set, it can be determined to what extent disruptions fall within this budget and should be able to deal with at the DoO. It is up to KLM to set this budget, which enables Network to schedule sufficient flexibility in the schedule to cover this budget. This flexibility budget can be compared to the deductible of an insurance, which is for one's own account. Whereas OPiuM determines the insurance premium to be paid by multiplying the probability of a disruption times the cost of a disruption. The anticipation function considers what it is going to cost KLM if it disruption actually occurs and to what extend are they accountable. That is whether the disruption falls within the deductible, i.e., the flexibility budget. The idea is not to be able to deal with all disruptions, such as severe weather which falls outside the flexibility budget, but sufficient disruptions to provide robust airline operations. This model incorporates the propagation of disruptions on consecutive flights in the schedule enabling proactive behavior. For each of the MEL-items it should be determined whether their deadline set in the MEL is operationally feasible and whether they can be solved in the budget. Figure 20 illustrates the different steps in the anticipation function. The following section 5.3.1 will illustrate the cost and lead-time of the different decision variables in case of a late incoming aircraft.

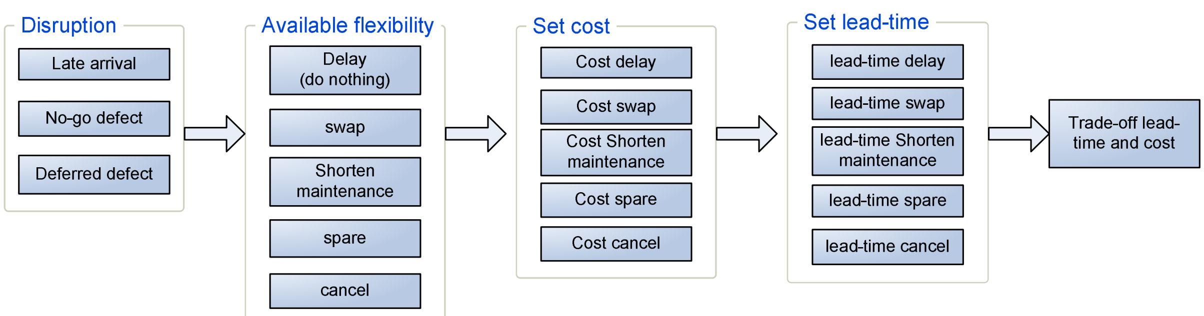


Figure 20. Structure anticipation function

5.3.1 The cost and lead-time of decision variables

This section will present the consequences of a disruption in terms of time and cost and how this can be limited by the different decision variables. First, it is graphically represented what the propagation of a late incoming aircraft is when no action is taken in fig. 21 and 22.

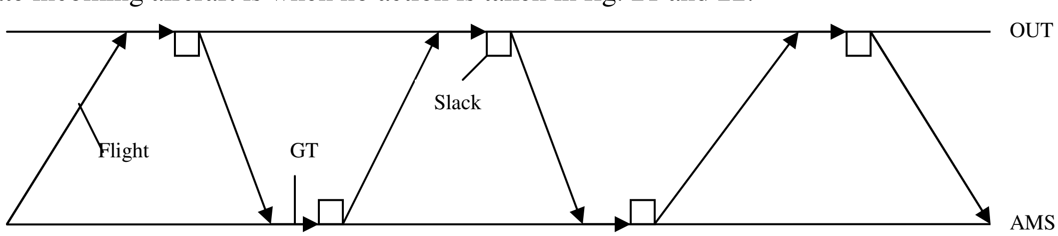


Figure 21. Schedule without disruptions

Note: AMS= Schiphol airport, OUT= Out station, GT=ground time

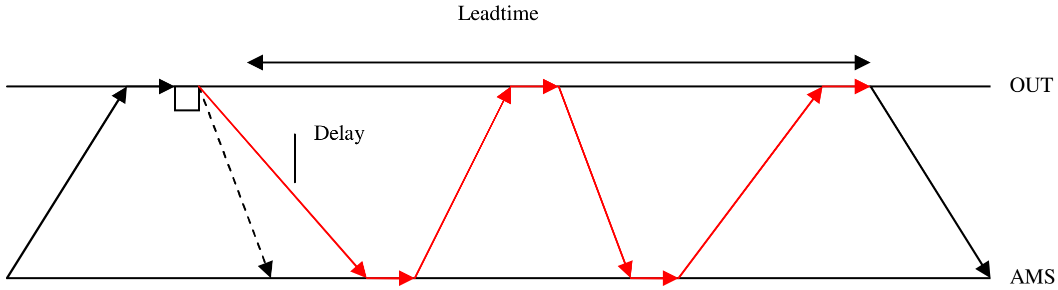


Figure 22. The lead-time of a delayed aircraft

Figure 21 shows the flights scheduled for an aircraft with the slack in the ground time. Figure 22 then illustrates the effect when the aircraft is delayed and no action is taken. This will be the base line in this model as this option is always available and will be the results of a disruption when no SOC was present. The scheduled slack is used to get back on schedule which requires delaying the delayed flight and three consecutive flights. So the lead-time (L_b) of the disruption in the base function is $L_b = t_i + \sum_{d=1}^{n} t_{df}$. Where t_i is the time of the disruption and n the number of delayed flights where t_d indicates the duration of flight number f. The cost of the base function is a summation of delaying these four flights and the associated costs (C_b), i.e., $C_b = \sum_{d=1}^{n} C_{df}$ and. Where n again are the number of delayed flights and the C_d the cost of the delayed flight with flight number f as given in the TFM-tool.

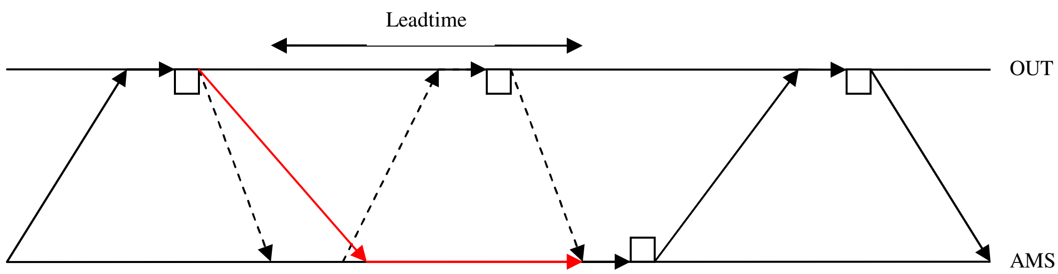


Figure 23. The lead-time of the disruption when a flight is cancelled

Figure 23 shows the lead-time of the same disruption as in fig. 22. However this time the subsequent flight is cancelled. This shows that the time it takes to get back on schedule is shorter compared to the base function (fig. 21). The lead-time for a cancellation ($\underline{L_c}$) is $L_c = t_{cf}$, i.e., the duration of the cancelled flight (t_c) with flight number f. The cost of this reduction in lead-time is the cost of the cancellation of the flight (C_c) as given in the TFM-tool. Based on this a comparison is made between the cost of cancelling a flight and the cost of 'doing nothing', i.e. delaying the flight. This can be done for the different decision variables.

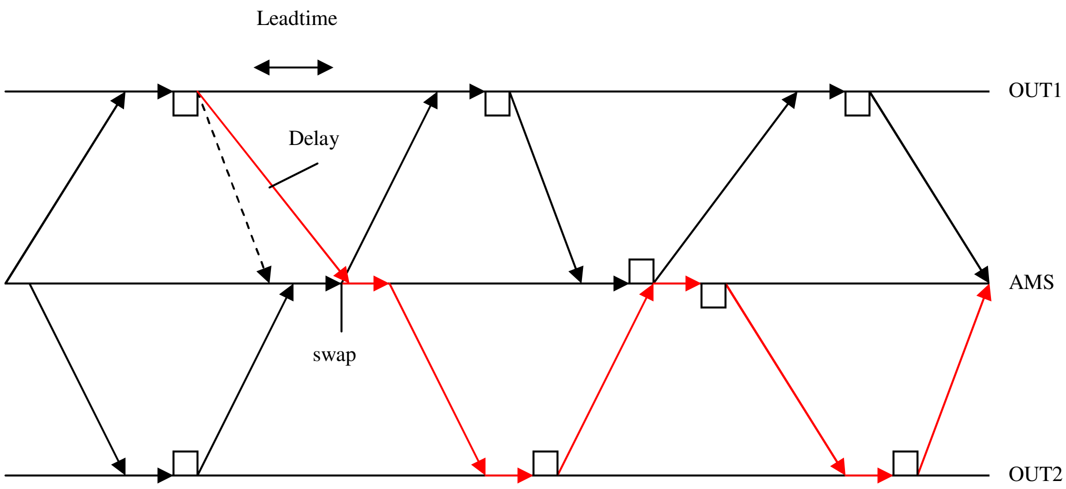


Figure 24. The lead-time of a disruption when the flight is swapped

Figure 24 graphically represents how a disruption is resolved by a swap. This upper part is the same aircraft schedule as in fig. 21, while the lower part is the schedule of a second aircraft. Due to a delay on the aircraft, it is too late for its scheduled flight to OUT1. It is however on time for the flight to OUT2 and therefore the aircrafts are swapped. The delayed aircraft continues to fly the red line, while the other aircraft flies the black line. The lead-time (L_s) of the disruption is further reduced to solely the delay of the effected flight, i.e., $L_s = t_i$. The cost for this disruption involves the cost of the delayed flight and the cost for a swap (C_s).

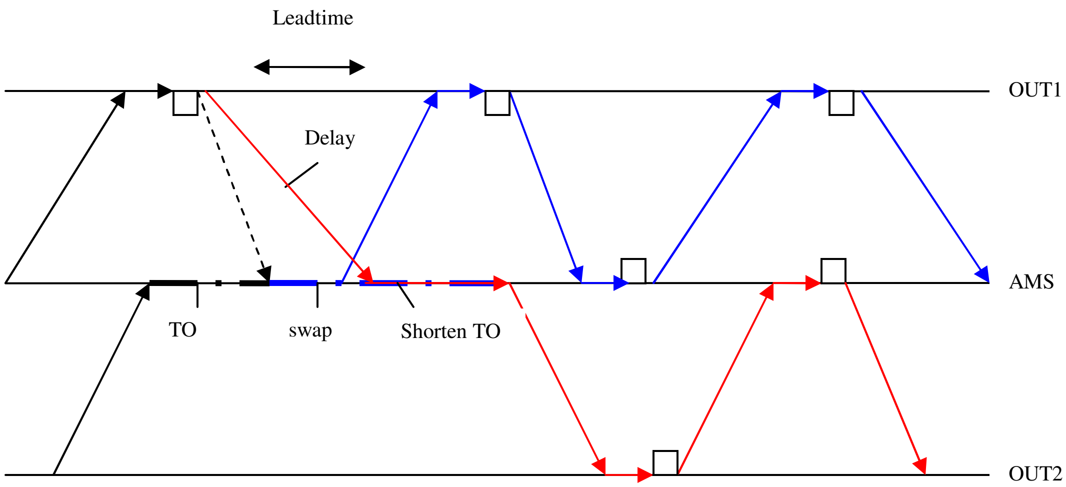


Figure 25. The lead-time of a disruption is maintenance is shortened
Note: TO = maintenance slot

Figure 25 illustrates the effect of shortened maintenance to resolve a disruption. The TO-slot is cut such that the aircraft continues to fly the scheduled flights of the delayed aircraft to OUT1 and the delayed aircraft can fly to OUT2. The lead-time (L_m) is equal to the time of disruption (t_i). The cost is equal to the cost for the delayed flight and the cost to shorten the maintenance slot (C_m). This decision variable should incorporate the trade-off of taking the delay now or in the future as maintenance has to be done eventually either way.

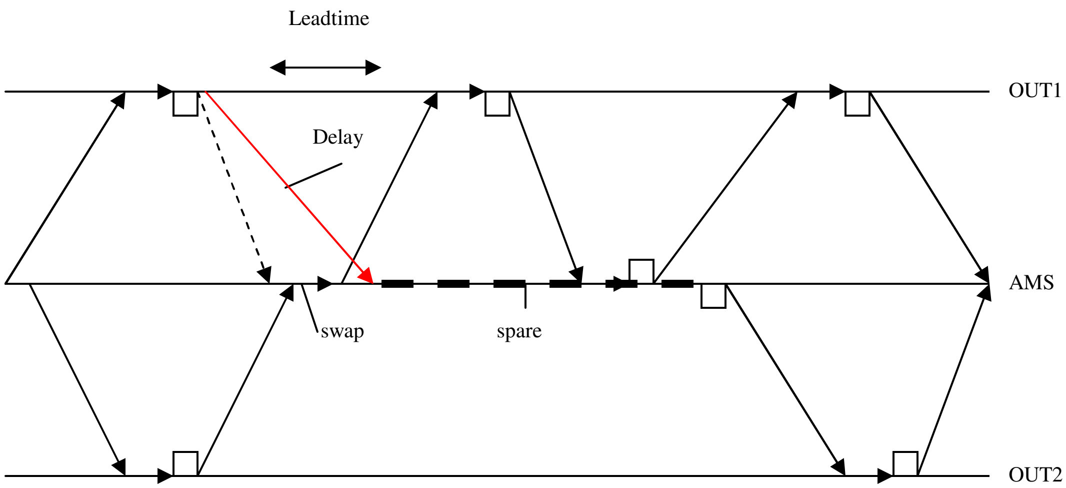


Figure 26. The lead-time of the disruption when a spare aircraft is used

Figure 26 illustrates the use of a spare aircraft. The lead-time (L_r) is again equal to the delay of the flight (t_i). The costs involve this delay and the use of the spare aircraft (C_r). The illustration of the effect of the different decision variables shows that they are used to expedite the lead-time of the disruption. This method evaluates the cost of the different decision variables compared to the base line 'doing nothing', i.e., delaying the flight (and consecutive flights). This enables a trade-off between the lead-time of the disruptions and the cost in reduction of lead-time, i.e., the cost of flexibility. This method can be applied to disruptions caused by defects, which will be illustrated in § 5.3.2.

5.3.2 The cost and lead-time of defects

The previous section illustrated the effect of a late incoming aircraft. A no-go defect or deferred defect can be modeled in a similar way as is shown in fig. 27 and 28.

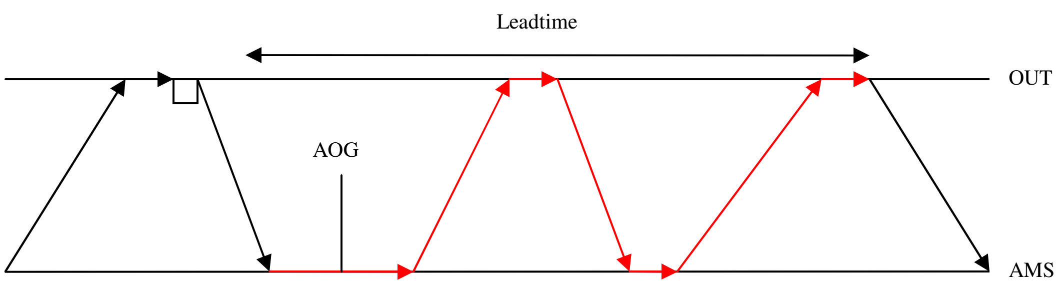


Figure 27. The lead-time of a no-go defect
Note: AOG = Aircraft on ground.

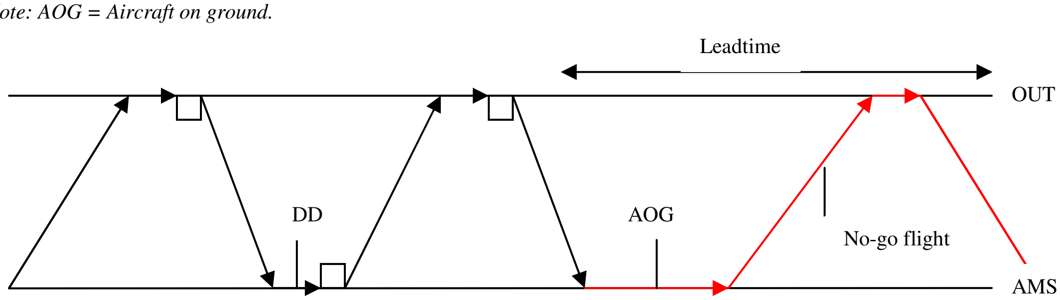


Figure 28. The lead-time of a deferred defect
Note: DD=Deferred defect, no-go flight is a flight with a route restriction for that flight

A no-go defect is the same as a delayed aircraft, the only difference is that the aircraft is at Schiphol Airport in stead of on its way to the airport as is shown in fig. 27. A deferred defect however only keeps the aircraft on the ground when it runs into a route restrictions or a deadline for repair. This is illustrated in fig. 28 where the deferred defect is discovered upon its first return at AMS. There is no restriction for the subsequent flight. The following flight however has a no-go restriction leaving the aircraft on the ground for repair if no action is taken. At this point, it should be checked what the available decision variables are for recovery treating the deferred defect as a no-go.

By incorporating the propagation of the disruption it can be determined whether the deadlines set for the different deferred defects are feasible. It enables a trade-off by taking the delay for repair now or to postpone the delay until the first available maintenance slot. For the deferred defect, it is therefore checked what the subsequent scheduled flights are and whether there is a maintenance slot available for repair. If one of the scheduled flights has a route restrictions or it hits the deadline without an available maintenance slot, it is treated as a no-go defect. A comparison should be made between the cost of incurring the disruption now or later. It might be cheaper to incur the delay now as this flight is cheaper to delay instead of delaying the no-go flight. The different flexibility parameters are discussed in § 5.3.3.

5.3.3 Flexibility parameters

This section will discuss how flexibility can be determined in the schedule. The base line involves doing nothing, i.e., delaying the flight and all subsequent flights until the scheduled slack is sufficient to get back on schedule. The previous paragraph 5.3.1 has shown the lead-time (L_b) and the associated costs (C_b), which are the lead-time and costs for delaying the flight. The costs for a delay are based on the costs in the TFM-tool which involve: 1) the service recovery costs, 2) the costs for rebooking passengers, 3) the future value costs of delay passengers, 4) the future value for no-connecting passengers.

The flexibility in the schedule, i.e., the available decision variables, is determined as follows:

- t_{flex} is the time available for recovery. This is a maximization of the time gained with a swap (t_s), the time a spare is available (t_s), the time maintenance can be shortened (t_m) and the time created by cancelling the subsequent flight (t_c). Per flight is checked which recovery options are available and what the maximum available time is for recovery, i.e., $t_{flex} = \max(t_s, t_m, t_r, t_c)$.
- C_i is the cost for the recovery, which is a cost minimization of the available recovery options, i.e., the cost for a swap (C_s), shortened maintenance (C_m), a spare aircraft (C_r) and cancellation (C_c). These costs are based on the TFM-tool or expressed in hours and need to be multiplied with the recovery times, i.e., $C_i = \min(C_s * t_i, C_m * t_m, C_r * t_r, C_{cf})$ where t_i is the time of the disruption and f the flight number of the effected flight.
- The C_i should be compared with the C_b ,i.e., the cost of delaying the flight, to determine whether the SOC should take action or do nothing, while taking into account the lead-time of the disruption (L). In addition, a predetermined flexibility budget (C_{max}) can be set in order to determine for each of the MEL-items whether this disruption can be dealt with within the flexibility time and budget, i.e., $t_i < t_{flex}$ and $C_i < C_{max}$.

The data structure in § 5.2.2 enables to determine the repair lead-time of defects. Based on this distribution it can be determined whether the disruptions can be resolved within the C_{max}, i.e., $C_i * t_{flex} < C_{max}$. In addition, the standard deviation of the distribution indicates the preference in flexibility time distribution, e.g. if the average lead-time is 2 hours with a standard deviation of 0.001, the added value of swaps that gain 2 hours is a lot higher compared to a standard deviation of 2.

The costs should be set such that the order of preference in using the decision variable should be taken into account, i.e., a swap should be cheapest and a cancellation the most expensive. A distinction can be made between the costs in the scheduling phase and the DoO. In this case consider the costs incurred at the DoO when that decision variable is used. The costs structure can be in line with the sanction structure used in OPiuM. Using such a cost structure enables to anticipate the decision at the DoO and what would be chosen in case the first decision variable is not available indicating the added value of an additional decision variable. Furthermore, it is in line with the performance measures of KLM as the focus is on achieving the KPIs. The cost of the different parameters consists of the following elements.

- The costs of a swap are zero when known a few hours in advance as nothing changes. Last minute swaps however involve organizational costs just as changing gates for either the aircraft and/or the passengers.
- The costs of a spare aircraft are the variable costs incurred for using the spare aircraft at the DoO.
- The costs for shortening a maintenance slot involve the costs of the resources to execute the maintenance.
- The costs for a cancellation are based on the costs in the TFM-tool and involve: 1) the KLM rebook costs for economy passengers, 2) the KLM rebook costs for business passengers, 3) the rebook costs to other airlines, 4) the service recovery costs, 5) future value costs.

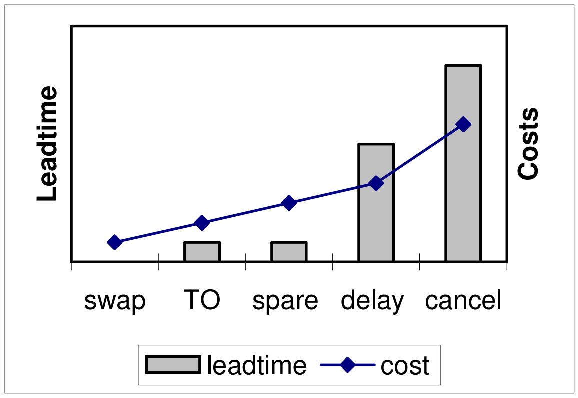
The time available for recovery of the disruption is determined as follows:

- The time related to a swap (t_s) is based on the available aircrafts upon arrival of the specified flight and the time of departure of the subsequent flights, i.e., the possible swap options for the specified. The more time between arrival time (t_{sta}) and the departure time (t_{std}) of a possible swap the more time is available to resolve the disruption on the aircraft. So $t_s = t_{std}$-t_{sta} for the available swaps. The preferable swap is the one where the time of the disruption (t_i) is closest to t_s.
- The time related to a spare aircraft (t_r) is equal to the hours a spare aircraft is scheduled.
- The time related to shortening maintenance is equal to the available TO-slot, which are the spare maintenance slots.
- The time for a cancellation (t_c) is equal to the duration of the cancelled flight.

The lead-time (L) is the time it takes to get back on schedule again and is therefore dependent on the disruption and action taken. It can be determined as follows:

- In case of a swap, which does not effect the remainder of the schedule, the L_s is zero as everything still flies on schedule.
- In case a spare TO-slot is used the lead-time is equal to the duration of the disruption.
- In case of spare aircraft, the L_r is equal to the duration of the disruption. As soon as the disrupted aircraft is back in operation they are back on schedule again.
- In case of a cancelled flight, the lead-time is equal to the duration of the cancelled flight after which everything is back on schedule.

A trade-off is enabled by setting the value of the different parameters. This provides an overview of the cost of the different decision variables and the associated lead-times. Figure 29 gives an indication of the expected trade-off between cost and lead-time in case of a no-go of 1 hour and 6 hours. This shows the different considerations. When the lead-time of the disruption is limited, swapping an aircraft is preferable. However with the increase in duration of the disruption a cancellation might be preferable to limit the propagation of the disruption. With a disruption of 6 hours, it is difficult to find a swap that creates 6 hours of ground time. Therefore it often goes together with a delay. This is represented by the lead-time in the right figure.



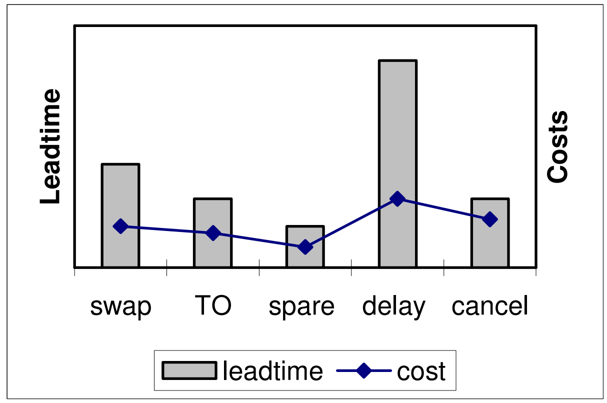


Figure 29. Expected lead-time cost trade-off with a disruption of 1 hour and 6 hours
Note: TO represents the shorten maintenance decision variable

Often a disruption results in a combination of recovery actions, e.g. a swap is executed in combination with a delay to prevent further delays. In this case the cost and lead-time is a summation of the decision variables used.

5.3.4 Limitations

The presented anticipation function considers an aircraft with a disruption and the flexibility options.

- Further research is required to incorporate the effect of a combination of disruptions in the fleet and the required flexibility.
- The assumption is made that a deferred defect results in a no-go defect when it hits a restricted flight. Apart from that, it does not take into account the limited flexibility to swap with another aircraft.
- As the tail assignment is done three days ahead, only for those three days can be checked whether the aircraft flies to a restricted destination.
- It is assumed that TO slots are spare maintenance, which can be used in case of a disruption. It can however be scheduled maintenance upon the DoO.

5.3.5 Applicability of the anticipation function

The anticipation function provides the link between the top – and the base level, which enables the top level to anticipate upon the base level. The discussion in § 3.1 has illustrated how the distributed decision making framework fits the scheduling process at KLM (fig. 30). This section will discuss how the presented anticipation model contributes to this coordination process.

- *Day of Operations (DoO):* This anticipation function indicates the available flexibility at the DoO and to what extent it can deal with disruptions. It illustrates the effect of an increase in technical – and scheduling restrictions and to what extent the front office is capable of dealing with these restrictions within a set budget. By modeling the propagation of the disruptions, it enables more proactive behavior allowing the front office to see the consequences of today's decision

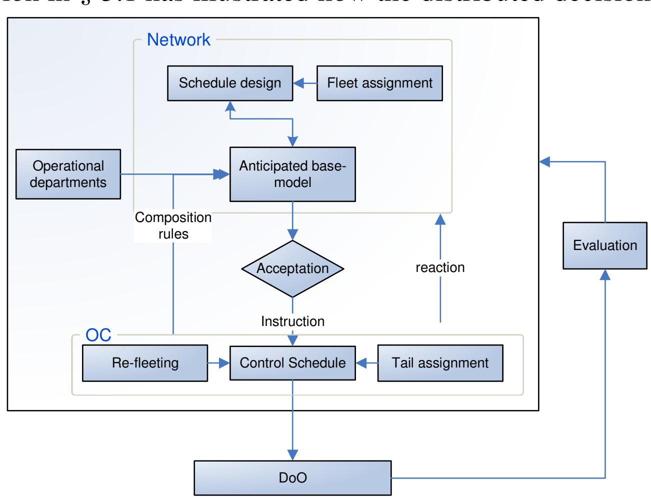


Figure 30. The Scheduling process

on subsequent days.

- *Operation Control (OC):* The OC can consider the trade-off between the effect of technical – and scheduling restrictions. Regarding the technical restrictions, it can question the repair lead-time of the different MEL-items and indicate their operational feasibility. The model enables to determine whether increased flexibility is required in the schedule or the lead-time of deferred defects needs to be reduced. Furthermore, it can control the flexibility in the schedule based on the set flexibility budget.
- *Network:* The model enables Network to anticipate upon the required flexibility in the schedule. When a flexibility budget is set, it can be determined whether the OP has sufficient slack and decision variables to fulfill stay within this budget.

6. Conclusion and Recommendations

This chapter will discuss the conclusions which can be drawn from the discussion in the preceding chapters. First, the major findings in the theoretical and practical analysis are discussed in § 6.1. Second, the major findings in the design phase and its contribution to the project assignment are presented in § 6.2. Third, recommendations and suggestions for further research are suggested in § 6.3.

6.1 Conclusions from the analysis phase

The literature review provided insights regarding the applicability of distributed decision making in the airline scheduling context. Due to the sheer size and complexity of the airline scheduling problem a decomposition of the process is suggested. This project was the first in applying the distributed decision making framework to the airline scheduling process with schedule design at the top-level and the operation control at the base-level. This provided insight into the importance of an anticipated base level, which established the link between the top – and base level. Furthermore, the literature review discussed the objectives for a robust schedule. This requires both flexibility and stability, i.e., the number of recovery options in the schedule and limiting the probability for a disruption to spread through the schedule.

The analysis of the scheduling process at KLM indicated the applicability of distributed decision making with the importance of an improved anticipation function. Further analysis on the current performance highlighted the impact of technical defects and operations control. These disruptions can be translated into technical – and scheduling restrictions which limit the flexibility at the DoO. Flexibility is identified by the different decision variables in the schedule. During the design phase, further insight needs to be gained on the propagation of the disruptions and the added value of flexibility.

6.2 Conclusion from the design phase

The design involves both 1) a data structure to establish the link between a defect and KPIs and 2) a cost function which shows the added value of flexibility or the cost of limited flexibility.

The data-structure categorizes the defects with their restrictions and relates their repair lead-time to the available ground time to determine whether a defect results in a disruption with operational consequences. These disruptions arrive at the SOC, who has to resolve the disruption with the decision variables available. By indicating to what extent their options are restricted and linking the chosen option to the KPIs, the effect of technical restrictions can be quantified. In addition, the data enable to elaborate on the suggested anticipation function.

The anticipation function considers the amount of flexibility in the schedule and assumes a disruption on an aircraft, i.e., either late arrival, no-go defect or deferred defect. It determines the cost of 'doing nothing' ,i.e., delaying the flight and consecutive flights, with the associated lead-time, i.e. the time it takes to get back on schedule. This is regarded as the base line and compared with the cost and lead-time of the different decision variables. This shows the cost of dealing with disruptions with given a certain amount of flexibility. By modeling the propagation of the disruption with the associated cost a time-cost trade-off is enabled. This is in line with the robust scheduling literature which indicates that flexibility and stability is required for robust scheduling. This model considers flexibility through the number of available recovery options and by incorporating the propagation of the disruption it determines the stability of the schedule. The trade-off between expediting time and additional cost is similar to crashing a project in project management. Where there are various ways to shorten the lead-time of the project with the associated costs, e.g. through hiring additional resources or cancelling activities. This can be related to the use of the different decision variables in airline operations.

Robust scheduling does not involve being able to deal with all disruptions, such as severe weather. Based on a flexibility budget, the number of disruptions that can be dealt with at the DoO is determined. By incorporating the propagation of the disruption,the pro-active behavior is enabled as it provides insight into the consequences of the use of decision variables. This enables a trade-off between the reduction of the repair lead-time (or deadline in MEL) and additional flexibility, i.e., limiting scheduling restrictions.

In retrospect, the project assignment involved the development of an anticipation function to optimize the flexibility at the DoO and minimize the effect of disruptions. The anticipation function establishes a link between the top – and base level of the distributed decision making framework for airline scheduling. The designed model anticipates upon the required flexibility in the schedule to deal with the restrictions at hand. On the other hand, the choice can be made to reduce these restrictions on the DoO to keep the schedule operationally feasible. The implementation of the model enables to indicate the major restrictions in the schedule, which can be acted upon. This provides an optimization in flexibility, which minimizes the effect of disruptions.

6.3 Recommendations and suggestions for further research

6.3.1 Recommendations for implementations

The data structure and anticipation function are suggested concepts which require further validation for implementation. The presented data structure is based on discussions with the SOCs and the technical specialists and the anticipation function is based on robust – and project scheduling literature.

The implementation of the data structure enables to determine the effect of technical restrictions. In order to do so, it is recommended to first align the technical restrictions 'list' at the different departments. This can be realized by providing an updated route matrix that incorporates all technical restrictions as stated in the MEL+ for the ICA fleet. The tailrouter is operated in *Flash* and therefore accessible for the different departments before the DoO. Through the implementation of tailrouter in Planboard, the DoO gains insight in the technical restrictions in the fleet. This in addition illustrates the propagation of swapping an aircraft allowing for more proactive behavior at the DoO. Having determined the appropriate list of technical restrictions, a test phase is required to determine whether the data-structure needs to be elaborated upon. As is suggested in § 5.2.2 most data regarding defects is already recorded but requires restructuring, which might involve minor changes in the current data set. By recording the suggested data structure for several weeks it can be determined, how to restructure the current data set of technical services.

The data structure for the SOC however requires more structural change as they currently do not to provide argumentation for the use of the different decision variables. It is therefore expected to lead to more resistance during the implementation as it will result in additional workload and the perception of loss in control. Therefore during the test phase someone should join the SOC to record the data. This provides the opportunity to gain the understanding and support of the SOC for the implementation of the data structure. Apart from that, this will provide an objective result and enables to determine whether the data structure needs to be elaborated. In addition, the most efficient way to record the data should be determined to limit the additional workload for the SOC in the end. During the test phase the costs and benefits of the implementation should be determined.

For the implementation of the anticipation function further validation and elaboration is required. The concept of a time-cost trade-off to expedite time from the future is a well-known concept in project management. This project has shown that a similar trade-off is made in the disruption management of airline operations. Further research is required to implement the concept and elaborate upon this. Several limitations were mentioned in § 5.3.4, which need to be taking in to account for further research such as the effect of a combination of disruptions on the flexibility. In addition, a deferred defect is now considered as a no-go when it hits a route restriction or deadline, while limited swap options are not incorporated, which requires further research. The implementation of the data structure can provide more insight regarding the effect of technical restrictions and what needs to be taken into consideration in the anticipation function. Further research should determine the appropriate software program to develop the anticipation function in and how to relate it to *Flash* and the technical services database on defects.

6.3.2 Suggestions for further research

This project is the first in relating project scheduling to airline operations. Further research is required to elaborate upon the proposed concept and to determine the link between project scheduling and airline operations and specifically operational flexibility.

This project has focused on the aircraft availability process and therefore on the technical and scheduling restrictions. Other resources that effect the dispunctuality and completion factor are crew and ground services. Further research should consider to include these aspects in the model.

Apart from that, this project only considered the operational impact of technical restrictions. Further research at E&M is required to consider the feasibility of lead-time reduction of the (deferred) defects in terms of hangar capacity, manpower and (maintenance) ground time.

7. *References*

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8. Appendices

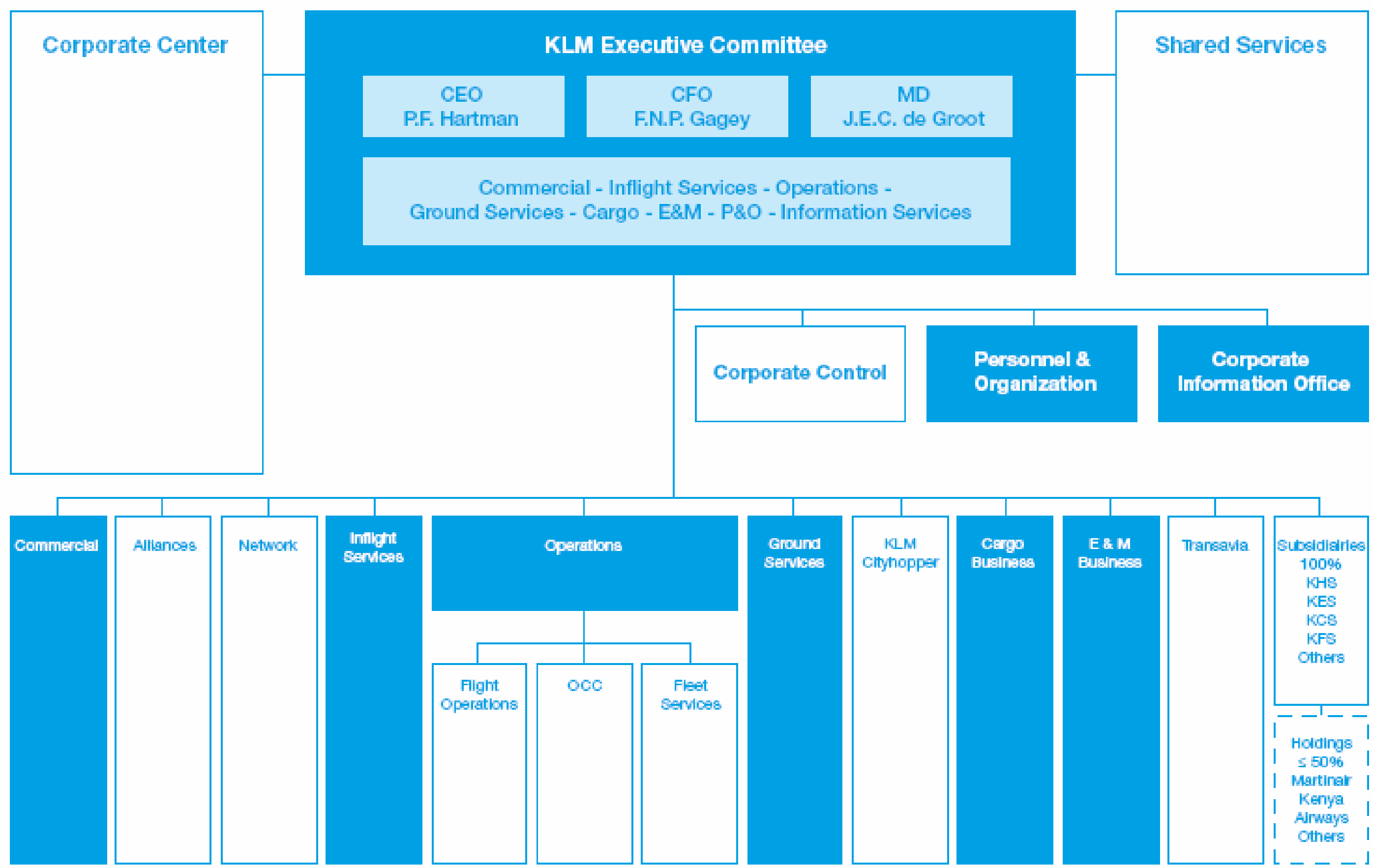
Appendix A. List of abbreviations[2]

AA	Aircraft availability
AAM	Aircraft assignment model
AC	Aircraft
AMS	Amsterdam airport
APU	Auxiliary power unit
ARM	Aircraft rotation model
BOP	Basic operating philosophy
CAT	Category
Cb	Cost of base function
Cc	Cost of a cancellation
C_d	Cost of a delay
CDL	Configuration deviation list
CDM	Collaborative decision making
C_m	Cost of shortening maintenance
Cmax	Flexibility budget
C_r	Cost of a spare aircraft
C_s	Cost of swapping a flight
d	Delay
DDM	Distributed decision making
DELPRO	Delta profit method
DMM	Duty maintenance manager
DoO	Day of operations
DV	Decision variable
E&M	Aircraft maintenance division
ETOPS	Extended-range twin-engine operational performance standards,
EUR	Europe
f	Flight number
FAP	Fleet assignment problem
GT	Ground time
ICA	Inter continental
KPI	Key performance indicators
L_b	Lead-time of disruption when 'doing nothing'
L_c	Lead-time of the disruption when a flight is cancelled
L_d	Lead-time of the disruption when the decision variable delay is used
L_m	Lead-time of the disruption when maintenance is shortened

[2] Apart from the reason codes for cancellation, which can be found in appendix F.

L_r	Lead-time of the disruption when a spare aircraft is used
L_s	Lead-time of the disruption when the flight is swapped
MEL	Minimum equipment list
MMEL	Master minimum equipment list
n	number of delayed flights
OC	Operations control
OCC	Operations control centre
OP	Operational plan
OPiuM	Operational management in operation
OUT	Out station
P	Probability
P_s	Probability to swap flight based on the schedule
P_t	Probability to swap flight based on the technical state of the fleet
SLA	Service level agreement
SOC	senior operation controller
t_c	Time created by cancelling a flight
TD	Technical services (Technische dienst)
t_d	Time of delay
t_{flex}	Available time to resolve a disruption
TFM	Traffic flow management
t_i	Duration of the disruption
t_m	Time maintenance can be shortened
TO	spare maintenance
t_r	Time a spare is available
t_s	Time available to swap
TSV	Technical condition of the fleet

Appendix B. Organizational structure KLM Group



Appendix C. Preliminary cause and effect tree

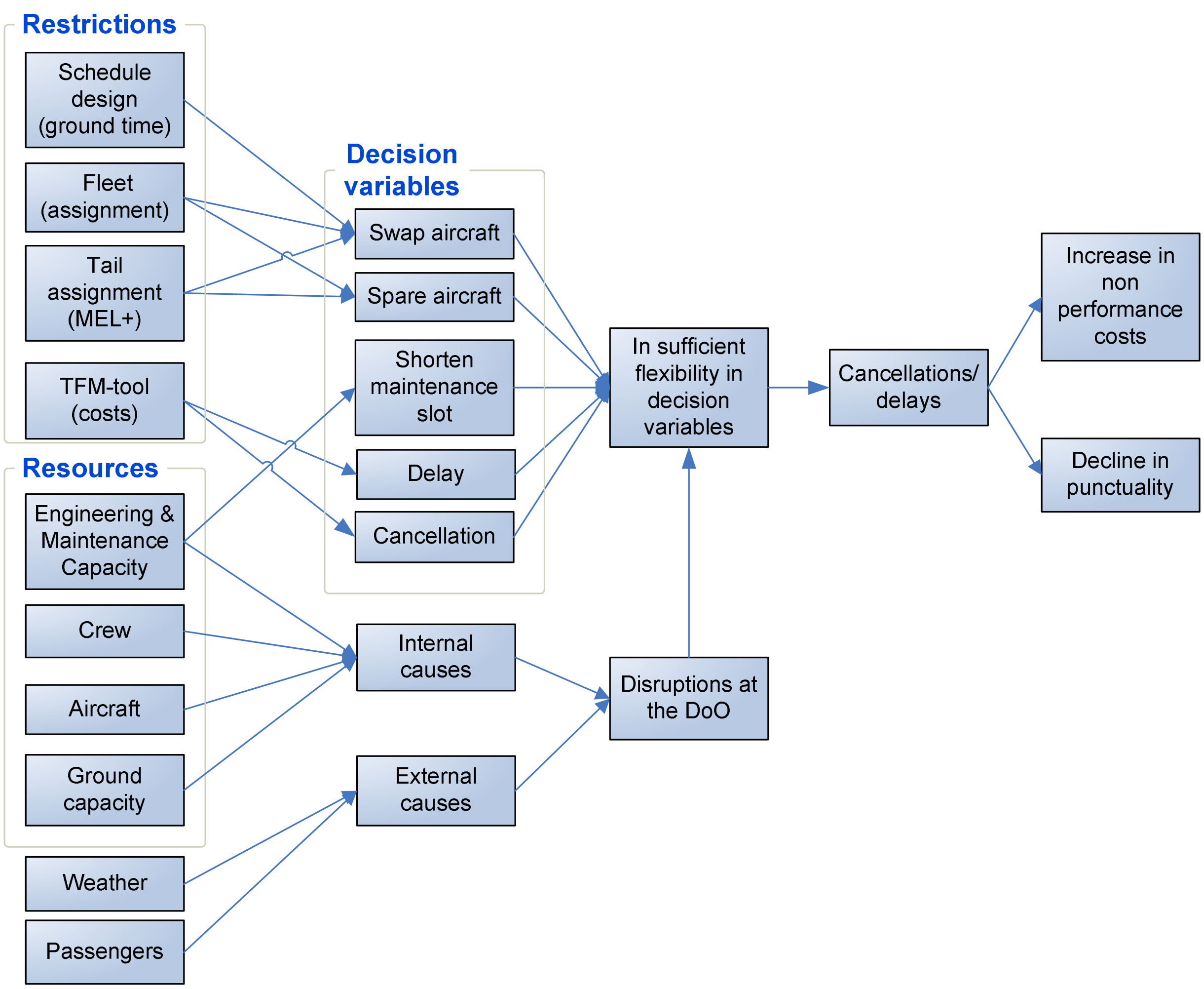


Figure 31. Preliminary cause and effect tree

Appendix D. Conceptual project design

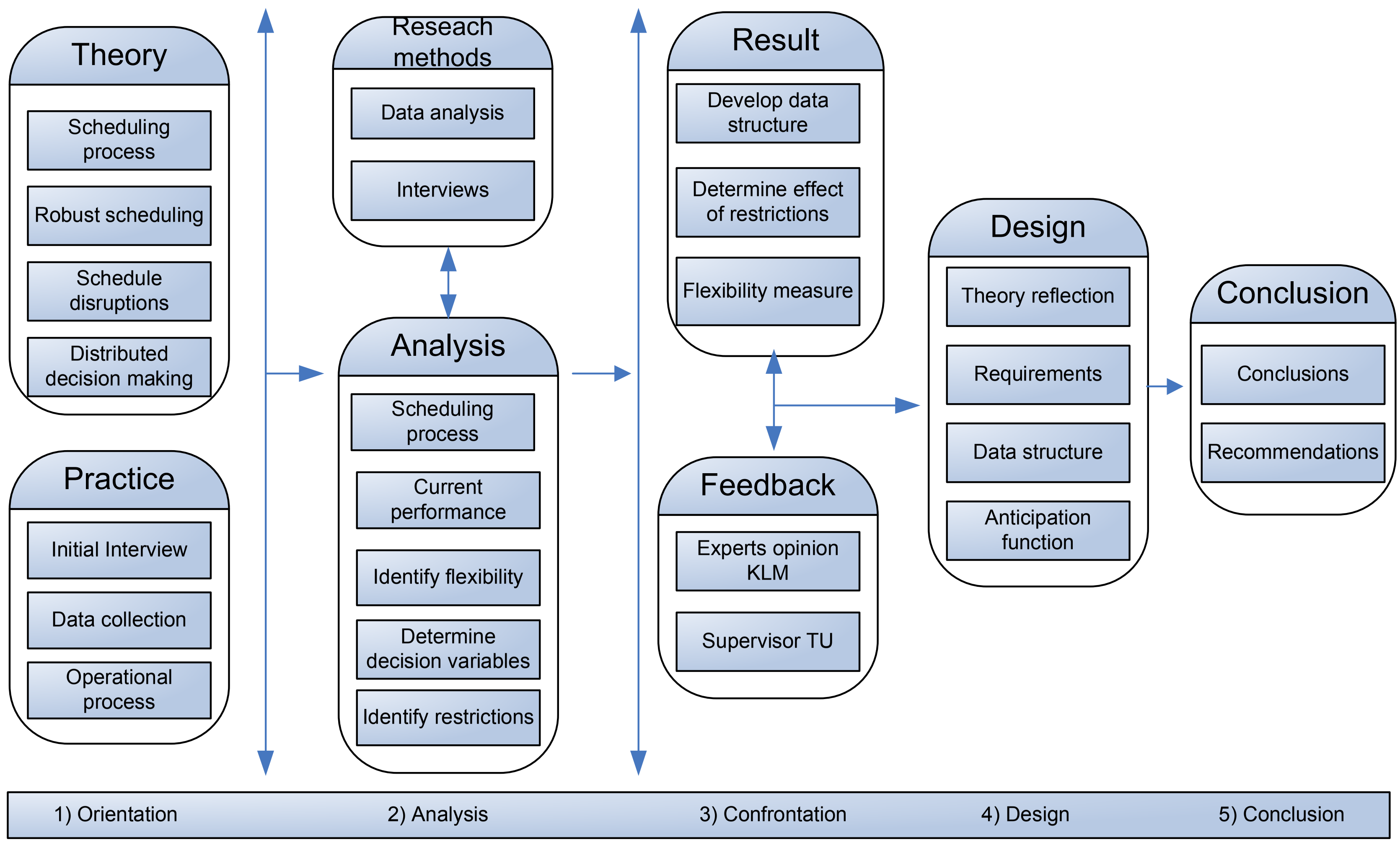


Figure 32. Conceptual project design

Appendix E. The effect of technical restrictions on decision variables

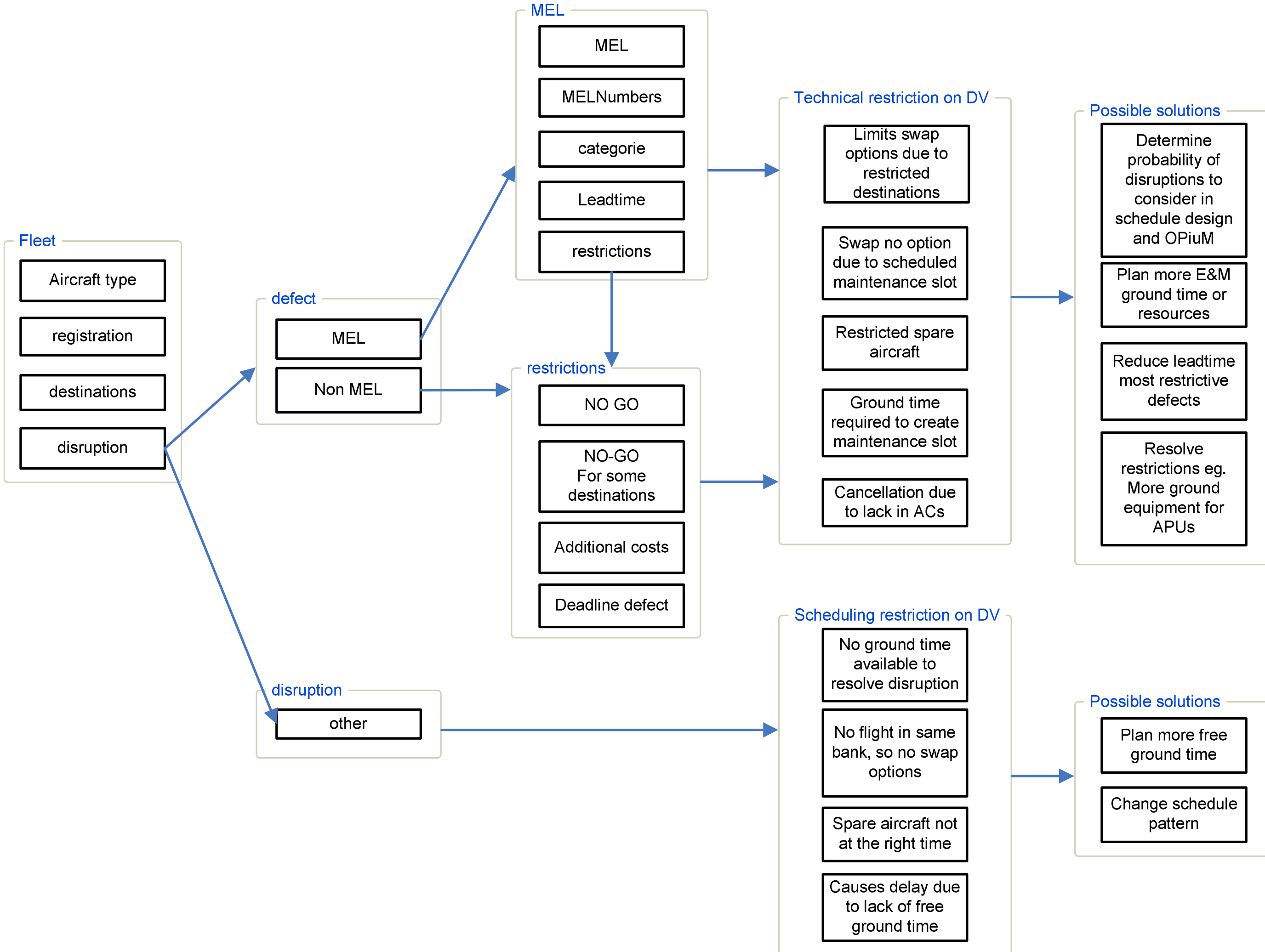
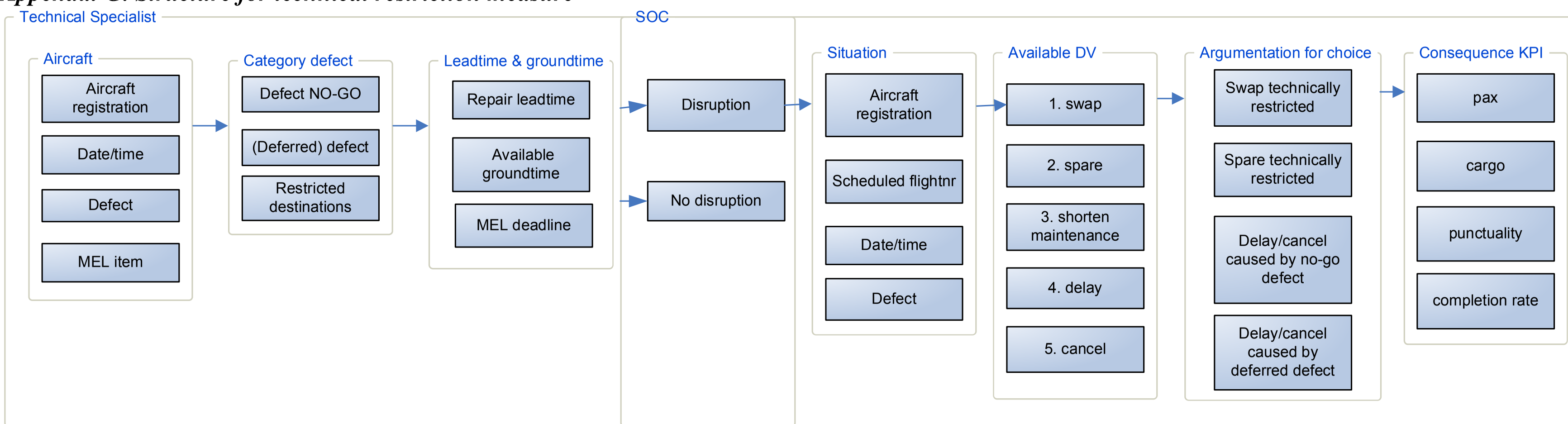


Figure 33. The effect of restrictions on decision variables

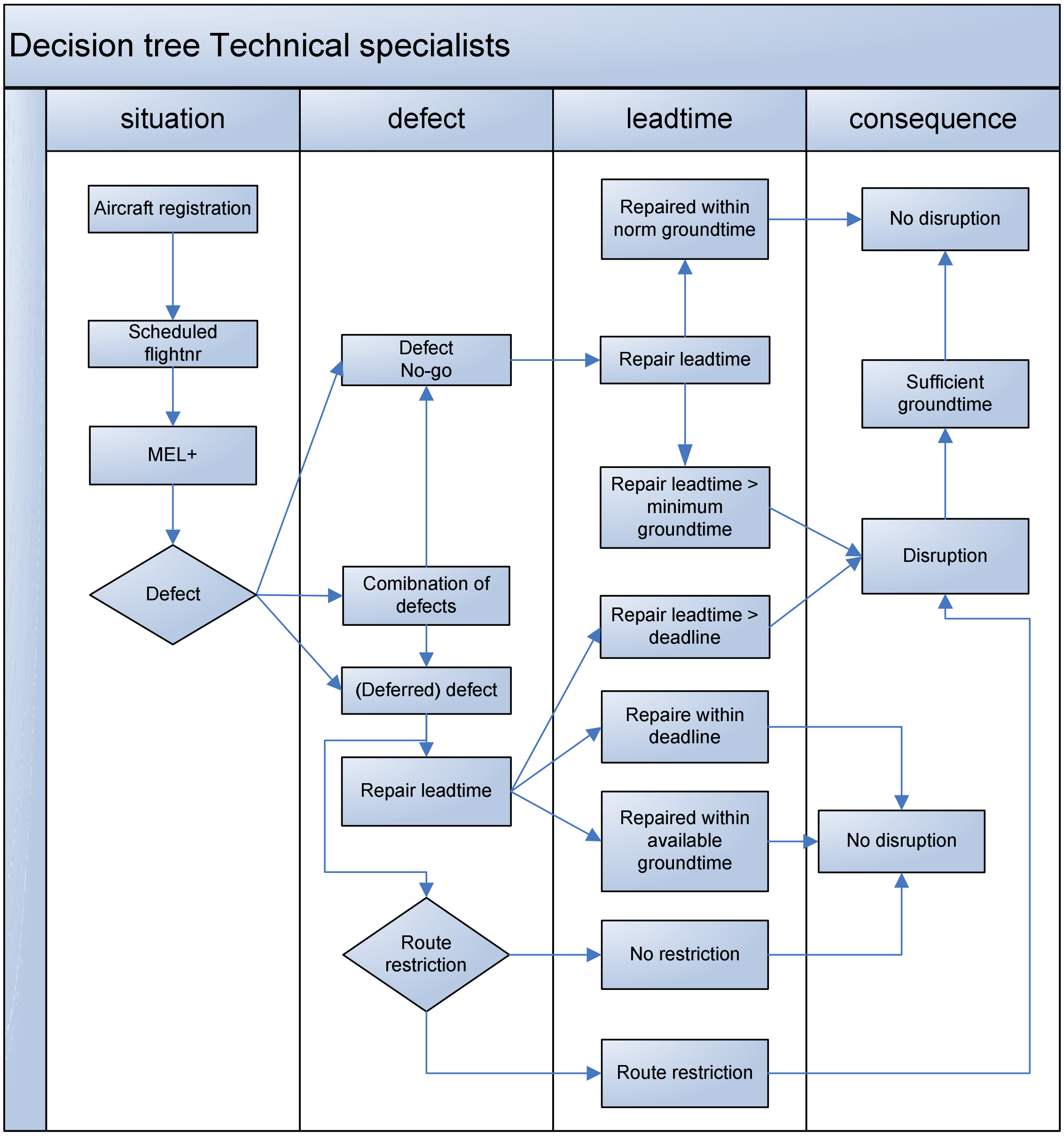
Appendix F. Reason codes for cancellations

Dept	Reason Code	Blame	Description of Reason
Fleet Maintenance	TI	OTH	No aircraft available due to technical reasons
	CI	OTH	Consequences of no aircraft available due to technical reasons
	TU	OTH	Exceeding technical maintenance (internal TD, incl. test flight)
	CU	OTH	Consequences of exceeding technical maintenance (internal TD, incl. test flight)
	OO	ARL	Maintenance optimization (protection FA Check)
	ES	OTH	External damage (pre-flight and in flight)
	CS	OTH	Consequences of external damage (pre-flight and in flight)
Crew	CR	ARL	Cabin crew, medical urgency, unruly pax
	CB	ARL	Consequences of cabin crew, medical urgency, unruly pax
	CC	ARL	Cockpit crew (incl. training-, position-, ferry-, demo and delivery flights)
	CP	ARL	Consequences of cockpit crew (incl. training-, position-, ferry-, demo and delivery flights)
ATC	WE	OTH	Weather/ATC-problems
	CW	OTH	Consequences of weather/ATC-problems
	VP	OTH	Strike, Runway closure, Political situation, Eruption
Commercial	CM	ARL	Commercial change, incl. cost saving reasons, extra flights and lease/hire
	CO	ARL	Consequences of commercial change, incl. cost savings, extra flights and lease/hire
	FE	ARL	Commercial change due to special days (Christmas, football games and other events)
	FC	ARL	Consequences of commercial change due to special days (incl. change-over, consequences changes schedule and configuration change)
	PE	ARL	Commercial change due to prognosis
	LR	ARL	Systematic commercial/operational changes
	LC	ARL	Consequences systematic commercial/operational changes
Network	ER	OTH	Late arrival (reduce chain effects)
	EC	OTH	Consequences of late arrival
Consequences	GW	OTH	Resulting aircraft change (incl. readjusting the fleet)

Appendix G. Structure for technical restriction measure



Appendix H. Decision tree for Technical Specialists



Appendix I. Decision tree for Senior Operation Controller