Architectural Design of a Future Flight Management System Supporting 4D Trajectories

Architektonisches Design eines zukünftigen Flugmanagementsystems zur Unterstützung von 4D Trajektorien

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Für meinen Vater

Abstract

While worldwide air traffic keeps growing, the involved stakeholders, especially aircraft operators, are faced with several challenges. Ecological goals are imposed by governments and society, fierce competition demands increasing efficiency to stay profitable and passengers expect a raise in quality of service. Additionally, the growth of air traffic pushes the capacities of airspace and airports to its limits. Initiatives put into work by nations and unions are developing and implementing operational concepts and supporting technology to overcome these issues. An enabling concept to increase capacity are Trajectory Based Operations, which are only supported to a limited extent by traditional Flight Management Systems.

This thesis contributes a possible system architecture of a Trajectory Execution and Optimization System, that is intended to replace traditional Flight Management Systems. The proposed architecture supports planned future flight operations and, at the same time, allows airlines to increase their overall operational efficiency. This is achieved by redistributing functionality of the traditional Flight Management System onto an Operationally Approved device and a certified system. The certified system, labeled CoreFMS, is responsible for executing trajectories, while trajectory planning and optimization functions reside on the Operationally Approved device. A fileserver onboard the aircraft connects the two entities, where the fileserver additionally is connected to the airline's operations center. Means of establishing safe and secure connections between the two entities were developed in this thesis, as well as an assessment of the system's certifiability. In order to showcase the benefits of the proposed architecture, a demonstrator was developed and implemented into a research flight simulator at TU Darmstadt.

A usability study was conducted to evaluate the applicability of the proposed system architecture. Commercially rated pilots conducted a task comprising of route planning and activation, using both the system demonstrator as well as a traditional Flight Management System in the research flight simulator. The results of the trials point to a confirmation of the usability of the architecture. Compared to the traditional Flight Management System the Trajectory Execution and Optimization System received higher usability ratings. The participants experience of working with the traditional Flight Management System varied.

A trajectory optimization algorithm, intended to be deployed on the Operationally Approved device, was developed and evaluated. While the evaluation proved the feasibility of a trajectory optimization imposed with time constraints, the need for precise constraint determination was shown by a considerable amount of unsuccessful optimizations. Also, high computation times call for a target hardware and computation speed oriented implementation of such algorithms.

Kurzfassung

Einhergehend mit dem weltweiten Wachstum des Luftverkehrs werden seine Akteure, insbesondere die Betreiber von Flugzeugen, mit Herausforderungen konfrontiert. Zum einen fordern Politik und Gesellschaft die Einhaltung ökologischer Ziele, zum anderen erfordert heftige Konkurrenz eine ständige Steigerung der Effizienz, um profitabel zu bleiben. Zusätzlich erwarten Passagiere eine steigende Servicequalität. Der Wachstum des Luftverkehrs lässt zudem die Kapazitäten des Luftraumes und von Flughäfen an ihre Grenzen stoßen. Verschiedene Nationen und Staatengemeinschaften haben Initiativen gegründet, welche an operationellen Konzepten und unterstützender Technologie arbeiten, um die genannten Herausforderungen zu meistern. Ein Eckpfeiler der Kapazitätserhöhung sind Trajektorien basierte Operationen, welche von heutigen Flugmanagement System nur begrenzt unterstützt werden.

Diese Dissertation trägt mit der Entwicklung und Validierung der Architektur eines Trajektorien Durchführungs- und Optimierungssystems dazu bei, heutige Flugmanagementsysteme zu ersetzen. Die vorgeschlagene Architektur unterstützt zukünftige Operationen und erlaubt es Fluggesellschaften zusätzlich ihre betriebliche Effizienz zu erhöhen. Dies wird durch die Neuverteilung der Funktionen traditioneller Flugmanagementsysteme auf ein betriebsgenehmigtes Gerät sowie ein zertifiziertes System erreicht. Während das zertifizierte System für das sichere Abfliegen von Trajektorien verantwortlich ist, werden Planungs- und Optimierungsaufgaben auf dem betriebsgenehmigten Gerät durchgeführt. Ein an Bord befindlicher Datenserver verbindet die beiden Geräte, wobei der Datenserver zusätzlich mit einer Verbindung zur Zentrale der Fluggesellschaft ausgestattet ist. Neben der Bewertung der Zertifizierbarkeit eines solchen Systems wurde für diese Arbeit eine sichere Schnittstelle zum Verbinden der Geräte eingeführt. Ein Systemdemonstrator wurde entwickelt und in den Forschungsflugsimulator der TU Darmstadt integriert.

Um die Einsetzbarkeit der vorgeschlagenen Architektur zu bewerten, wurde eine Studie zur Gebrauchstauglichkeit durchgeführt. Berufspiloten haben in der Studie eine Aufgabe zur Trajektorienplanung und Aktivierung jeweils auf dem vorgeschlagenem System und einem heutigen Flugmanagementsystem durchgeführt. Die Ergebnisse der Studie deuten auf den Nachweis der Gebrauchstauglichkeit der vorgeschlagenen Systemarchitektur hin. Im Vergleich zum Flugmanagementsystem erzielte das Trajektorien Durchführungs- und Optimierungssystem eine bessere

Bewertung der Gebrauchstauglichkeit, wobei aber die Erfahrung der Studienteilnehmer auf dem benutzten Flugmanagementsystem variierte.

Zusätzlich zur Studie der Gebrauchstauglichkeit wurde ein Algorithmus zur Trajektorienoptimierung entwickelt und evaluiert, welcher auf dem Electronic Flight Bag eingesetzt werden soll, um die Vorteile der vorgeschlagenen Architektur herauszustellen. Die Evaluierung zeigt die generelle Machbarkeit der Optimierung einer mit Zeitvorgaben belegten Trajektorie. Dabei belegt eine beachtliche Anzahl erfolgloser Optimierungen jedoch die Notwendigkeit einer präzisen Berechnung der Zeitvorgaben. Auf Grund hoher Rechenzeiten wird eine auf die Zielhardware und Rechenzeit optimierte Implementierung derartiger Algorithmen empfohlen.

Contents

Nomenclature

Symbols

Notation	Description	Unit
C	Leg Center Point	$[\lambda, \varphi]$
CI	Cost Index	$[lbs/h]$
C_F	Fuel Cost	$[\$/lbs]$
C_T	Time Cost	$[\$/h]$
$I_{ControlValue}$	Integral part of $\Delta\psi_{course}$	$[-]$
M	Mach Number	$[-]$
$M_{MAXRANGE}$	Maximum Range Cruise Mach Number	$[-]$
M_{MO}	Maximum Operating Mach Number	$[-]$
$R_{\oplus}$	Earth Radius	$[m]$
T	UTC Time	[hh:ss]
T_{actual}	Present Time	[hh:ss]
T_{RTA}	Time of time constraint	[hh:ss]
V	Speed	[m/s]
$V_{Command}$	Speed Command send to the autopilot	[m/s]
$V_{GS_{i-1}}$	Groundspeed at waypoint WP_{i-1}	[m/s]
V_{max}	Maximum speed allowed per BADA	[m/s]
V_{min}	Minimum speed allowed per BADA	[m/s]
V_{TAS}	True Air Speed	[m/s]
$V_{TAS,horizontal}$	Horizontal componen of True Air Speed	[m/s]
V_{Wind}	Wind speed in aircraft axial direction	[m/s]
$\overrightarrow{XTE}_{memory}$	Cross Track Error Memory	$[-]$
d	Distance	$[m]$
d_{i-1}	Distance from WP_{i-1} to blending point	$[m]$
d_m	Half distance of a leg	$[m]$
d_{total}	Overall leg distance	$[m]$
h	Altitude	$[m]$
h_{MO}	Maximum Operating Altitude	$[m]$
k_{acc}	Acceleration Gain parameter	$[-]$

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Notation	Description	
k_i	Gain Parameter of integral controller part	$[-]$
k_p	Gain Parameter of proportional controller part	$[-]$
t	Time	$[s]$
$t_{available}$	Available time until time constraint	$[s]$
t_{i-1}	Time from WP_{i-1} to blending point	$[s]$
$t_{RTA,i}$	Time from beginning of flight to waypoint i	$[s]$
$t_{RTA,i-1}$	Time from beginning of flight to waypoint i-1	$[s]$
r	Leg Radius	$[m]$
$\Delta\psi_{course}$	Commanded deviation from leg course	[degree]
$\Delta\psi_{Intercept,max}$	Maximum Angle to intercept leg heading	[degree]
λ	Latitude	[degree]
λ_m	Latitude of leg midpoint	[degree]
μ	Mean	$[-]$
ρ_0	Standard sea level air density	$\left[kg/m^3\right]$
ρ_{Air}	Surrounding air density	$\left[kg/m^3\right]$
σ	Standard Deviation	$[-]$
φ	Longitude	[degree]
φ_m	Longitude of leg midpoint	[degree]
ψ	Heading	[degree]
ψ_{target}	Target heading commanded to the autopilot	[degree]

Acronyms

ACARS	Aircraft Communications Addressing and Reporting System
ADC	Air Data Computer
ADN	Aircraft Data Network
AFDS	Autopilot and Flight Director System
AFDX	Avionics Full-Duplex Switched Ethernet
AID	Aircraft Interface Device
AIP	Aeronautical Information Publication
AIRAC	Aeronautical Information Regulation and Control
AIXM	Aeronautical Information Exchange Model
AMI	Airline Modifiable Information
ANSP	Air Navigation Service Provider
AOC	Airline Operations Center
API	Application Programming Interface
ARINC	Aeronautical Radio Incorporated
ARP	Aerospace Recommended Practice
ASA	Aircraft Safety Analysis
ATC	Air Traffic Control
ATM	Air Traffic Management
AWN	Aircraft Wireless Network
BADA	Base of Aircraft Data
CCA	Common Cause Analysis
CCD	Cursor Control Device
CDU	Control and Display Unit
CI	Cost Index
CMA	Common Mode Analysis
CMU	Communications Management Unit

COTS	Commercial off the Shelf
CPDLC	Controller-Pilot Data Link Communications
CPT	Captain
CPU	Central Processing Unit
CTA	Controlled Time of Arrival
CTO	Controlled Time of Overfly
D2D	Door2Door
D-AERO	Darmstadt Aircraft Environment for Research on Operations
DAL	Design Assurance Level
DME	Distance Measuring Equipment
EASA	European Aviation Safety Agency
ECAM	Electronic Centralized Aircraft Monitor
EFB	Electronic Flight Bag
EFIS	Electronic Flight Instrument System
EICAS	Engine Indication and Crew Alerting System
EIS	Entry Into Service
ELOC	Executable Line of Code
ETA	Estimated Time of Arrival
EUROCONTROL	European Organization for the Safety of Air Navigation
EWD	Engine and Warning Display
FAA	Federal Aviation Administration
FBW	Fly-by-Wire
FCC	Flight Control Computer
FCU	Flight Control Unit
FF-ICE	Flight and Flow Information for a Collaborative Environment
FHA	Functional Hazard Analysis
FIXM	Flight Information Exchange Model
FMC	Flight Management Computer

FMEA	Failure Mode and Effect Analysis
FMES	Failure Mode and Effect Summary
FMS	Flight Management System
FO	First Officer
FSR	Institute of Flight Systems and Automatic Control
FTA	Fault Tree Analysis
FWC	Flight Warning Computer
GNSS	Global Navigation Satellite System
GRIB	Gridded Binary
GS	Groundspeed
HF	High Frequency
HIRF	High Intensity Radiation Field
HMI	Human Machine Interface
i4D	Initial 4D
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
IMA	Integrated Modular Avionics
IP	Internet Protocol
IRU	Inertial Reference Unit
ISA	International Standard Atmosphere
KCCU	Keyboard Cursor Control Unit
LRU	Line Replaceable Unit
LSK	Line Select Key
MAC	Media Access Control
MCDU	Multipurpose Control and Display Unit
MCP	Mode Control Panel
MFD	Multi Function Display
MFK	Multi-Function Keypad
MTOM	Maximum Take Off Mass
NAA	National Aviation Authority
NAS	National Airspace System

NASA	National Aeronautics and Space Administration
Navaid	Navigational Aid
ND	Navigation Display
NextGen	Next Generation Air Transport System
NFZ	No Fly Zone
NOAA	National Oceanic and Atmospheric Administration
OEM	Original Equipment Manufacturer
ONS	Onboard Network System
OpsApproval	Operational Approval
OpsApproved	Operational Approved
OS	Operating System
PASA	Preliminary Aircraft Safety Assessment
PBN	Performance Based Navigation
PED	Portable Electronic Device
PFD	Primary Flight Display
PIN	Personal Identification Number
PSSA	Preliminary System Safety Assessment
RNAV	Random (Area) Navigation
RNP	Required Navigation Performance
ROC	Rate of Climb
RPK	Revenue Passenger Kilometer
RTA	Required Time of Arrival
RTAI	Real Time Application Interface
RTCA	Radio Technical Commission for Aeronautics
RTO	Rejected Take Off
RTOS	Real Time Operating System
SAE	Society of Automotive Engineers
SD	System Display
SDAC	System Data Acquisition Concentrator
SES	Single European Sky

SESAR	Single European Sky ATM Research Program
SESAR JU	SESAR Joint Undertaking
SFO	Senior First Office
SID	Standard Instrument Departure
SIGMET	Significant Meteorological Phenomena
SO	Second Officer
SOP	Standard Operating Procedure
SSA	System Safety Analysis
STAR	Standard Terminal Arrival Route
SUS	System Usability Scale
SWIM	Systemwide Information Management
TAS	True Airspeed
TBO	Trajectory Based Operations
TEOS	Trajectory Execution and Optimization System
TCC	Thrust Control Computer
TCP	Trajectory Change Point
TLX	Task Load Index
TOC	Top of Climb
TOD	Top of Descent
UAS	Unmanned Aerial System
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UI	User Interface
UTC	Universal Time Coordinated
VHF	Very High Frequency
VOR	VHF Omnidirectional Radio Range
WXXM	Weather Information Exchange Model
XML	Extensible Markup Language
XSD	XML Schema Definition
XTE	Cross Track Error

1 Introduction

According to the International Civil Aviation Organization (ICAO), the worldwide commercial air traffic measured in Revenue Passenger Kilometers (RPKs) will continue to grow at a rate of 4.5% each year until 2042 [Int16b], with the highest growth rate expected for Central South West Asia at 8.2%. While the growth rates are an economic boost [Int17; Fed16], they put pressure on all involved stakeholders to accommodate an increasing number of aircraft[1] into the airspace. Additionally, ecological goals are imposed in order to reduce emissions and noise [Eur11a]. To face these challenges, nations worldwide have formulated visions (as for example Flightpath 2050 by the European Commission [Eur11a]) and implemented programs to research and develop technical solutions to support those visions.

At the same time, aircraft operators are demanding support in their transformation into integrated airlines. The integrated airline optimizes its operations[2] by using connected services and software tools, which are driven by an increased amount of information available [Bar11], rather than the sequential approach used today [Pap09]. Integrated operations yield an improved efficiency and therefore cost savings [Pap09]. Part of the required information volume is sensor data being available in the aircraft domain only. To make this data available for optimization processes, novel technology is required onboard aircraft.

Advanced flight operation concepts are developed to increase the capacity of the airspace, namely Trajectory Based Operations (TBO) [SES15]. Amongst other equipment, TBO requires on board avionics[3] capable of executing four dimensional trajectories within specified constraints, such as advanced Flight Management Systems (FMSs).

Aircraft remain in service for twenty to thirty years [Jia13], using the same avionics. According to Smedt and Berz [SB07], traditional FMS support TBO only to a limited extent, which hinders the introduction of TBO. At the same time new air-

1 While RPKs are not a measurement for the amount of conducted flights, an increase of RPK indicates an increased number of conducted flights since aircraft seating capacity is limited.

2 Operations include: flight planning and execution, fleet planning, maintenance planning and execution and passenger services.

3 Avionics is a coinage derived from the words *AVIation eletrONICS* and describes key electronics embedded on aircraft and spacecraft, such as navigation and human-interface equipment [MSJ13].

craft models are introduced to market. TBO enabling technology is required to retrofit existing aircraft models as well as for new aircraft designs.

Retrofitting existing aircraft avionics with advanced technology faces the challenge of expensive and invaluable re-certification processes [Spi00]. Consequently, research was conducted in order to develop solutions to enable older aircraft for TBO without replacing their avionics. As an example, WESTPHAL [Wes14] developed a Trajectory Management System deployed on an Electronic Flight Bag (EFB), which computes speed commands in order to comply with time constraints.

An automated system for the process of trajectory optimization and execution is desirable, taking advantage of increased computation power available today e.g. on the EFB and the connectivity of such devices enabling the transmission of information. The development of new aircraft models offers the opportunity to introduce such avionics. Research on this topic is a valuable contribution to the goal of achieving capacity and emission targets as well as supporting airlines in their transformation towards integrated operations.

1.1 Aim of this Thesis

In order to contribute to the development process of avionics that support future needs, this thesis provides an architecture for an advanced FMS that is composed with respect to all aspects of future airline and flight operations. The architecture will integrate the EFB into the FMS compound in order to shift functionality from the FMS to the EFB, where utmost care is taken designing a safe and secure system. Accompanied by the development of a demonstrator and a herein executed evaluation of the architecture, it is intended to give scientific proof of the usability of systems developed based on the proposed system design. In addition, the thesis will show the benefits of including the EFB into the FMS architecture on the basis of an exemplary trajectory optimization algorithm.

1.2 Structure

To guide the reader through this thesis, this section provides an overview of the structure and contents of the following chapters. The structure is outlined in figure 1.1 and is further explained in the subsequent text.

Chapter 1: Introduction
The first chapter introduces the research topic,the motivation to conduct research in this field as well as the aim of the research.

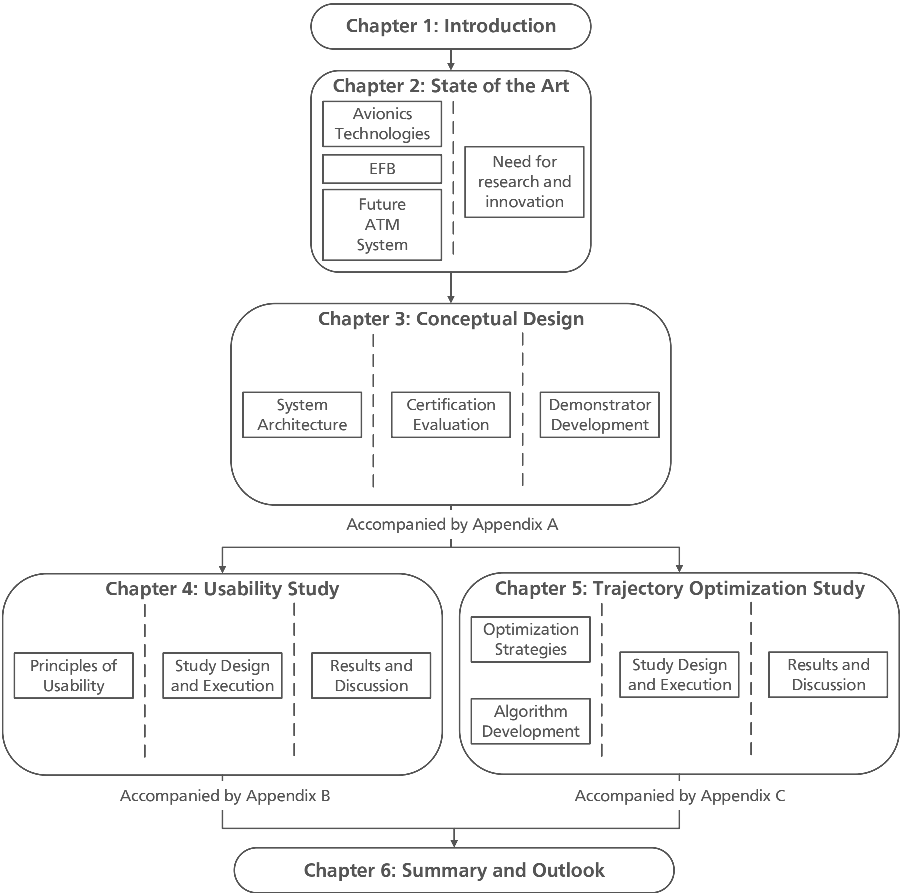


Figure 1.1.: Structure of this thesis [illustration by author]

Chapter 2: State of the Art of Flight Management Systems and Electronic Flight Bags
This chapter exposes technical details and standards of current relevant systems and procedures to the reader. The overview begins with the FMS and interavionics communication and is followed by a description of aircraft data networks and specifications of EFBs. Subsequently, brief descriptions of the current and envisioned future Air Traffic Management (ATM) system are provided. The technical description ends with a survey of certification requirements for airborne systems.

Identification of the need for research and improvement finalizes the chapter.

Chapter 3: Conceptual Design for a Coupled Mobile and Avionics Trajectory Execution and Optimization System
The architecture and functionality of the proposed system is developed in this chapter. It is commenced by a presentation of the design methodology that was exercised as well as of the environment the system is expected to operate in. Subsequently, the system architecture development process is described as well as certification aspects focusing on safety, security, and certification cost. A presentation of the implemented architecture demonstrator and its capabilities completes the presentation of the conceptual design. Following chapter 3, the architecture was evaluated in a two folded manner.

Chapter 4: Usability Study Based on the Demonstrator
The proposed architecture was evaluated regarding its usability. This chapter first presents the principles of usability, the study design and its execution. Subsequently the study results are presented and discussed. The chapter closes with a summary of the findings.

Chapter 5: Development and Evaluation of an Advanced Trajectory Optimization Algorithm
At the same time while executing the usability study, the evaluation of an exemplary trajectory optimization algorithm was planned and executed. This chapter presents the development of an optimization strategy and a corresponding algorithm as first steps, followed by the evaluation of the algorithm. The evaluation is structured in the study design, execution and the presentation of its results and their discussion.

Chapter 6: Summary and Outlook
This chapter summarizes the work presented in this thesis as well as a conclusion drawn by the findings of the presented studies. The chapter and the thesis is completed by an outlook on recommended future reserach.

2 State of the Art of Flight Management Systems and Electronic Flight Bags

Designing a new Flight Management System (FMS) requires an understanding of the evolution of FMSs as well as their current state. Their system structure and interaction with other aircraft systems are exposed to the reader. Additional attention is paid to efforts of the aviation industry to circumvent shortcomings of current FMS without changing the system itself. These efforts mainly concentrate on Electronic Flight Bag (EFB), as shown by the increasing market for EFBs [YCoT05], hence the capabilities of EFBs are detailed too.

Several initiatives in different areas of the world are undertaken to reform the structure of air traffic management [SES12b; Fed15b; Stu10]. These initiatives aim, amongst others, to use the available airspace more efficiently and reduce the emissions [SES12b; Fed15b; Stu10]. A cornerstone of the changes are Trajectory Based Operations (TBO), which the system proposed in this thesis is likely to operate [SES15] in. TBO and other relevant components of Air Traffic Management (ATM) modernization initiatives are presented to the reader.

2.1 Flight Management System

This thesis proposes a new design concept for FMS. In this section the evolution and importance as well as current implementations of FMS and their shortcomings are detailed.

2.1.1 Evolution

As Liden [Lid94] states, the FMS was introduced in order to support flight deck crews in tasks of flight planning and navigation. Though other supporting technology (aircraft performance and navigation computers) existed before [Bra06], the first integrated FMS was introduced on the Boeing 767 aircraft in 1982 [Mil09; Lid94]. Eventually, the FMS and other improvements such as the glass cockpit reduced the workload of the flight deck crew enough to allow the flight engineer being removed from the cockpit [Swe95].

2.1.2 Functions and Capabilities of Flight Management Systems

The FMS has seven functions, which are defined by Aeronautical Radio Incorporated (ARINC) A702A-3 [Aer06b] as Navigation, Flight Planning, Lateral Guidance, Vertical Guidance, Trajectory Prediction, Performance Calculations and Data Link & Entry. The functions are supported by the navigation and performance databases. Figure 2.1 depicts the functions and their dependencies between each other.

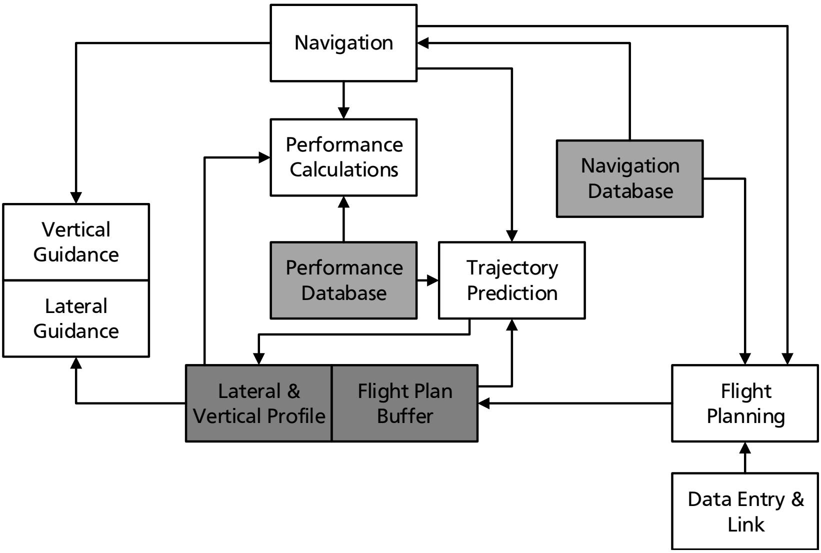


Figure 2.1.: Flight Management System functionality after [Spi00]

The following sections describe each of the functions as well as the integration of the FMS with other aircraft systems and the user interface.

2.1.2.1 Hierarchy and Connected Systems

This section describes the position of the FMS regarding its position within other aircraft systems. The FMS forms the outermost element of aircraft control, the flight mission control [MSJ13], see Fig. 2.2. The pilot is able to give input to the

FMS via the Control and Display Unit (CDU)[1]. The CDU, along with Electronic Flight Instrument System (EFIS) displays, provide output to the pilot. The FMS passes steering and thrust commands to the next level of control (trajectory control), the Autopilot and Flight Director System (AFDS). The autopilot finally passes commands to the Fly-by-Wire (FBW) system, which translates the commands into the necessary control surface deflections and engine commands. The FBW system has responsibility to not give any commands that would cause the aircraft to leave its safe flight envelope as long as it is operating in its normal mode [MSJ13].

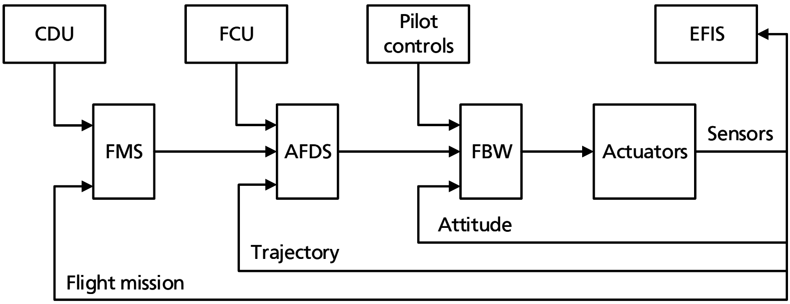


Figure 2.2.: Hierarchy of flight functions after [MSJ13]

Fig. 2.3 displays the connection of the FMS to other aircraft systems, which provide input to the FMS or receive output from the FMS. For the sake of simplicity an installation with a single Flight Management Computer (FMC) and two CDUs is shown.

In the center of figure 2.3 is the FMC, which is the main processing unit of the FMS. Around it several systems providing input to the FMC or receiving output from the FMC are depicted. The lower part of figure 2.3 shows connections to sensors which output is utilized by the FMC:

- Global Navigation Satellite System (GNSS),
- Inertial Reference Unit (IRU),
- Air Data Computer (ADC),

[1] While serving basically the same functions, the CDU is named Multipurpose Control and Display Unit (MCDU) on Airbus aircraft. This thesis will use the term CDU throughout. Compare also to section 2.1.2.8 for the functions of the CDU.

- Instrument Landing System (ILS),
- Distance Measuring Equipment (DME),
- VHF Omnidirectional Radio Range (VOR),
- Thrust Control Computer (TCC).
- Weight and Balance System

This data does not include inputs from the flight deck crew or inputs that are uplinked to the FMS. The flight deck crew uses the CDUs to make inputs to the FMS, via Aircraft Communications Addressing and Reporting System (ACARS) and the Communications Management Unit (CMU) messages can be uplinked directly from the Airline Operations Center (AOC) to the FMC [Spi00]. The FMC mainly produces output to the Flight Control Computers (FCCs), the autothrust system and the EFIS. The FCC and autothrust receives steering commands to follow the flight plan as computed by the FMS, the EFIS receives parameters for depiction on the flight deck main displays. An additional mean of output is the connected printer, which is used to print ACARS messages [Spi00].

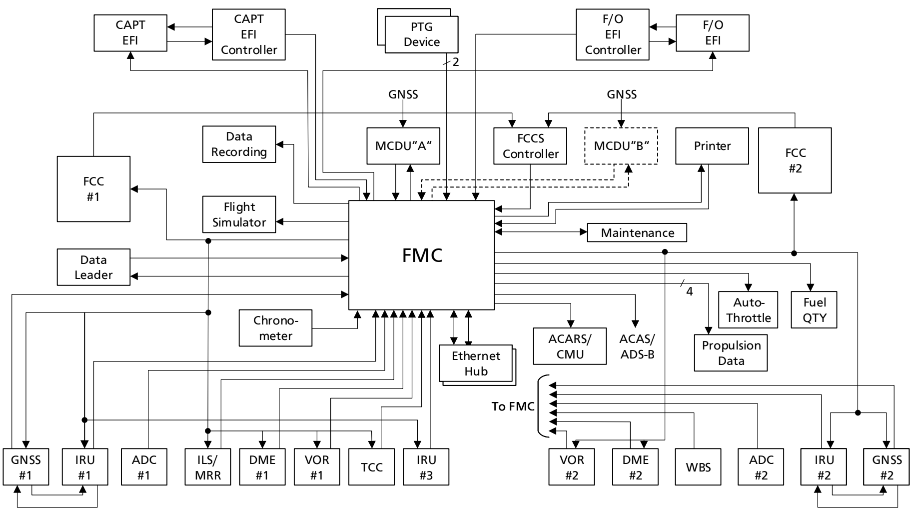


Figure 2.3.: FMS inputs and outputs after [Aer06b]

2.1.2.2 Navigation

The navigation function, as described in [Aer06b], determines the position of the aircraft using all appropriate sensor data. The navigation function determines automatically which sensor combination provides the most accurate result [Aer06b] in accordance with Required Navigation Performance (RNP) regulations[2]. The position is provided in terms of latitude, longitude, altitude as well as velocity in terms of ground speed, wind, track angle, true and magnetic headings, magnetic variation and inertial flight path angle.

2.1.2.3 Flight Planning

The flight planning function supports the flight deck crew in defining their route for the flight. The sequencing of flight plan elements is executed in this function. These elements are all possible combinations of waypoints, airways, fixes, procedures and flightlevels between the origin airport and the destination and/or alternates. The FMS supports the handling of several flight plans at the same time. At startup, when no flight plan is stored in the memory, a plan needs to be initialized by manual inputs or by an uplink (compare section 2.1.2.7). Modifying this flight plan creates a temporary flight plan, which can be inserted as active flight plan. An independent secondary flight plan can be created and stored for quick access.

Navigation Database:
The flight plan elements are provided by a navigation database, which is stored in the FMS via the Dataloader (see figure 2.3). The navigation database is formatted following the ARINC A424 standard [Aer11] and is being updated regulary. ICAO Annex 15 [Int13] specifies that each member state of the ICAO must publish relevant aeronautical navigation information Aeronautical Information Publication (AIP) in a fixed cycle of 28 days [Int13]. The cycle is referred to as the Aeronautical Information Regulation and Control (AIRAC) cycle. The information is clustered in Navigational Aid (Navaid), enroute, and airport sections [Aer11].

The navigation database has been a limiting factor for the flexibility of FMS [Her12]. The storage provided by the FMC hardware is limited so that an aircraft

[2] RNP describes a navigation concept that shifts from equipment based navigation [Sch15] to Performance Based Navigation (PBN), hence combining sensor data to achieve a navigation solution with the current highest accuracy, and imposing accuracy constraints on airways and procedures. The concepts and requirements of PBN and RNP are outlined in International Civil Aviation Organization (ICAO) Doc9613 [Int08] and Radio Technical Commission for Aeronautics (RTCA) DO-236C [Rad13].

often is unable to carry a navigation database covering the whole world [Her12]. Additionally to hardware constraints, the FMC often contains a limited number of procedures. E. g. only a certain number of departure and arrival procedures per airport and/or runway are allowed. With a growing set of Random (Area) Navigation (RNAV) procedures, the FMC often does not offer sufficient data volume to store all existing procedures, hence the aircraft operator needs to define which procedures should be loaded.

2.1.2.4 Lateral and Vertical Guidance

Lateral guidance is conducted along the active flight plan. The function is based on a control of the Cross Track Error (XTE) and path angular error [Spi00]. Vertical guidance is provided with respect to altitude constraints defined in the navigation database, a computed optimal profile or manually entered values.

Whether the guidance values computed by the FMS are forwarded to the autopilot, is chosen by the pilot. The input is given via device located on the glareshield of the flight deck, called Mode Control Panel (MCP) on Boeing aircraft [Boe14] and Flight Control Unit (FCU) on Airbus aircraft [Air11][3]. Lateral and vertical guidance channels can be either fed with manually entered values or switched to use the FMS source [Boe14; Air11]. The autopilot commands the desired attitude to the FBW system, which computed the needed deflection of relevant control surfaces[4] and engine thrust to achieve the commanded attitude.

2.1.2.5 Trajectory Prediction

Based on the flight plan constructed by the flight planning function, the trajectory prediction periodically computes distances, times, speeds, altitudes, and gross weights for all future waypoints of the flight plan. The prediction includes artificial waypoints like the top of climb and top of descent as well as well predictions for current climb or descent segments.

The output is provided to the CDU for textual representation as well as to the navigational display [Aer06b]. On the Navigation Display (ND), the lateral and, on recently introduced aircraft models, the vertical profiles are depicted in a "What you see is what you fly" manner [Air; Air11].

3 This thesis will use the term MCP except when discussing explicitly Airbus related architectures or implementations.

4 Such as elevators, ailerons, rudder and spoilers.

2.1.2.6 Performance Calculations

With respect to constraints and defined goals, the performance calculation optimizes the vertical and speed profile to minimize the cost of the flight. Current FMS use the Cost Index (CI) to define the optimization goal (compare to section 2.1.3). An aircraft performance model is stored in the performance database.

2.1.2.7 Air-Ground Data Link

The Air-Ground Data Link provides two folded possibilities of communication. A connection to the airline's operations facilities enables a direct feed of messages into the FMS. The messages can contain flight plans, position reports, weather data, take off speeds, or free text [Aer06b]. The second channel provides connection to air traffic control, so called Controller-Pilot Data Link Communications (CPDLC). Predefined messages like requests or clearances can be up- and downlinked between the pilot and the controller [Deu12].

2.1.2.8 Pilot Interface

Each flight deck contains one or several devices to let the flight crew interface with the FMS. Until the introduction of the Airbus A380, these devices were the CDU on Boeing aircraft and MCDU on Airbus aircraft. Their design and functionality is described in ARINC A739 [Aer90] and ARINC A739A-1 [Aer98] respectively. Figure 2.4a depicts a CDU as it is found on many aircraft types, as for example the Airbus A320 [Air], Boeing 737MAX and Boeing 777.

The CDU Human Machine Interface (HMI) consists of a display, an alphanumeric keyboard, quick access buttons and line select keys located left and right to the display. The display contains a title line, twelve lines (divided in a subtitle content lines) and the scratchpad. The scratchpad displays the input made on the alphanumeric keys or feedback given by the FMC. For interaction with the data displayed in the content lines, the line select keys are pressed. A color and symbol code is used to distinguish content types like computed data, modifiable data, temporary data, browsing functions and needed pilot interaction. CDUs on modern aircraft aggregate the interfacing functionality not only to the FMS, but also to other aircraft systems like ACARS.

Beginning with the introduction of the Airbus A380, aircraft manufacturers introduced new interfaces to the FMS and other aircraft systems [Vog09]. The Airbus A380, as well as the Airbus A350, feature the Keyboard Cursor Control Unit (KCCU)

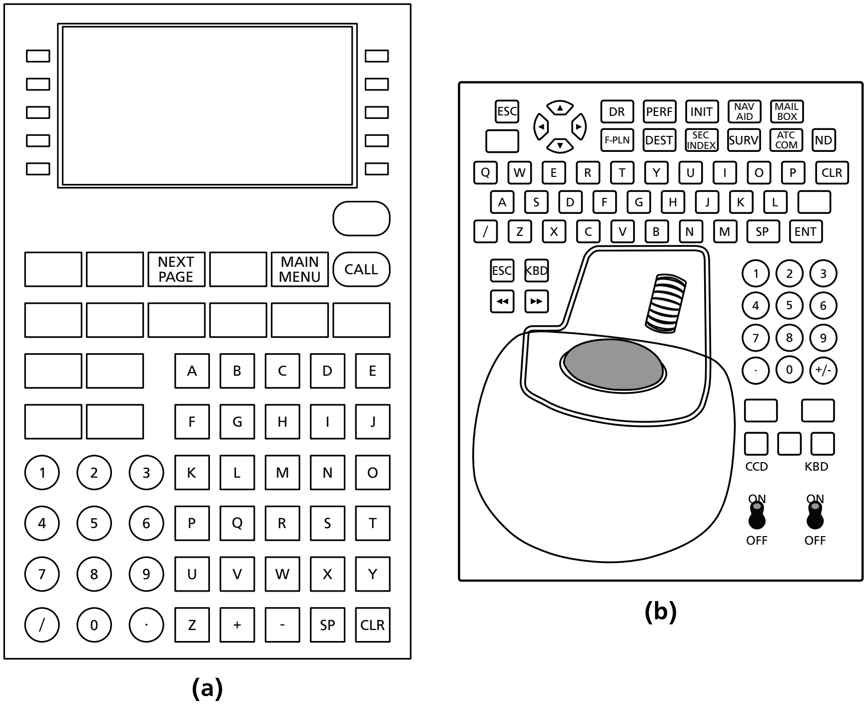


Figure 2.4.: (a) Exemplary layout of a CDU after [Aer98] and (b) KCCU of the Airbus A380 after [Air06]

which integrates a keyboard and a trackball device to interact with the FMS[5] interface on the Multi Function Display (MFD) [Air11]. Figure 2.4b depicts the KCCU of an Airbus A380.

On the Boeing 787, a similar functionality is used by making input to the Multi-Function Keypad (MFK) and Cursor Control Device (CCD) to interact with an animated version of the CDU [Boe14; Vog13].

2.1.3 Optimization Method

The current optimization method for vertical and speed profiles in the FMS relies on the concept of the CI, as Scheiderer [Sch08] presents. The idea of the CI is to

[5] The KCCU allows to interact with other systems such as the ND too [Air06].

set fuel cost C_F in relation to time dependent cost C_T and prioritize between them, see equation 2.1.

$$CI = \frac{C_T}{C_F} \tag{2.1}$$

The CI therefore represents a fuel flow in pounds per hour. By setting the CI[6], the user specifies by which factor fuel cost are prioritized over time cost. The FMS is using this input to compute an optimized vertical and speed profile, since fuel burn, climb schedules and experienced weather differ with the chosen CI. Figure 2.5 depicts this relationship along with the fixed cost of each flight, resulting in a function for direct operating cost of a flight.

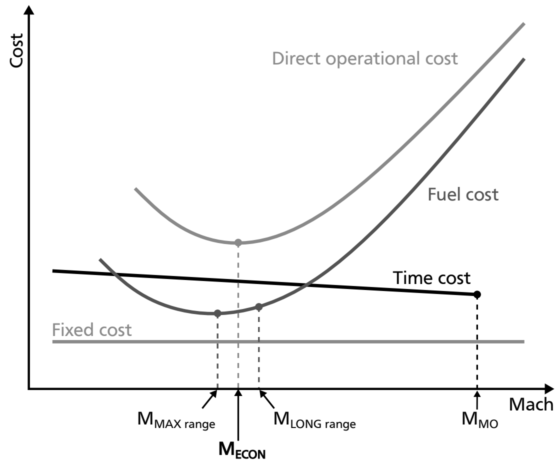


Figure 2.5.: Relationship of time cost, fuel cost and fixed cost after [Sch08]

As can be seen, a minimum of direct operating cost occur at a specific mach number, labeled as M_{ECON}. In certain cases the aircraft operator may choose to operate at other mach numbers than M_{ECON}, for example in order to absorb a delay (higher mach number) or to make use of beneficial winds (lower mach number) [Sch08]. The upper and lower boundaries are not used in line operations, airlines

6 Depending on the aircraft manufacturer and FMS vendor, the CI can range from 0 up to 999 or 9999 [Air98; Rob07]. The lower end reflects operating at the maximum range cruise mach number $M_{MAXRANGE}$, where the upper end reflects operating the maximum operating mach number M_{MO}.

rather define CIs tailored to their cost model and, if necessary, specific routes and used aircraft models [Rob07].

2.1.4 Hosting Methods

Avionics architectures, and therefore the way in which functionality is hosted, has developed over time. As shown in figure 2.6, the development of avionics architectures can be grouped in four periods [MSJ13]. In the beginning of avionics development, the architecture was distributed analogue, where functionality was provided by separated, discrete avionic subsystems. This architecture evolved to the distributed digital architecture, where the former analogue elements were replaced by digital ones. In line with this, data exchanges (busses) were changed to digital ones, however subsystems remained to be separate. Computations were done by functionality specific computations units, called Line Replaceable Unit (LRU). LRUs were designed by subsystems suppliers and are propriety, whereas their interconnection was provided by standardized busses (compare to section 2.2). Aircraft using the distributed digital architecture are the Airbus A320 and A330 as well as the Boeing 737 and 757.

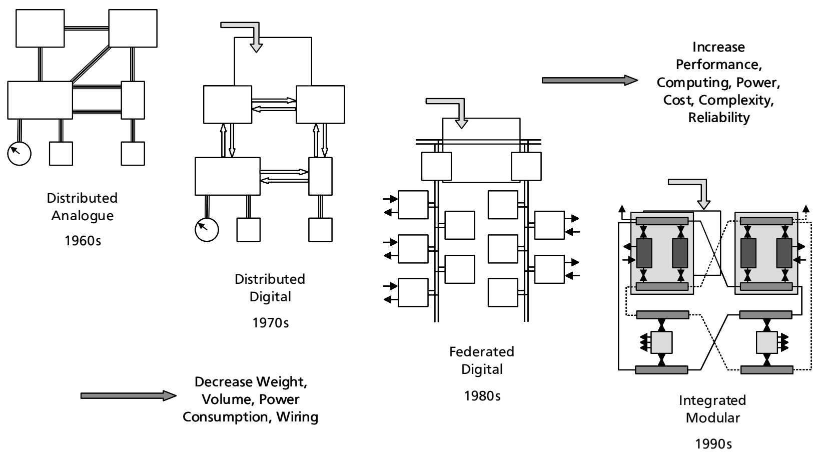


Figure 2.6.: Evolution of avionics architectures over time after [MSJ13]

Next, the federated digital architecture puts emphasis on the interdependency of avionic subsystems. Related subsystems are grouped into domains, where information inside the domain is distributed on the domains sub-network. Relevant information between the domains is shared on a top level network. Tasks are still carried out by LRUs. Federated digital avionics were largely deployed on military aircraft as well as the Boeing 777 commercial airliner.

An increased amount of data generated on-board aircraft and the drive to make use of the developments in the Commercial off the Shelf (COTS) hardware sector pushed avionics development a step further. The results are Integrated Modular Avionics (IMA), in which the coupling of hardware and functionality is loosened. The IMA provides a common processing unit and memory, which is shared between multiple functionalities. The functions are strictly partitioned. This enables the IMA to optimize the distribution of computational power to the different functions. A shared I/O interface[7] allows to reduce the amount of needed wiring to interconnect avionics. The IMA concept reduces the aircraft weight as well as the power consumption of avionics [WW07].

Figure 2.7 shows the comparison of a federated and an IMA architecture. As can be seen, the IMA architecture reduces the number of needed Central Processing Unit (CPU) cores, inter-wiring and I/O modules. The common CPU of the IMA drives all computations and all information is distributed via standardized, common interfaces. The IMA architecture was introduced on the Airbus A380, and is since implemented in all major airliner programs such as the Airbus A350 and Boeing 787 [MSJ13].

2.2 Interavionics Communication

In this section relevant ways of communication between avionics are described. The presented protocols provide safe and reliable means of communication which are used throughout the whole aircraft.

2.2.1 Common Communication Busses

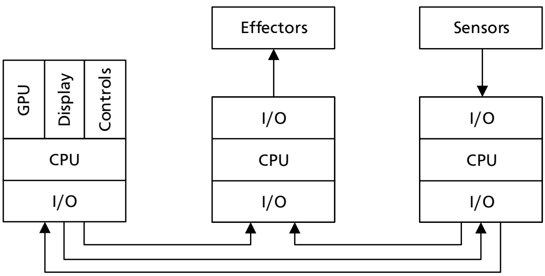
ARINC 429:
The ARINC A429 [Aer12a] standard defines a data bus used on many commercial aircraft called the "Mark 33 Digital Information Transfer System". The ARINC A429 bus was introduced in 1978 and is still in usage today [Aer12a]. It can have a layout as a lowspeed bus transmitting data at 12.5 kbit/s or highspeed bus transmitting at 100 kbit/s. The transmissions have a set length of 32 bits, in which the data, data label and control sequences are embodied. The standard description defines a set of labels of data that can be transmitted on defined pins on the connector. The bus'

[7] Usually ARINC A664, compare to section 2.2.

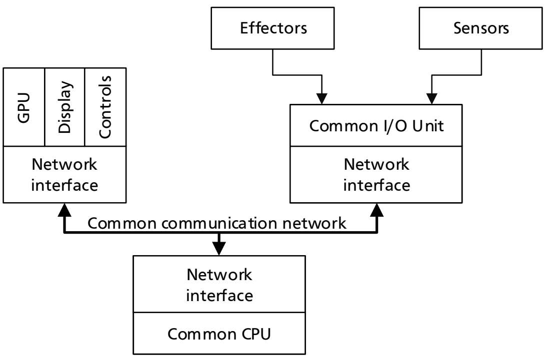
layout is a 1-to-n connection with one sender and n receivers.

ARINC 664:
The drive for weight reduction and higher transmission rate led to the development of a new communication standard [Buc08]. An intermediate step is shown in ARINC A629 which allowed transmission rates of 2 Mbit/s, but needed costly dedicated hardware. Thus, it was implemented only on the Boeing 777 aircraft family [Aer99].

In a further effort, the ARINC A664 [Aer06a] standard was developed and first deployed in form of the Avionics Full-Duplex Switched Ethernet (AFDX) system on the Airbus A380 [MSJ13]. While the AFDX is an implementation of ARINC A664 and patented by Airbus [Mor99], it is currently used throughout other hull man-



(a) Federated



(b) Integrated

Figure 2.7.: Comparison of a federated and an integrated avionics architecture after [WW07]

ufacturers on recently developed aircraft[8]. The architecture reduces the needed wiring for bidirectional communication between avionics compared to an ARINC A429 architecture [BBB+10].

2.3 Aircraft Networks and Datalinks

Communications between aircraft systems and other elements are carried out using the Aircraft Data Network (ADN) and datalinks. This section describes the ADN and related datalinks that connect the aircraft to the ground.

2.3.1 Aircraft Networks

As described in section 2.2, interavionics communication is using certain data protocols to exchange information. On a higher level, communications are divided in several domains, as depicted in figure 2.8.

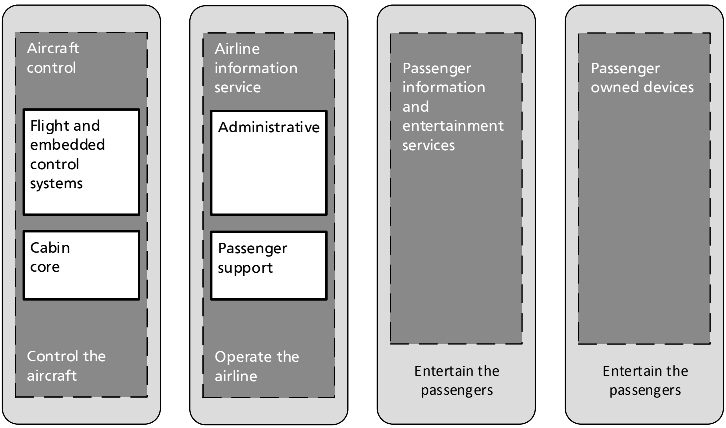


Figure 2.8.: The domains of the ADN after [Aer06a]

The ADN description was developed for the ARINC A664 [Aer06a] standard, where the domains are ordered by the criticality (see section 2.5) of the systems they are connected to. Placed on the highest level is the aircraft control domain, which includes flight control as well as cabin environment control systems. On the next lower level, the airline information services domain is located. This domain

8 Such as the Boeing 787, Airbus A350, Sukhoi Superjet 100 and COMAC ARJ21 [MSJ13].

includes administrative support functions such as communication to the AOC. The next two domains are passenger exclusive, where the first one incorporates functions to entertain and inform passengers via build in systems and the second one allows passengers to connect their own devices to the ADN.

The domains must be seperated from each other, since they include functions of varying criticality. On the other hand, granting read access for lower domains to higher is wanted for the sake of passenger comfort and information. For example, passengers expect to view the intended route and current position of the aircraft on a display at their seat, where route and current position can only be extracted from the aircraft control domain. For this reason, lower domains are granted read access to higher ones, read-only access is guaranteed by hardware as well as software measures.

2.3.1.1 Aircraft Interface Device

With the upcoming of EFBs (see section 2.4), airlines saw the need to connect them to the ADN. Older aircraft relying on the ARINC A429 standard had no possibility to integrate an EFB. Aircraft Interface Devices (AIDs) were introduced to overcome this gap. The AID is connected to the ADN and allows read access for the EFB. The physical description of an AID is defined in ARINC A759 [Aer14], where the functions and available read parameters are given in ARINC A834 [Aer12b].

2.3.2 Datalinks

Aircraft continuously exchange information with ground stations. The flightcrew interacts with Air Traffic Control (ATC), the AOC, and maintenance staff, where the passengers are using phones and inflight internet.

Besides traditional Very High Frequency (VHF) and Ultra High Frequency (UHF) voice communication for ATC purposes, datalinks are used to exchange digital information. As datalinks any means of transporting digital information are described, independent of the transport medium [Joi15]. Currently used transport mediums are High Frequency (HF) radiowaves as well as satellite communications. Onboard the aircraft, communications are routed via the CMU. The CMU is connected to all relevant communication channels and senders/receivers on the aircraft. Each incoming and outbound message is routed to the appropriate communications channel [Aer10].

2.4 Electronic Flight Bag

As the technology of Portable Electronic Devices (PEDs) advanced, the industry recognized the potential of their usage in aviation [Fit02]. Soon air carriers began to transfer documents from paper to an electronic format stored on the EFB [All03]. This allowed to reduce the weight carried in paper charts and other documents by about 35kg [All03]. To guide air carriers and hardware and software vendors, aviation authorities issued guidelines to the usage and certification of EFBs.

2.4.1 Classification of Electronic Flight Bag Hardware and Software

Both European Aviation Safety Agency (EASA) and Federal Aviation Administration (FAA) published guidelines to the usage and certification of EFBs. EASA AMC 20-25 [Eur14] and FAA AC120-76D [Fed17] describe hardware and software classes for EFBs.

Portable EFB:
Portable devices are EFB hosting platforms used on flight deck, which are not part of the certified aircraft configuration. The portable device may be powered with a certified on board connection and can be used on and off board. If the EFB is mounted, it is removable without the use of a tool and the removal is not considered a maintenance action. The portable EFB may be part of an installed system, which provides a certified mounting for the EFB. The installed components are part of the aircraft airworthiness approval.

Installed EFB:
The EFB is installed in the aircraft and considered an aircraft part. It is covered by the aircraft airworthiness approval. The EFB may host certified applications along with non-certified applications, but needs to ensure that non-certified application do not adversely affect certified functions. This can, for example, be achieved by a robust partitioning.

Type A Software:
These applications have no safety effect upon a failure and do not need certification. These applications include the depiction of electronic forms of the air operator certificate, passenger and cargo manifests and maintenance manuals.

Type B Software:
Type B software applications have minor failure conditions and do not substitute

or duplicate a system functionality that is required by airworthiness regulations, airspace requirements or operational rules. Type B applications do not require an airworthiness approval, but an operational assessment. Type B applications include chart depiction through all phases of flight, aircraft flight and operation manuals, airport moving map displays and take off performance calculations.

2.4.2 Connections of Electronic Flight Bags to other Avionics

In today's operations airlines strive to use applications on EFBs that need read and/or write access to aircraft data, which can only be provided by other avionics [McK17]. An example are Airport Moving Map Displays, on which the aircraft's position on the airport ground facilities is displayed. While the charting data resides on the EFB, the current position in latitude and longitude is provided by the navigation function of the FMS (compare to section 2.1.2). Since installed EFBs and the applications running on them are part of the aircraft certified configuration, a read access to other certified systems can be considered already in the design process. All EFB hardware and software systems must then meet certification criteria to not interfere with those systems. Portable EFBs, which are not part of the aircraft airworthiness approval, need special considerations when they are supposed to receive data from other avionics. AMC2025 [Eur14] lists possible data connections for portable EFBs as it may receive data from any aircraft system but limits data transmission to systems that when failing do not have an adverse affect on the aircraft. An example for systems being designed to receive data from EFBs are AIDs (compare to section 2.3.1.1). Other examples for systems are the aircraft Inflight Entertainment System and Passengers Personal Devices.

A different standard was released for aircraft utilizing ARINC A664 or similar communications. ARINC A834 [Aer12b] describes an Aircraft Data Interface Function, which can be implemented as an AID but also with other means, like a general network service. The Boeing Onboard Network System (ONS) is an example for such a system [WP14].

2.5 Certification Considerations

All systems installed on an aircraft, hardware and software, need to undergo a strict certification process. In the following section the general process of certification is outlined, followed by the description on an analysis on how the system proposed in this system is considered to be validated in a certification process.

2.5.1 Certification Procedure

The general certification requirements are published by National Aviation Authoritys (NAAs) like FAA or EASA. Over time the aviation industry developed own standards which show a way to comply with the certification requirements. The Society of Automotive Engineers (SAE) publishes these Aerospace Recommended Practices (ARPs). ARP4754 [Soc10] and ARP4761 [Soc96] show a way of system design and evaluation for aircraft to comply with the certification requirements, where it is not mandatory to follow them. The ARPs do not give guidelines specific to aircraft parts or software, but rather guide through the development cycle of aircraft and systems implementing aircraft functions. The proposed processes apply to hardware as well as software development, the description in this thesis will focus on software development.

ARP4754 gives the overall approach to the designing process, where ARP4761 gives examples on how the methods required in ARP4754 are implemented. Figure 2.9 depicts the development and safety process cycle. As described in the figure, the process contains system development and its safety validation on parallel tracks. The cycle is depicted for the development of an whole aircraft and begins with the identification of the requirements for the same.

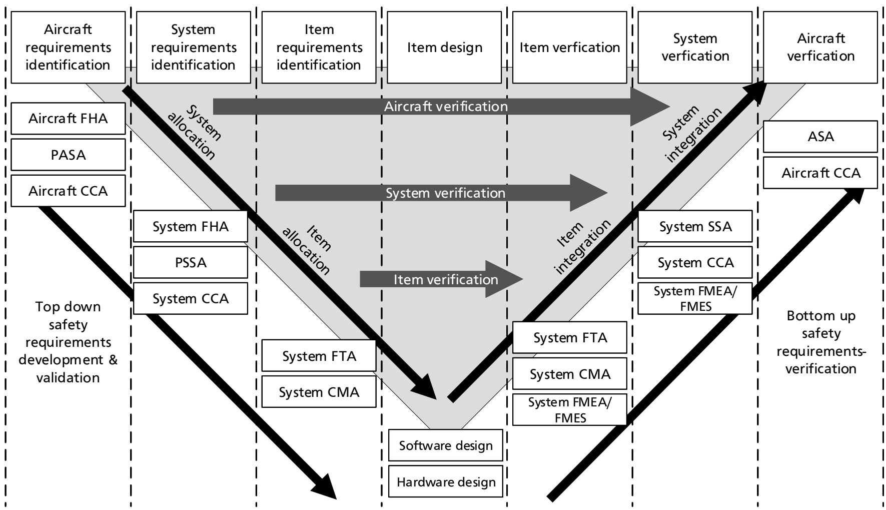


Figure 2.9.: The system development and safety process after [Soc10]

Once the requirements are identified, the first safety assessment is carried out. The assessments follow a top down path from aircraft level, over system level to item level. The results of an Functional Hazard Analysis (FHA) is the classification of each aircraft function into a Design Assurance Level (DAL). This classification is based on the assessment which effect a failure of each function would have on the aircraft, its crew and its passengers. The basis for decision making is given in NAAs documents as FAA AC25.1309 [Fed02] and FAA AC23.1309 [Fed11] and depicted in table 2.1[9].

Table 2.1.: Relationship among severity of failure conditions, probabilities after [Fed02] and DAL after [Rad12]

Classification of failure condition	No safety effect	Minor	Major	Hazardous	Catastrophic
Allowable qualitative probability	No probability requirement	Probable	Remote	Extremely remote	Extremely improbable
Allowable quantitative probability	No probability requirement	$< 10^{-3}/h$	$< 10^{-5}/h$	$< 10^{-7}/h$	$< 10^{-9}/h$
DAL	E	D	C	B	A

The DALs are categorized in six levels ranging from A to E, where the failure conditions have effects ranging from *Catastrophic* to *No Safety Effect*. The FHA does not determine how a failure condition could occur, but only assesses how the failure will affect the aircraft. The FHA on the aircraft level is followed by the Preliminary Aircraft Safety Assessment (PASA) which determines how a certain failure condition could occur and the aircraft Common Cause Analysis (CCA). The CCA is an assessment which determines if several failure conditions can be triggered by a single cause. Results of the CCA show whether independence between functions exists or not where acceptable. By conducting the safety assessment on the aircraft level, requirements regarding the aircraft design are derived.

On the next level, the system assessment is carried out. For each aircraft system, a FHA, a Preliminary System Safety Assessment (PSSA) and system CCA determine

9 Quantitative probabilities are given in the order of average probability per flight hour.

the above described results on the system level. The output of the assessment is translated into requirements on the system level for each aircraft system.

After assessing the system level, the items which eventually implement the system function need to be assessed, hence the next level is called the item level. First, a Fault Tree Analysis (FTA) is conducted. The FTA is a top-down method that moves from higher to lower levels of system design with increasing detail on the system components. It connects items with Boolean logic operators to show which failure mode can lead to certain failure effects. On the lowest level, each event is given a probability that is computed using average failure rates on similar systems and exposure time. By combining the failure probabilities on each system design level, each function that a DAL was assigned to receive a failure probability. This probability needs to match the probability that is connected to the functions DAL. A Common Mode Analysis (CMA) is conducted for each item to verify that all events connected with a Boolean AND in the FTA are independent in the implementation so that the AND condition can not occur. Several iterations of the above described assessments may be needed to satisfy the requirements identified in the FHAs.

Following the top-down methods of the safety requirements analysis, is the item design phase. Each item is designed with respect to its identified requirements. To ensure the requirements were met, a bottom-up phase follows the item design, which starts to verify the system requirements on an item level, moves to the system level and finally to the aircraft level. The phases are referred to as *Item Integration* and *System Integration* phases. In the item verification process, FTAs are used in conjunction with CMAs as well as Failure Mode and Effect Analysiss (FMEAs) and Failure Mode and Effect Summarys (FMESs). The FMEA is a bottom up method which examines the effect of the failure of an implemented feature onto the system. A FMES is a group of failure modes that, if they occur, lead to the same failure effect. A FMES can be derived from the results of several FMEAs.

On the system verification level, the System Safety Analysis (SSA) is conducted along with the system's CCA and FMEA/FMES. The aircraft level is verified by conducting the Aircraft Safety Analysis (ASA) and the aircraft CCA.

2.5.2 Development of Certified Software

Along with the general guidelines regarding the development of certified aircraft systems described in section 2.5.1, a more thorough guideline for the development of certified software is given in RTCA DO-178C [Rad12]. In dependence of DALs, DO-178C states documentation and coding requirements for software.

2.5.3 Operational Approval of Electronic Flight Bags

To use EFBs for their flight operation, an airline needs to be certified for the intended hardware, its installation and software. This certification process is referred to as Operational Approval (OpsApproval) and is described in FAA AC120-76D [Fed17], AC20-173 [Fed14] and EASA AMC20.25 [Eur14] respectively. Both documents describe the types of EFBs and software (compare to section 2.4) along with acceptable means of gaining OpsApproval. OpsApproval includes the used hard- and software as well as the installation of the EFB in the cockpit, power supply and airline Standard Operating Procedures (SOPs) regarding the usage of EFBs. Since the cockpit installation and power supply is unique to each aircraft type, OpsApproval needs to be obtained individually for each aircraft type operated by the airline.

Modifications to existing OpsApprovals can be gained with less effort, where updating already approved applications or Operating Systems (OSs) do not require any new approval at all [Fed17].

2.6 Future Air Traffic Management System

The system proposed in this dissertation will interconnect with other systems acting in the ATM environment. The understanding of the ATM environment, the proposed changes and their justification are crucial to the design and the acceptance of the system proposed in this dissertation. This section gives an overview on the current state of the ATM system and current research and implementation efforts on proposed changes.

2.6.1 Current Air Traffic Management System

The ATM system developed over time along with the general growth of air traffic [KF96]. The task of the system is to ensure safe and efficient operations [SG16]. With increasing air traffic, the historically developed system is reaching its capacity limits.

2.6.1.1 Capacity Limits at Airports

Airports are the bottleneck of the ATM system [YC13]. The terminal airspace around the airport and its runways have a limited certain capacity[10], where capacity is not only dependent on the physical airport structure, but also on current weather conditions [Hir08; SG16]. Arrival and departure streams need to be separated and ground traffic needs to be coordinated.

Efforts were made to improve airport capacity. Airports are categorized, where level three airports are coordinated airports [Int14]. At coordinated airports, operators are assigned slots for their operations. Each country may organize the slot assignment differently. Examples for coordinated airports are London-Heathrow and Frankfurt. Airports strive to expand their capacity and available slots by constructing additional runways and concourses.

2.6.1.2 Capacity Limits in Airspace

Capacity is not only limited at airports, but also in enroute airspace, where controller workload is the limiting factor [Wel15]. With regards to aircraft separation, an airspace volume can only handle a certain number of aircraft at the same time. To avoid congested airspace or expensive holdings, aircraft are held back at their departure airport if an airspace is expected to be at its capacity limit at the time of crossing [EUR18a]. In Europe, European Organization for the Safety of Air Navigations (EUROCONTROLs) Network Manager is in charge of predicting the state of the European airspace and issuing directives to enable efficient operations [Eur11b].

2.6.2 Future Air Traffic Management Initiatives

To overcome the limitations of the current ATM system as shown above, the European Union and the United States launched ATM transformation programs. In Europe, the foundation of the Single European Sky (SES) program was layed by Regulation (EC) No 549/2004 [Eur04] in 2004. The programs technical pillar is the Single European Sky ATM Research Program (SESAR) project, which in turn is managed by the SESAR Joint Undertaking (SESAR JU) since 2007 [SES15]. SESAR is currently undergoing its implementation phase which is structured in a short

[10] Capacity is the ability of an object in the ATM system, such as an airspace sector, to handle a certain amount of flights inside a certain time period.

term (up to 2012), midterm (2013 - 2019) and longterm (from 2020 onwards) phase [SES08].

In the United States, the Next Generation Air Transport System (NextGen) program was established by following the NextGen Integrated Plan [Nex04]. Mainly responsible for managing the efforts is the FAA.

The system proposed in this thesis is expected to operate in the environment implemented by the programs mentioned above. Its design must consider the expected changes and make best use of them. The following sections outline the conceptual cornerstones of the initiatives relevant for this thesis as well as the accomplishments achieved in development.

2.6.3 Trajectory Based Operations

In the current ATM system, flights are carried out considering estimated times based on planned speeds and altitudes filed with the flight plan [Fed15a]. Since estimates contain an uncertainty, available resources like airspace, air traffic controllers and airport ground operations are planned with uncertainties, too. TBO[11] is the concept of shifting operations to paths defined in space and time. Defined waypoints along the route are imposed with temporal constraints (Required Time of Arrivals (RTAs)), which are agreed throughout the systems stakeholders. RTAs can either be of the Controlled Time of Overfly (CTO) or Controlled Time of Arrival (CTA) type [SES12c]. The FMS onboard aircraft is responsible to execute the flight in a way to achieve the imposed constraints. The shift to TBO is expected to increase predictability of air traffic and in turn also airspace capacity.

The concept of TBO was demonstrated by SESAR and its partners on testflights in 2012 and 2014 [SES14]. The testflights demonstrated the Initial 4D (i4D) concept, which is the initial stage of TBO where a flight plan contains only a single RTA.

2.6.4 System Wide Information Management

Information exchange in today's ATM system is mainly carried out using technologies implemented only for a single task [SES11]. Many systems are needed to connect all stakeholders in the ATM environment. SESAR and NextGen propose the introduction of a network to share information amongst all stakeholders which is expected to increase interoperability and efficiency. Systemwide Information

[11] TBO is also referred to as 4D trajectory operations, with the temporal domain being the fourth dimension apart from the three dimensional spacial system represented by latitude, longitude and altitude.

Management (SWIM) relies on several concepts [SES11]:

Separation on Information Provision/Consumption:
All stakeholders in the ATM system are information providers as well as consumers. In the current situation, it is predetermined who can send or receive which information. Using SWIM, this behavior can change over time and allow for higher flexibility.

Loosely System Coupling:
The components inside SWIM are only loosely coupled which is implemented by giving them only little knowledge of the other components. By doing so, interfaces are kept open and compatible to each other.

Service Oriented Architecture:
The SWIM architecture shall be oriented towards a service centric architecture. This will enable the usage of a single service for different tasks, if the needed service is similar.

The implementation of SWIM will consist of information definition models, information exchange service models and a ground infrastructure. It is not expected to establish a single, dedicated infrastructure to run SWIM services. The open definition of SWIM will enable the operation of several platforms with broad access. Finally, applications need to be developed which make use of SWIM. This can include new developments as well as the adaption of existing applications. As application all tools supporting the ATM stakeholders in their task are defined.

2.7 Research Gap

FMSs have developed over time to the central entity of mission execution and trajectory optimization on the flight deck. Introduced later, but rapidly developing, are EFBs, which brought substantial computing power and storage capacity to the flight deck. While having the potential to improve the efficiency of mission execution, stringent certification requirements and the FMS being a blackbox designed by its vendors prohibit information exchange of FMS and EFB.

Research conducted focuses on workarounds for this problem, but still forgo a direct connection and on retrofit solutions, which promise an early Entry Into Service (EIS) date, as for example WESTPHAL [Wes14]. On the other hand, advanced trajectory optimization algorithms are proposed without detailing on which entity those algorithms are envisioned to run onboard, and how their results will be used for mission execution [Abb15; Cha95; DeJ92; SP09].

The research conducted in this thesis explores the feasibility and potential of a novel system design to directly couple EFBs and a certified system similar to the FMS. At the same time the system design supports goals of initiatives like SESAR as well as the efficiency of airline operations. Table 2.2 depicts a comparison of selected research and the work presented in this thesis.

Table 2.2.: Comparison of research efforts

	Traditional FMS	4D FMS [SP09]	WESTPHAL [Wes14]	SCHULZE
TBO Support	-	✓	✓	✓
Functionality Shifting	-	-	-	✓
Advanced Optimization Methods	-	✓	✓	✓
Integrated Airline Support	-	-	✓	✓

To make use of the computational power that resides on the EFB and to reduce the complexity of the FMS, the system architecture will provide means to shift functionality from the FMS to the EFB without infringing safety and security requirements. This approach offers an environment for any advanced algorithm that is allowed to run on an EFB under Operational Approved (OpsApproved) conditions. While this research does not intend to provide a contribution in the search for the perfect trajectory optimization algorithm, its result is envisioned to provide a contribution towards implementing future ATM systems, where hosting platforms for optimization algorithms are needed.

3 Conceptual Design for a Coupled Mobile and Avionics Trajectory Execution and Optimization System

In the following chapter the design process of the proposed system is described. The process covers considerations on the operational environment, functional architecture and certification of the system. A system architecture was developed that allows the shifting of relevant functionality to the Electronic Flight Bag (EFB) while maintaining safety and security. The system architecture was implemented into an exemplary demonstrator.

3.1 Methodology

This section describes the methodology and approaches that were used to design the system proposed in this thesis. The methodology of the design process focuses on safety, as the Flight Management System (FMS) is a safety critical component (compare to section 2.1.2). The certification process and its defined analysis (compare to section 2.5) ensure a safety centric design.

As depicted in figure 3.1, the design process begins with the initial design step which includes the idea for the system itself and the corresponding functional architecture. The operational environment the system is intended to be used in is considered in the initial design step, since it already has an impact on hardware requirements such as communications equipment.

The initial design step is succeeded by the certification evaluation and adaptions step. This step focuses on evaluating the software architecture as well as implementing security measures for the chosen hardware and software design. These processes are to be considered iterative, as a change in one of them might have impact on the others. At the end of the step, a cost analysis for the current solution is conducted. Subsequently, the final design is the output, where the design was evaluated and tested to ensure safety, security and profitability.

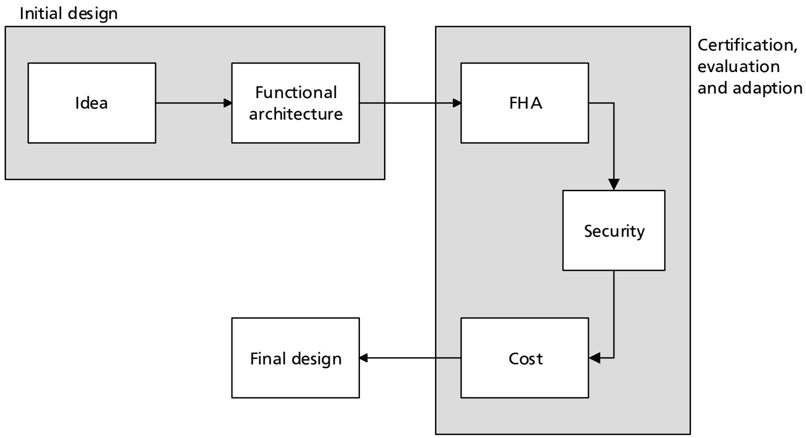


Figure 3.1.: Methodology of the design process [illustration by author]

3.2 Operational Environment

The proposed FMS will work in the future Air Traffic Management (ATM) environment which was outlined in section 2.6. Therefore it shall support full 4D operations and aspects of future information management. In [SES12a] the implementation of the future ATM system takes place in several stages, where only the last stage will include full 4D operations. One of the intermediate steps is referred to as Initial 4D (i4D), which includes one time constrained waypoint per flight plan. The time constrained waypoint can be placed either in the enroute or the approach phase of flight.

The system proposed in this thesis is expected to support full 4D operations. The operational environment is considered to be the final stage of Trajectory Based Operations (TBO) as envisioned by Single European Sky ATM Research Program (SESAR).

The proposed system is expected to work within integrated airline operations. Today, airlines use a variety of software tools across the company to perform planning and scheduling tasks. These tasks include flight planning, crew and maintenance scheduling as well as ground operations planning. However, the tools are often not connected (integrated), which leads to optimized solutions for subsystems of the airline on the cost of a decreased efficiency of overall airline operations [Pap09]. In case of a disruption, employees of the different departments coordinate solutions via personal communication, which is time consuming and only can reach a certain degree of efficiency, as depicted in figure 3.2.

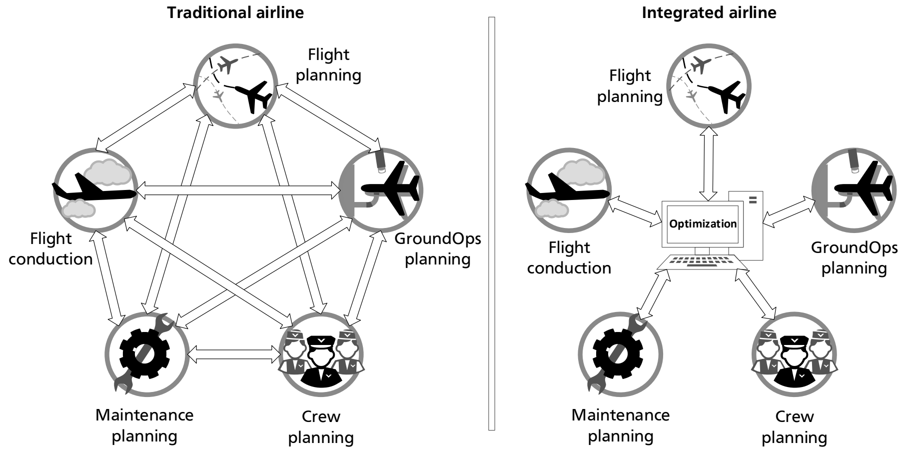


Figure 3.2.: System integration in a traditional and an integrated airline [illustration by author]

In contrast, in an integrated airline all software tools are integrated and exchange information [Ki-10; Cro16]. This results in an overall airline operations optimization. In an integrated airline flight planning, crew and maintenance schedules as well as ground operations are optimized to guarantee highly efficient operations. The integration also allows to decrease the impact of disruptions in the airline operations, such as unplanned maintenance or adverse weather.

3.3 System Architecture

This section outlines the architecture of the proposed FMS. A cornerstone of the system is the reallocation of functionality of the traditional FMS. The functions are reallocated onto two domains, an at least Design Assurance Level (DAL) C certified system[1], the CoreFMS, and an Operationally Approved system. The Operational Approved (OpsApproved) system is expected to be deployed on a mobile device, such as an EFB, as well as a fixed installed Filer Server which is located in the avionics bay. The reallocation of functionality changes the hierarchy of flight

[1] DAL C was chosen since according to Avery traditional FMSs are certified under at least DAL [Ave11]

control, since it is adding the EFB to the loop. Figure 3.3 depicts the hierarchy including the added elements.

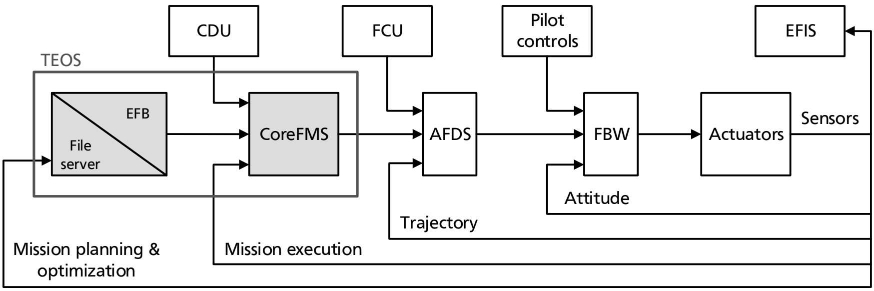


Figure 3.3.: The alternated hierarchy of flight control functions integrating the EFB [illustration by author]

As can be seen, the former FMS task of "Flight Mission" (compare to figure 2.2) has been divided into two subtasks. The subtask "Mission Planning and Optimization" is now carried out on the EFB, where the subtask "Mission Execution" resides on the CoreFMS. The EFB is supported by the Filer Server which serves the system as a data aggregator. The server is connected to the CoreFMS as well to the Communications Management Unit (CMU) which allows it to access aircraft avionics data and using a datalink to receive information from ground stations. In this role, the server incorporates the functionality of an Aircraft Interface Device (AID), too, since it has control over the areas the EFB has access to and aggregates information it is receiving via datalinks routing through the CMU.

In order to distinguish the new system architecture from traditional FMS and to emphasize its focus on trajectory execution and optimization, it is dubbed Trajectory Execution and Optimization System (TEOS).

3.3.1 Integration with other Avionics

As can be seen in figure 3.4, the CoreFMS is replacing the Flight Management Computer (FMC) as presented in the Aeronautical Radio Incorporated (ARINC) A702 FMS structure (compare to section 2.1.2.1). Interconnections to avionic subsystems, such as navigation sensors, the Air Data Computers (ADCs), the Flight Control Computer (FCC), the autothrust system, the Control and Display Units (CDUs) and the Electronic Flight Instrument System (EFIS) remain unchanged.

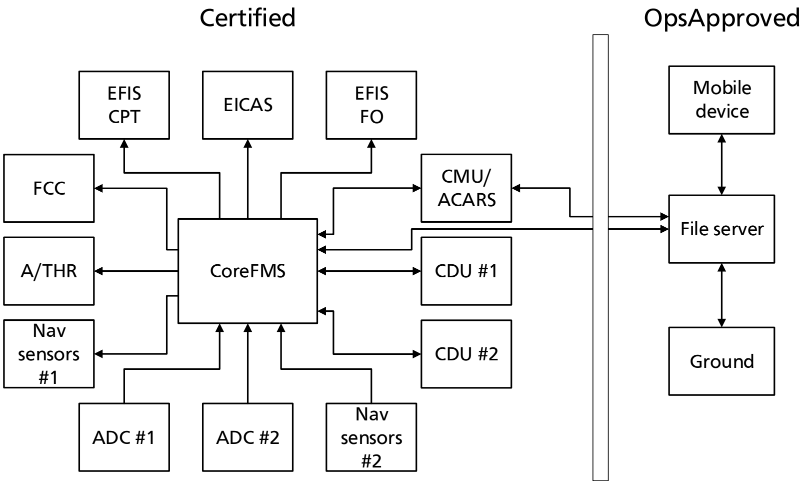


Figure 3.4.: The interaction of the system with other avionics [illustration by author]

As already mentioned, the CoreFMS connects to the OpsApproved domain via the Filer Server. The server itself connects again to the EFB and the CMU. The Filer Server has a two folded function. On one hand, the connection of the server to the CMU allows the server to receive information via the aircraft datalinks. This information then can be forwarded to the EFB, where it is used to optimize and plan the flight. On the other hand, the file server is the gateway to the CoreFMS. This function represents the tasks of an AID. It allows the EFB to access information that reside on the CoreFMS such as ADC parameters, navigation sensor data or aircraft and engine performance parameters. In difference to current AIDs, the file server also allows write access to the CoreFMS. This enables TEOS to optimize the flight's trajectory on the EFB and then send it to the CoreFMS for execution.

3.3.2 Data Exchange Formats

In order to enable bi-directional communication between the CoreFMS and the file server, an exchange protocol and message format needs to be defined. TEOS is expected to be implemented into an ARINC A664 avionics structure, which puts the exchange protocol to an Ethernet Avionics Full-Duplex Switched Ethernet (AFDX). To ensure the integrity of sent or received messages, a fixed set of messages is defined. Both communication partners check the message structure along with their checksum and drop messages that do not match any known structure or contain a wrong checksum. These checks prevent the handling of unknown message types, as well as handling messages that were altered during transmission. Altering messages could be conducted by malicious network participants or happen by transmission errors.

While data exchange formats between the CoreFMS and the file server need to be defined, data exchange between the file server and the airline ground stations can be designed arbitrarily to best fit the needs of the respective airline. Since several standards were developed to exchange certain kinds of data, it is recommended to stick to those formats.

Trajectory Exchange

The CoreFMS and the file server exchange a variety of parameters. On one hand, the CoreFMS receives the optimized trajectory from the file server. The trajectory is compiled into the Flight Information Exchange Model (FIXM) [FIX17] format, which is being developed in a collaborative effort by European Organization for the Safety of Air Navigation (EUROCONTROL) and the Federal Aviation Administration (FAA). FIXM is developed to support the exchange of flight data between stakeholders in the ATM system and supports the description of full 4D trajectories. The flight information depicts only information required as per International Civil Aviation Organization (ICAO) Doc4444 [Int16a] and the ICAO Flight and Flow Information for a Collaborative Environment (FF-ICE) [Int12]. With its capabilities, FIXM and its linked information exchange models Aeronautical Information Exchange Model (AIXM) and Weather Information Exchange Model (WXXM) are meant to support ATM operations via the Systemwide Information Management (SWIM) network, see figure 3.5. Even though FIXM was developed for flight information exchange between stakeholders in the ATM system, it resembles an agreed upon and standardized trajectory model, where no other model is known. FIXM was also used to transfer flight information to FMS in other studies, as for example by Stansbury et al. [SRT+15][2].

The format is Extensible Markup Language (XML) based, where end users validate data against the XML Schema Definition (XSD) of FIXM. Attention needs to be given to the accuracy of trajectory description, as Torres [Tor13] points out. As trajectories are defined as an object's continuous path in space and time, a trajectory description containing discrete points will always be an approximation of the underlying trajectory. Discrete points in a trajectory description contain waypoints

[2] Stansbury et al. examined how to integrate Unmanned Aerial System (UAS) into the National Airspace System (NAS) and used FIXM modeled trajectories to feed UAS FMSs [SRT+15].

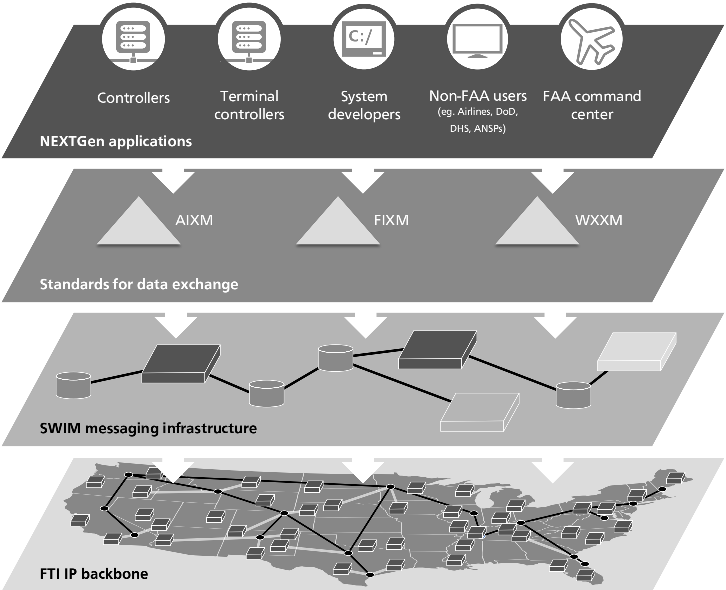


Figure 3.5.: Infrastructure of SWIM and position of information exchange models after [Che14]

as they are defined in an ICAO Doc4444 flight plan, as well as Trajectory Change Points (TCPs). At a TCP, the trajectory profile experiences a change. FIXM [FIX16] defines three types of TCP:

TCP-Altitude An altitude level off begins or terminates

TCP-Speed A change in speed is initiated or the target speed is reached

TCP-Lateral Course, track or heading of the aircraft is changed

As depicted in figure 3.6 , TCPs can, but are not required to, coincide with waypoints defined in the flight plan.

As Torres [Tor13] states, TCPs need to be inserted into the trajectory description in a thoughtful manner. In his study Torres researched on the impact of the sampling method on the accuracy of trajectory representation. The findings were that careless trajectory sampling can introduce large errors in the lateral, vertical and temporal profile. None of the analyzed trajectory exchange models, among them

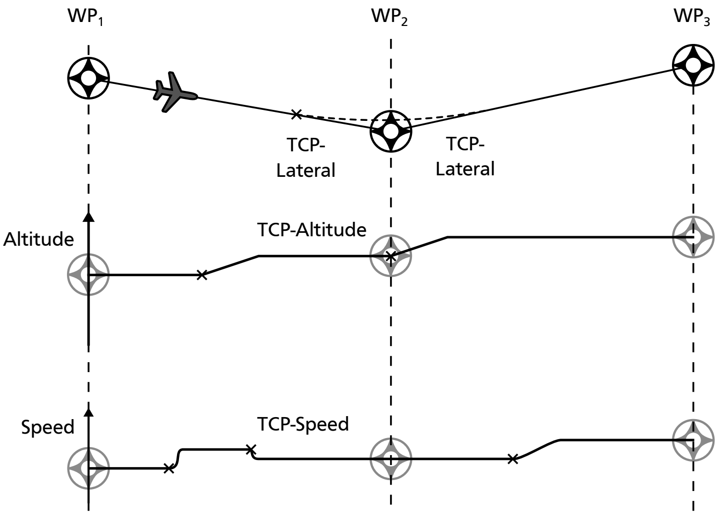


Figure 3.6.: The three different types of TCP: Lateral, altitude and speed [illustration by author]

FIXM, contains acceleration data at TCPs. Considering a section of a trajectory where speed changes occur with high accelerations, coarse spaced TCPs will lead to longitudinal errors when the trajectory is remodeled by the consumer. Since no acceleration data is present, the consumer will use the beginning and ending speed of the segment to compute an average acceleration, which will not represent the trajectory section adequately[3]. Other examples are included in Torres' work considering the sampling of vertical profiles. When sampling the trajectory in sections at high changing rates, TCPs need to be placed in appropriate distances to represent the trajectory in a satisfying accuracy[4].

Aircraft Data

Various parameters that are collected by aircraft sensors or describe the aircraft's current state are valuable to the trajectory optimization as well as to the optimiza-

[3] Torres [Tor13] found that in a 5 minute segment with an acceleration having its maximum at 118 kts/min, the longitudinal error can add up to 6NM. This error is unacceptable considering the aircraft may be operating in an Required Navigation Performance (RNP) environment.

[4] Torres [Tor13] also proposes to expand trajectory exchange models with additional relevant parameters such as accelerations as well as measurements of uncertainty.

tion of overall airline operations. Moving this information to the file server enables the EFB to use it for trajectory optimization on one hand. On the other hand the information can be downlinked to the Airline Operations Center (AOC) for further use.

A central place is taken by maintenance data. Maintenance data includes flight critical data and information on uncritical aircraft equipment. Flight critical data is forwarded by the aircraft Flight Warning Computers (FWCs), which collect and process data from aircraft sensors and System Data Acquisition Concentrators (SDACs). The FWCs subsequently check the received data for arising or existing malfunctions [5]. Uncritical information contains data on equipment not relevant for flight safety. This information may be valuable for the airline to plan maintenance and tail schedules. Using Airline Modifiable Information (AMI), airlines are able to define which data is transmitted to the file server. Potential use of the data is the trajectory optimization which can compute a new trajectory incorporating knowledge on any malfunction or unusual behavior of flight controls or engines.

Weather Information

In order to support trajectory optimization, the most recent weather forecasts need to be available on TEOS, in specific the file server. This means that no specific file format needs to be used. As mentioned in section 3.3.2 though, FAA and EUROCONTROL developed the weather information exchange format WXXM [WXX17]. Similar to FIXM, it is XML based and intended to represent weather elements as they are required by ICAO Annex 3 [Int07]. WXXM is expected to evolve to a global standard for weather information exchange, hence its usage is recommended.

3.3.3 Operation in an Integrated Airline

TEOS is an important part on the way towards an integrated airline as it was described in section 3.2. The introduced connectivity between TEOS and the AOC enables to receive information that was not present on the flight deck before, or to increase the quality of information. This information in turn can be used to optimize the flights trajectory. Figure 3.7 gives an overview over possible exchangeable information.

The overall concept enables customer specific solutions. Each airline is able to use its preferred applications on the EFB and connect to its specific ground tools.

[5] In today's aircraft systems, the warnings generated by the FWC are displayed on the Engine Indication and Crew Alerting System (EICAS) display.

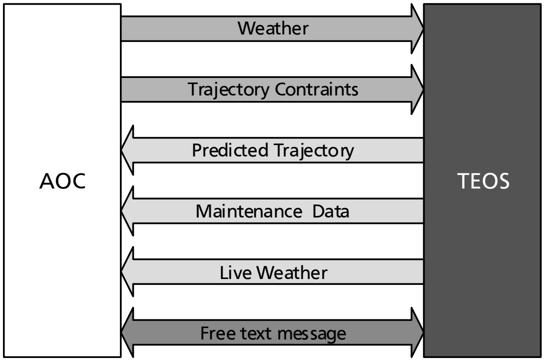


Figure 3.7.: Possible exchangeable information between AOC and TEOS [illustration by author]

This adaption will integrate each aircraft equipped with TEOS into an overall optimization process and increase the efficiency of the airline's operation.

3.4 Certification Evaluation

As stated in section 3.3, the basis of TEOS is the reallocation of functionality onto several subsystems. According to 2.5.1, a Functional Hazard Analysis (FHA) needs to be carried out in order to identify the impacts of failures on the system under consideration. Furthermore, an analysis of the security of the system is carried out, as well as estimation of the cost of certification for the new system.

3.4.1 Functional Hazard Analysis

This section describes the conduction of the FHA, which was executed as proposed in [Soc10].

3.4.1.1 Initial Definitions

Aircraft Definition:
The aircraft on which the proposed system is embedded is considered to be a state of the art two-engined longrange aircraft, comparable to the Boeing 787. The typical cruise mission length is considered to be 10 hours with a range of 7500NM,

carrying 250 passengers [Boe17].

System Boundaries:
The system boundaries chosen for the FHA are pictured by the dashed line in figure 3.8. The system boundaries define which elements' functions are being evaluated in the FHA. Providing integral functions of the TEOS such as accepting and declining updated flight plans, the CDU's input (keyboard) and output (display) are defined as inside the boundaries. All other elements such as displays, sensors and supporting hardware are excluded from the FHA since their functionality will remain unchanged.

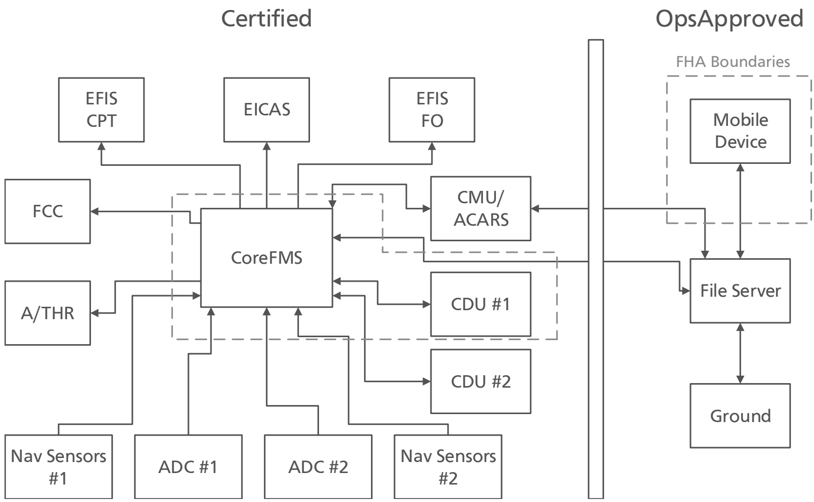


Figure 3.8.: The system boundaries of the FHA marked by dashed lines after [SWS17]

The EFIS and EICAS themselves are excluded from the FHA, while the communication of data between them and the TEOS is included. Also, the communication functions to AOC and Air Navigation Service Provider (ANSP) are considered in the FHA. Communications and their possible directions are pictured by arrows in figure 3.8.

Condition and Configuration Listing:
Table 3.1 lists the flight phases, environmental conditions and aircraft configurations that should be analyzed in a FHA. Each combination of those parameters

could yield a different classification of the aircraft functions. TEOS is expected to be mainly used during the enroute phase of the flight in normal flight conditions, which make up for the longest portion of the typical estimated flight.

Table 3.1.: Phases of flight, environmental conditions and emergency/abnormal Configurations

Phases of flight	Environmental conditions	Aircraft configurations
On Block	Normal Weather	Normal
Pushback	Adverse Weather	Ditching
Taxi	Contaminated Runway	Depressurization
Take Off Before V1	HIRF	Loss of Comms
Take Off After V1	Volcanic Ash	Two Engines Out
RTO		Hydraulic System Loss
Initial Climb		Electrical System Loss
Climb		Engine Out
Enroute		
Oceanic		
Descend		
Approach		
Final Approach		
Landing		
Decelerate		
Missed Approach		

Function Grouping:
Grouping functions in different types gives the advantage of predefining possible failure conditions for every type of function [WK98]. Table 3.2 gives the types of functions and their associated possible failure conditions for the present FHA. The given possible failure conditions for each function type are not inherited by every function, e.g. the function "Determine Position" can not return a "false high" or "false low" value, but only a "false" value, since the position can not be determined too high or too low. On the other hand, the function "Determine Speed" may return a value "false high" or "false low", where both possibilities have a different effect on the aircraft and need to be analyzed separately.

Failure Condition Classification:
Depending on the effects of a failure condition on the aircraft and its occupants, each failure condition will be classified following the definitions in [Fed02]. The

Table 3.2.: Types of functions and their associated possible failure conditions

Function type	Possible failure conditions	Example
Determination	False High, False Low, False, Total Failure	Position Determination
Communications	False High, False Low, False, Total Failure	Send Commands to AFDS, Receive Sensor Data
Control	Too High, Too Low, Too Early, Too Late, Total Failure	Lateral Flight Path Control
Visualization	Partial Failure, Complete Failure	Representation of Information on Displays
Event	Inadvertent Initiation, Failure to Initiate	Accept/Decline Flight Plan

effects on the humans on board is divided into effects on *occupants* (not crew) and *crew*. [Fed02] gives five possible severities of failure conditions and their qualitative and quantitative probability terms (compare to table 2.1).

Examined Functions:
The functions examined in this FHA are limited to functions essential for a safe flight conduction in the enroute portion as well as optimizing trajectories and handling the results. The functions examined are intended to cover the envisioned application of TEOS as described in section 3.2.

3.4.1.2 Functional Hazard Analysis Results

The results of the conducted FHA are given in a table, following the recommendations in [Soc96] for the representation of FHA results. The table contains data as exemplary depicted in table 3.3.

The results for the FHA for the CoreFMS functions and the Mobile Device functions are given, in detail, in appendix A. The goal of the FHA was to assess the DAL of the functions identified to be placed in the TEOS. To place a function on the EFB, the DAL needs to be E or F which corresponds to Minor or No Safety Effects (Compare to section 2.5.1). A failure of these functions will not have a more adverse effect than the effects specified in table 2.1. Appendix A groups the analyzed functions to their intended placement either on the CoreFMs or the EFB.

Table 3.3.: Example of results table

Function	Failure condition	Phase	Effect	Classification	Verification and supporting material
...	...	...	...	...	...

The FHA revealed that eleven out of twenty-six examined functions are classified as Minor or No Safety Effect which corresponds to 42.3% of all analyzed functions. All functions intended to be placed on the EFB are classified as Minor or No Safety Effect. An example for functions remaining on the CoreFMS are the position determination and the control of the lateral flight path. Both functions were classified with a Major effect for all failure conditions. An example for a function that is shiftable to the EFB is optimization of the vertical profile, which is classified as having No Safety Effect. Even though the FHA was carried out with a limited scope, the results implicate that the intended function shift is feasible.

3.4.2 Security Considerations

Security issues are concerning all parts of the modern digital world. All participants, private and business, of networks are endangered to be the victim of cyber attacks. These attacks may have the aim to gather information, alternate information, tamper with business operations or to disturb the network operations. As IASIELLO [Ias13] states, the aviation industry is no exception to the mentioned threats.

The architecture of TEOS necessarily includes a connection between the CoreFMS and the EFB. A breach in this connection will have strong impact on the safety of the aircraft and its occupants. An intruder can intercept messages, alternate them, compose own ones or bring the networks communication to a hold. This section analyzes measures to protect the connection and elaborates on the measures chosen for the approach of this thesis.

3.4.2.1 Connection between CoreFMS and Electronic Flight Bag

First considerations are made about the medium that connects the CoreFMS and the EFB. The Operational Environment envisions the EFB to be a Commercial off the Shelf (COTS) hardware. Naturally, those devices offer a wired connection and a wireless connection. Both connections offer advantages and disadvantages, which are highlighted in table 3.4, where the entries of table 3.4 are discussed in the following section.

Table 3.4.: Comparison of wirless and wired network connections

	Wireless	**Wired**
Batterylife	Not chargeable	chargeable
Installation effort	Wireless access point, certification of access point	Wires and wiresocket, certification of installation
Effort of EFB device change	New device needs to support installed WiFi protocol	Wire and wiresocket need to be changed, certification of new installation
Jamming resistance	No	Yes
Maintenance effort	EFB device can be maintained without ground time.	Wire and wiresocket need maintenance.

Batterylife:
As mentioned in section 3.4.1.1, the expected operational scenario for TEOS is a longhaul flight. In the most favorable scenario the pilots begin their flight with a fully charged EFB device. The screen of the EFB is expected to be active throughout the whole mission to depict charts and other information[6]. The battery life of a fully charged EFB device used today does not expand over the whole expected mission duration [Mic17; App17][7], which calls the need for charging equipment in the cockpit. Charging can only be supplied by a wire installed in the cockpit. Therefore, even if a wireless connection is used for communication between the CoreFMS and the EFB, an installation for charging the device is needed.

Installation Effort:
Both available connection options require a certain installation effort. A wireless

6 The mission contains pre- and postflight tasks.

7 The battery duration of two fully charged models that are in operational use as EFB today were considered [Mic14; Jep16]. The battery duration was determined by the manufacturers, where the duration under operating conditions may vary.

connection needs an access point that spans a wireless network in the cockpit that is able to provide a signal with sufficient strength all over the cockpit that does not interfere with other electrical equipment of the aircraft. In the scope of this thesis it is estimated that the aircraft is already equipped with such a device. Today AIDs are available that offer the same functionality, as an example [Ast17].

A wired connection has different needs. A wire needs to be installed in a way it does not hinder operations in the cockpit. The installation needs to be certified to ensure its safety. Additionally, the wire needs a socket that is connected to a power source and the aircraft's network. The installation of this socket needs to be certified, too. On the other hand, wired connections contribute 2-5% to an aircraft weight [ITU11], where care should be taken to keep any increase in wiring to a minimum.

Effort of EFB Device Change:
Hardware capabilities are increasing fast, especially in means of processing power [Moo06], which calls for frequent replacements of EFB devices. A wireless connection supports changes in EFB devices seamlessly, since new devices only need to support the installed wireless network protocol. The effort to change devices in a wired connection based solution is greater, since new wires and sockets might need to be installed and certified.

Jamming Resistance:
Wireless networks are vulnerable to jamming devices. Even though manifold countermeasures to jamming exist, there is no countermeasure that reduces the chance of being jammed to an acceptable minimum [AMH+15]. A jammed network will prohibit any communication between the EFB and the file server and imposes a danger to the flight. Even though an Aircraft Wireless Network (AWN) can employ a band of frequencies, a multi-spectrum frequency jammer is able to block all communications [AMH+15].

Maintenance Effort:
In both solutions, the EFB device itself can be removed from the aircraft and maintained off board, which does not impose any ground time for the aircraft. Both the wireless access point and the installed wired connection and socket need maintenance that requires ground time of the aircraft.

All factors mentioned above focus on cost influences, e. g. through certification efforts or maintenance, or safety related issues. Safety being of highest concern in system design, safety related aspects are of special interest. The inability to provide an effective jamming resistance is the crucial factor for the decision for a wired connection between the file server and the EFB.

3.4.2.2 Secure Network Connection and Communication

THANTHRY and PENDSE [TP04] mention three basic security requirements for avionic data networks independent of the type of connection. These are confidentiality, authentication, and integrity. Confidentiality depicts the privacy of users, integrity the secure transmission of data without a third party altering it and authentication controls access to the network. Most crucial is authentication, which prohibits a third party of gaining access to the network and carrying out malicious activities. As outlined in section 3.4.2.1, TEOS is using a wired connection, which itself is a protection against malicious third parties entering the network. A multifactor authentication is used to connect the EFB to the aircraft network. A multifactor authentication is using several objects to identify a user, as stated by BURR ET AL. [BDN+13][8]. The multifactor authentication on the proposed system consists of a Media Access Control (MAC)[9] address filter as well as a PIN. Upon the attempt of a EFB device which MAC address is deposited in a database to access the network, a PIN is displayed on the CDU display of the CoreFMS and needs to be entered on the EFB.

Even though MAC addresses are unique, more factors to secure the authentication are necessary since methods exist to eavesdrop and spoof MAC addresses of devices participating in a network, as outlined by JUNG ET AL. [JKK11]. The usage of PINs provide an additional layer of security. PINs are generated randomly and are session based, hence expire after the flight or if the connection to the EFB was lost.

The system provides integrity by using encryption algorithms to send and receive data, as it was proposed by AKRAM ET AL. [AMH+15] and DANG ET AL. [DMG12] for AWN. Two basic principles, symmetric and asymmetric encryption are employed. In symmetric encryption, all transmission participants use the same key to encrypt and decrypt a message. Measures must be taken to keep this key private. In asymmetric encryption each participant possesses a pair of public and private keys. The public key enables other participants to encrypt message for the corresponding participant which the recipient can decrypt using it's private key. The public key

[8] An example for multifactor authentication is the combination of a bank account card and a corresponding Personal Identification Number (PIN), where both can not be used to withdraw cash without possessing the other.

[9] MAC addresses are assigned to a piece of hardware during the production process. They are unique and described in ISO 15802 [Int95].

does not enable other participants to decrypt any message. Asymmetric encryption requires a higher computation effort then symmetric encryption, which slows down communication. Asymmetric encryption is only used to exchange the keys for symmetric encryption, which allows transmission at higher rates.

3.4.3 Certification cost

The certification cost of TEOS will differ from certification cost of traditional FMS. Original Equipment Manufacturers (OEMs) rely on their experience in certifying products, where existing products often are the base for new developments. TEOS requires a completely new system architecture, where it is expected that previous developments can only be used to a limited extent. Additionally, the shift of functionality is expected to have an impact on certification cost. With more stringent certification requirements according to the DAL, certification cost of software increases. Table 3.5 depicts two studies conducted by Hilderman [Hil09] and Real-Time Innovations [RTI17], which examine the cost increase of software certification with its DAL.

Table 3.5.: Certification cost increase with DALs

Model	DAL E	DAL D	DAL C	DAL B	DAL A
Hilderman [Hil09]	Baseline	$E + 5\%$	$D + 30\%$ $Baseline +$ 36.5%	$C + 15\%$ $Baseline +$ 57%	$B + 5\%$ $Baseline +$ 65%
Real-Time Innovations [RTI17]	Baseline	$E + 50\$$ per ELOC			$E + 100\$$ per ELOC

The two studies differ in examining the overall cost and the cost per Executable Line of Code (ELOC) respectively. Hilderman [Hil09] shows the highest cost increase of 30% occurs between DALs D and C, where Real-Time Innovations [RTI17] only offers the differences between DALs E, D and A. However, both studies state that overall certification cost also depend on the development teams' experience, project complexity and overall amount of line of codes.

Since for TEOS functionality is shifted from at least level C to level D or E, a decrease in certification cost is expected. The FHA conducted and described in section 3.4.1.2 found that 42% of the current FMS functionality is shiftable to the EFB. With regards to [Hil09], this shift from DAL C to D will decrease the certification cost by 12.6%. The complexity of TEOS as well as the lack of reusable code will purge these cost reductions to a certain extent.

Additional savings are expected to occur during the software life cycle, when patches are developed. The implementation of shifted functionality does not require an expensive recertification, therefore patches can be issued on a lower cost basis.

3.5 Demonstrator Development

Evaluation and demonstration are of utmost importance when designing new system architectures. Accordingly, a demonstrator of TEOS was developed. To ensure flexibility of the developed system, its architecture and functional span supports integration into virtually any flight simulator. The system was integrated into the research flight simulator, Darmstadt Aircraft Environment for Research on Operations (D-AERO), at Institute of Flight Systems and Automatic Control (FSR).

The demonstrator is not intended to have the full capabilities as TEOS would have, as they were presented in the sections above. The demonstrator showcases a system utilizing the TEOS architecture in an enroute flight condition, with the simplifying assumption that no wind is present. Also, no optimization algorithm was implemented into the demonstrator, since this is not necessary to carry out the intended evaluation. To exemplary analyze the benefit of advanced optimization algorithms, an optimization algorithm was designed and evaluated using fast time simulations, compare to chapter 5.

3.5.1 Demonstrator Architecture

As the demonstrator is intended to work in simulated environments and depict only partial functionality, its architecture is simplified. The basic architecture remains the same, as it is depicted in figure 3.9.

The central elements remain the EFB and the CoreFMS. As no restrictions exist imposed by aircraft network domains, it was possible to abstain from a file server which acts as an AID to simplify the demonstrators development. As a User Interface (UI) to the CoreFMS, a traditional CDU is used and adapted with new pages. Interfaces to other aircraft systems exist to the autopilot and the Navigation Display (ND).

As avionic systems require to behave deterministic, they need to run on operating systems supporting such behavior. Real Time Operating Systems (RTOSs) allow system developers to impose temporal requirements on the execution of applications, where the operating system then prioritizes applications and allocates resources

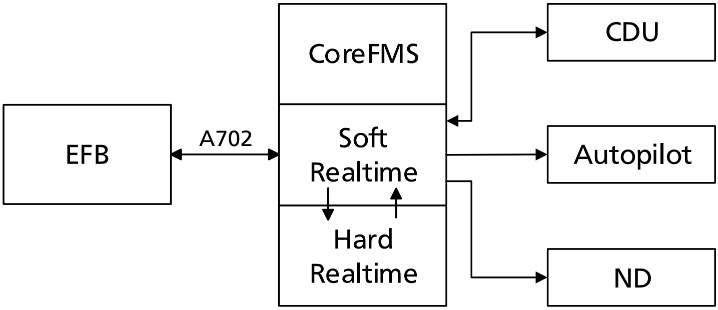


Figure 3.9.: Demonstrator architecture [illustration by author]

in order to fulfill the requirements. A RTOS was chosen to run the CoreFMS. After considering and comparing several RTOS, commercial and freely available, the Real Time Application Interface (RTAI)[10] was selected as the operating system for the CoreFMS. The CoreFMS is split in two sections, one of which runs periodically with a real time constraint of 40 Hz, where the other one in soft realtime without any time constraint. When the time constrained task is due for execution, the RTAI scheduler suspends all other tasks, including the Linux operating systems task. The real time task computes inputs for the autopilot, while the unconstrained task handles communication and administrative tasks. The data needed by the real time task to compute guidance values and the results are exchanged with the non-real time tasks via RTAI mutexes[11], which regulate access to data shared by the realtime and non-realtime task.

Communication between EFB and CoreFMS is bi-directional and carried out using messages defined in ARINC A702A-3 [Aer06b]. ARINC 702A-3 AOC messages form a difference to the exchange protocol described in section 3.3.2. The protocol was ready available and could seamlessly be integrated, while there was no functional advantage of implementing the FIXM message structure or the demonstrator. The messaging protocol relies on User Datagram Protocol (UDP) as it is

[10] RTAI is a patch for a Linux kernel, which makes it real time capable. The patch inserts a scheduler, which handles Linux tasks and application tasks and prioritizes them. RTAI also offers an Application Programming Interface (API) to enable the developer to impose requirements and implement inter-process and inter-task communication. [Man16]

[11] Mutexes (Mutual Exclusion) are a solution to the problem of two processes being in their critical section, i.e. reading or writing from or to a shared resource. The need for mutexes and a solution to the problem were first described in [Dij65].

defined in [Int80][12]. The communication protocol between the CoreFMS and the simulator infrastructure (CDU display and keyboard, ND and autopilot) depends on the simulator structure the system is integrated in. Therefore, every integration of the system into a simulator requires a certain effort to adapt to the simulator structure.

3.5.2 CoreFMS Demonstrator Capabilities

The CoreFMS is, as mentioned above, responsible for executing flight plans that it received from the EFB. In order to fulfill this task, the CoreFMS is able to hold several flight plans in its memory and activate them. Once a flight plan is activated, the CoreFMS begins to compute guidance values that are transferred to the autopilot. The functions of flight plan management and guidance value computation are presented below.

3.5.2.1 Flight Plan Handling

Flight plan handling describes the functions and their user interfaces of reviewing, activating or deleting flight plans. The flight plan handling functionality was designed with the corresponding UI in mind, which was chosen to be a contemporary CDU, since one was readily available in the targeted flight simulator.

The flight plan handling functions run in the non realtime tasks of the CoreFMS. As depicted in figure 3.10, the system is able to handle two primary flight plans, the active and the secondary one, as well as an infinite number of updated flight plans that were sent from the EFB. The two primary flight plans are accessible via quick access buttons on the CDU, whereas the updates are accessible via a context menu.

Initializing, Swapping and Updating Flight Plans Process

When starting the CoreFMS, all flight plan slots are empty. In order to initialize the system, a flight plan needs to be send from the EFB, which is automatically set to be active. Each successive received flight plan is stored in the update stack. When reviewing an updated flight plan on the CDU, the user has the option to either activate (insert) or delete the update, or leave the review page without any action

[12] UDP is an Internet Protocol (IP) based messaging protocol for computers inside a network. The protocol can not guarantee delivery, but is designed to keep protocol mechanisms to a minimum. [Int80]

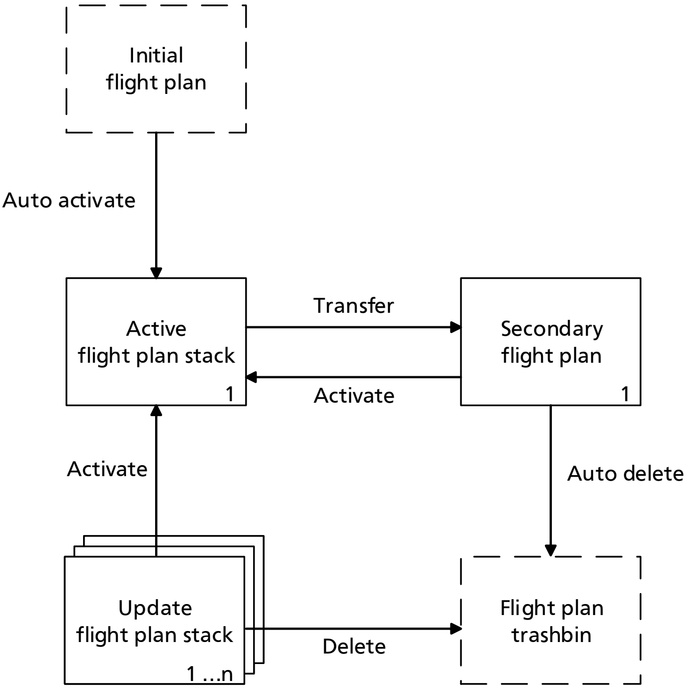


Figure 3.10.: Structure of flight plan handling [illustration by author]

as illustrated in figure 3.11. When reviewing a flight plan, the pilot is offered a scrollable list of waypoints, which contains waypoint names and coordinates. The list also depicts associated Required Time of Arrival (RTA) constraints at waypoints. Additionally, the reviewing page offers a comparison between the update identifier and the identifier of the current active flight plan (ACT ID), as well as the identifier of the flight plan the update is based on (CANCELS ID). Identifiers are assigned by the CoreFMS and then communicated to the EFB. They are designated to support pilots in their situational awareness. By comparing the identifiers on the review page, the pilot is able to identify if the currently reviewed update is based on the currently active flight plan or based on an older version.

If an update is selected for activation, it is copied to the active flight plan, whereas the current active flight plan is copied to the secondary flight plan. If both active and secondary flight plan exist, activating the secondary flight plan will cause a swap with the active flight plan. If both active and secondary flight plan

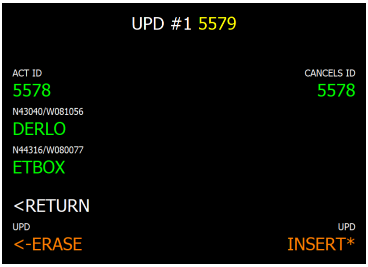
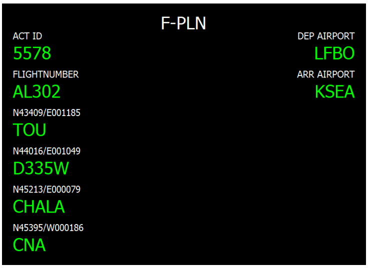


Figure 3.11.: Update review page on the CDU [screenshot by author]

exist and an update is selected for activation, the currently active flight plan will replace the current secondary flight plan, which is deleted. Until the user specifically deletes an updated flight plan, it remains in the stack and can always be re-activated. Similar to the update review page, the CDU offers a review page for the active and secondary flight plan as shown in figure 3.12, which do not offer a deletion option.



(a) Active flight plan page on the CDU

(b) Secondary flight plan page on the CDU

Figure 3.12.: CDU subpages [screenshots by author]

Flight Plan Depiction

The currently active flight plan is sent to the simulator environment for depiction on the ND. In addition, the currently active flight plan is sent to the EFB, where it is depicted visually and textually as well as used for flight plan editing (compare to section 3.5.3).

3.5.2.2 Lateral Guidance

Lateral guidance is a function that is computing commands for the lateral autopilot channel in order to keep the aircraft on its intended track along the active flight plan. The first step in lateral guidance is to determine to which of the legs of the flight plan the guidance value should be determined to. The determination of the current leg is done by checking two conditions, which are also exemplary depicted in figure 3.13 for two legs. First, it is checked if the aircraft is located inside the area of the radius of any leg (r_{12} or r_{23}). For all the legs for which this condition is true, the one to which the aircraft has currently the smallest Cross Track Error (XTE)[13] (XTE_{12} or XTE_{23}) to is set as active leg.

If the first condition is not true for any leg, the leg to which midpoint the aircraft has the shortest distance (d_{12} or d_{23}) is set as active leg.

Dependent on the required track changes between two legs and the current speed, TCPs are computed for each leg, which flyover triggers the CoreFMS to set the subsequent leg as active. Figure 3.14 depicts the different locations of TCPs with respect to the course change between two legs, to allow for a smooth transition and prohibit overshooting.

The goal of the lateral guidance function is to minimize the XTE and the track error for the current active leg. To achieve this goal, a PI control algorithm was implemented. The algorithm computes a target heading for the aircraft, which is forwarded to the autopilot. The target heading is determined by equation 3.1.

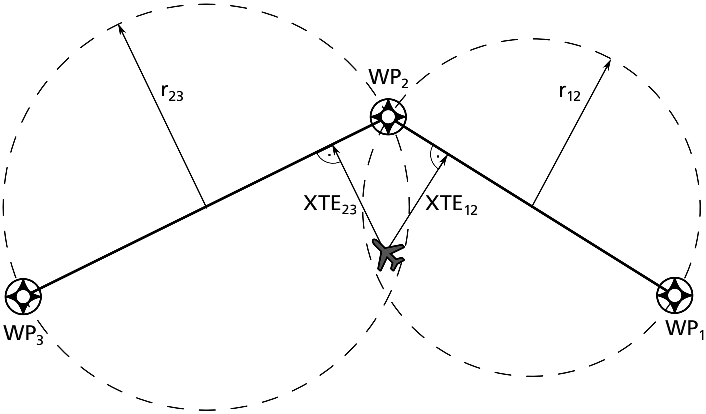
$$\psi_{target} = \psi_{WP12} - sgn(XTE) \cdot min\left(\Delta\psi_{course}, \Delta\psi_{Intercept,max}\right) \tag{3.1}$$

where ψ_{WP12} is the course of the active leg. Depending on the sign of the XTE, the smaller of either $\Delta\psi_{Intercept,max}$ or $\Delta\psi_{course}$ is added to ψ_{WP12}. $\Delta\psi_{Intercept,max}$ depicts the maximum intercept angle, which is dependent on the absolute value of the current XTE. As depicted in figure 3.15, the area next to a leg is divided in four sections, defined by perpendicular distances to the legs.

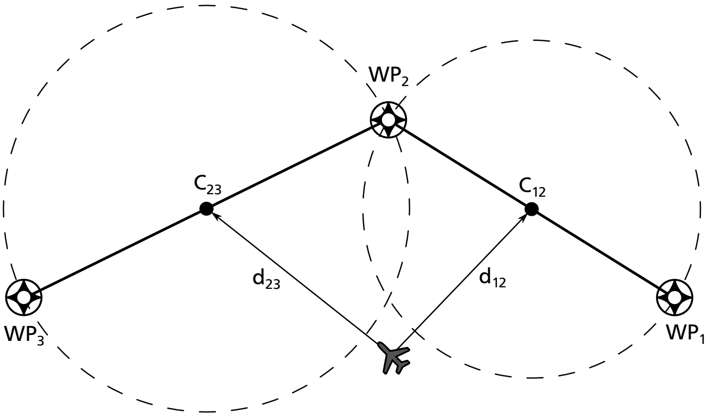
Table 3.6 depicts parameters that change within the sections. As can be seen, the maximum intercept angle increases with an increasing distance to the leg, to allow a fast approach to the leg. $\Delta\psi_{course}$, on the other hand, is computed as described in equation 3.2

$$\Delta\psi_{course} = k_i \cdot I_{ControlValue} + k_p \cdot XTE \tag{3.2}$$

[13] The XTE is defined as the perpendicular distance between a leg and the aircraft current position. It is defined to be positive if the aircraft is located to the right of the leg and negative to the left.



(a) Inside of leg radius



(b) Outside of leg radius

Figure 3.13.: Conditions for the determination of the active leg [illustrations by author]

where k_i and k_p are the gain parameters for the I and P part of the controller respectively. They also change with the perpendicular distance to the leg and their values are given in table 3.6.

The values for k_i and k_p were determined to allow control at higher altitudes and cruise speeds, since the demonstrator is intended to depict operations of the

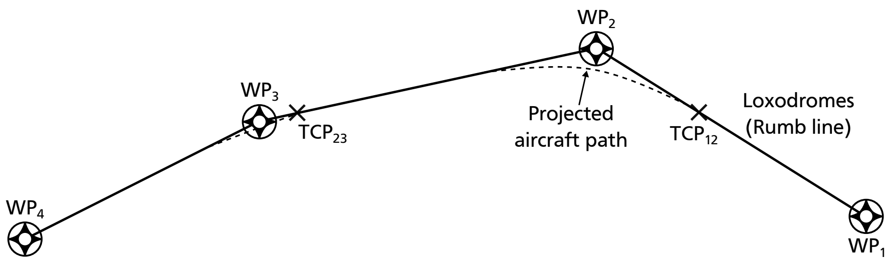


Figure 3.14.: TCP computation with respect to leg course change [illustration by author]

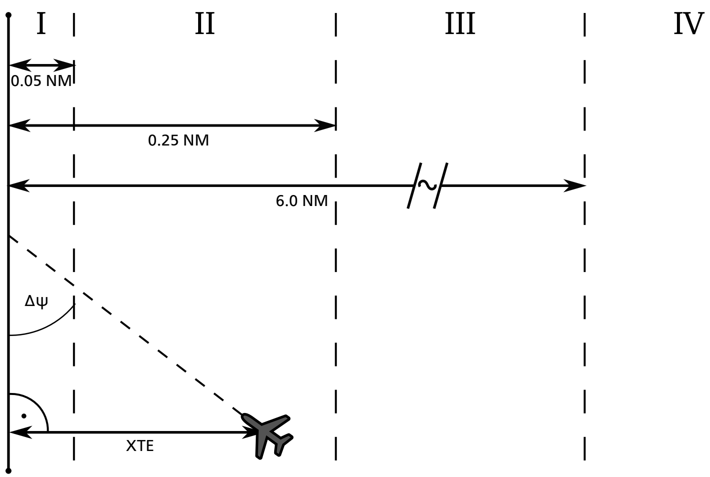


Figure 3.15.: Sections for XTE control [illustration by author]

Table 3.6.: Control parameters in section perpendicular to a leg

	I	II	III	IV
Distance in NM	0.05	0.25	6	> 6
$\psi_{Intercept,max}$	5	30	40	75
k_p	0.05	0.1	0.2	0.5
k_i	0.0003	0	0	0

system in enroute flight conditions. Lastly, $I_{ControlValue}$ is determined by equation 3.3.

$$I_{ControlValue} = \sum_{k=1}^{250} \overrightarrow{XTE}_{memory_k} \tag{3.3}$$

3.5.2.3 Vertical Guidance

Vertical Guidance is only provided to waypoints that are imposed with a vertical constraint in the ARINC A702A-3 message. If the vertical guidance function detects a constraint, the aircraft is steered into a corresponding climb or descent, until the constraint altitude is reached.

3.5.2.4 Temporal Guidance

Temporal Guidance is provided to waypoints that were imposed with a temporal constraint. Temporal constraints are included in the ARINC A702A-3 message along with vertical constraints. If a temporal constrained waypoint is located in the remaining legs of the flight plan, the temporal guidance functions becomes active. If there are no temporal constrained waypoints, the temporal guidance function issues a command to fly with a Mach number of $M = 0.77$[14].

Temporal guidance is held inactive until the aircraft reaches a certain temporal distance to the RTA constrained waypoint. This deadband aims to decrease throttle activity in order to save fuel. The initial deadband tolerance is set to five times the RTA tolerance $t_{RTA_{Tol}}$ at the constrained waypoint, as it is depicted in figure 3.16.

This tolerance is valid as long as the aircraft is more than $90 \cdot t_{RTA_{Tol}}$ away from the RTA constrained waypoint, from this point and until a distance of $60 \cdot t_{RTA_{Tol}}$, the tolerance is linear decreasing until it reaches $t_{RTA_{Tol}}$. At a distance of $30 \cdot t_{RTA_{Tol}}$, the commanded speed is held constant to avoid building up errors [15].

The speed command itself is determined via equation 3.4, where $d_{WP_{RTA}}$ represents the along track distance to the next RTA constrained waypoint and $t_{available}$ the duration in which the distance needs to be flown in order to meet the temporal constraint.

[14] This Mach number was chosen to match the intended simulated aircraft, an Airbus A320-200. Compare also to section 3.5.4.

[15] Compare to equation 3.4, where $t_{available}$ will decrease to an infinitesimal small value, which will result in an infinite high speed command.

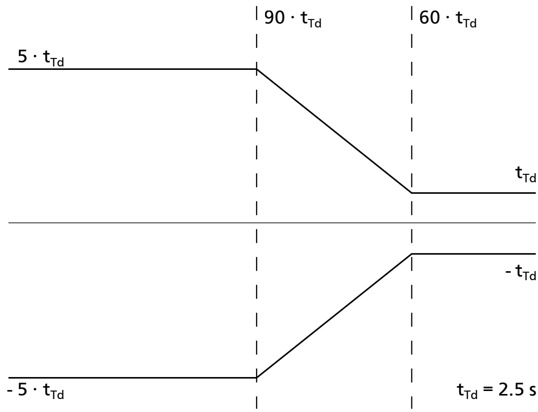


Figure 3.16.: Deadband for RTA control [illustration by author]

$$V_{Command} = \frac{d_{WP_{RTA}}}{t_{available}} \tag{3.4}$$

In addition, the computation of $t_{available}$ considers the factor k_{acc}, which takes into account the acceleration or deceleration needed to obtain the target speed (see equation 3.5).

$$t_{available} = k_{acc} \cdot (T_{RTA} - T_{actual}) \tag{3.5}$$

Equation 3.4 issues a Groundspeed (GS), whereas the autopilot requires an Indicated Airspeed (IAS) as input, hence $V_{Command}$ is transformed into IAS by equation 3.6

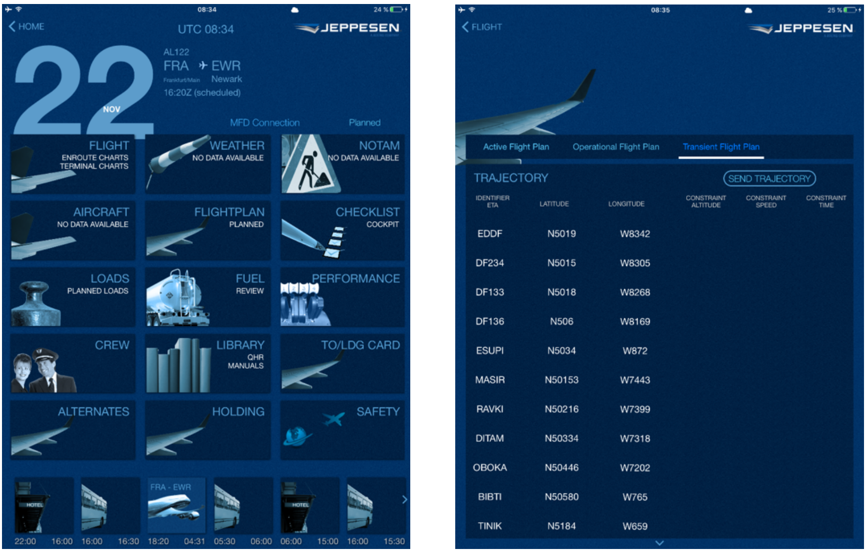
$$V_{Command,IAS} = V_{Command,GS} \cdot \sqrt{\frac{\rho_{Air}}{\rho_0}} \tag{3.6}$$

under the assumptions of no wind [16] and $\rho_0 = 1.225 kg/m^3$.

[16] Under the assumption that no wind is present, the GS equals the True Airspeed (TAS).

3.5.3 Electronic Flight Bag Demonstrator Capabilities

The mobile part of the demonstrator, the EFB, is meant to exemplarily represent the potentials an airline gains when operating a system according to the architecture developed in this thesis. Jeppesens Door2Door (D2D) application running on an iPad tablet computer was used as a basis for the EFB demonstrator. D2D was designed by HANKERS [Han15] as a mean to support pilot workflow during all phases of flight. Figure 3.17a depicts the main page of D2D, from which the Flight and Flightplan were expanded in the scope of this thesis. The Flight page offers the user a zoomable and panable map view, whereas the the Flightplan page offers textual representations of flight plans, both are presented in figure 3.17. The pages were expanded with functionality to edit, review and send flight plans to the CoreFMS.



(a) Flight Page ©Jeppesen

(b) Transient Flight Plan page ©Jeppesen

Figure 3.17.: D2D main and review pages [screenshots by author]

3.5.3.1 Flight Monitoring

On the Flight as well as on the Flightplan page, the user is offered information to monitor the progress of the flight. The Flight page offers a chart view together with an ownship symbol, showing the current position of the aircraft along with the flight plan and aeronautical charting information. The Flightplan page depicts the waypoints of the flight plan along with possible existent constraints (compare to figure 3.18b).

In figure 3.18a the active flight plan is represented as a green line, where the blue line depicts the original operational flight plan. Both active flight plan and ownship symbol information are retrieved from the CoreFMS via ARINC A702A-3 messages. D2D sends a request to the CoreFMS, which automatically answers with a message containing the requested data. Position reports, feeding the ownship symbol, are requested with a frequency of 1Hz and flight plan reports are requested with a frequency of 0.2Hz.

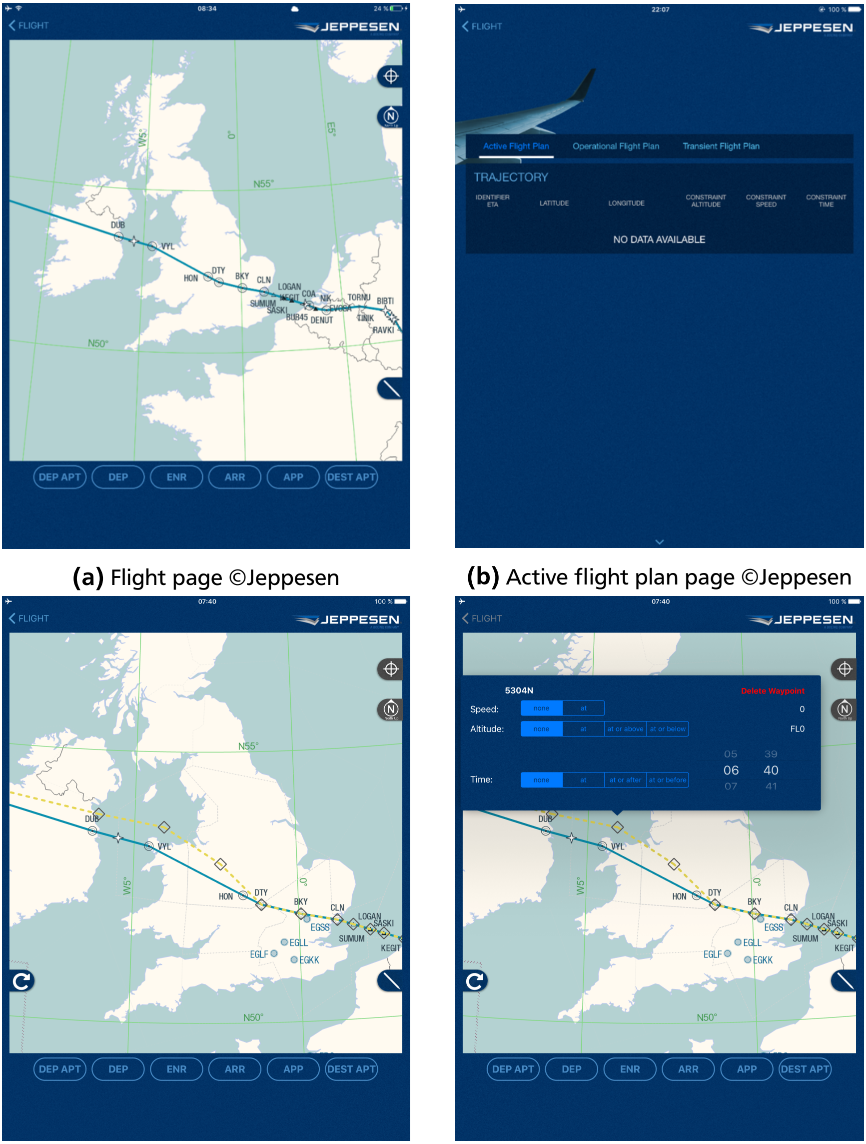
3.5.3.2 Flight Plan Editing

The flight plan editing function takes place on the Flight page. When touching the edit button, represented by a pen, the currently active fight plan is overlaid by a dashed yellow line, waypoints are depicted by a black diamond, see figure 3.18c. Now, the waypoints can be dragged and dropped on the chart, either on navigation aids contained in the database, or on arbitrary positions. Waypoints can be added by longpressing anywhere on the screen, except on existing waypoints. Arbitrary located waypoints are named following conventions laid out in [Aer11] with a five character name, depending on the hemisphere the waypoint is located in.

When a longpress on an existing waypoint is performed, the waypoint menu appears as shown in figure 3.18d. The waypoint allows the user to add constraints at a waypoint or delete the waypoint from the flight plan. Constraints can be added for speed, altitude and time.

3.5.3.3 Flight Plan Review and Sending

Once a flight plan was edited, a textual representation of it, named Transient Flight Plan, becomes available on the Flight Plan Page, see figure 3.17b. The Transient Flight Plan has the same format as the active flight plan, where waypoint names are depicted along with corresponding constraints. The Transient Flight Plan page offers a button to send the flight plan to the CoreFMS, where it is received as an update.



(a) Flight page ©Jeppesen

(b) Active flight plan page ©Jeppesen

(c) Flight page in editing mode ©Jeppesen

(d) Waypoint editing ©Jeppesen

Figure 3.18.: D2D Pages relevant for flight monitoring and editing [screenshots by author]

3.5.4 Integration into Research Flight Simulator

The demonstrator was integrated into the research flight simulator at FSR. The flight simulator D-AERO has been operated at FSR to support research projects since 1993. Though it has evolved over time, a collimated visual system remains the core of the simulator. In its current setup, D-AERO depicts an Airbus A320-200 aircraft in hardware and software functionality. Hardwarewise, the simulator consist of essential elements needed to control the aircraft such as sidesticks, an original Airbus A320 Flight Control Unit (FCU) and a CDU, as well as several touch screen displays, which allow for a seamless integration of pilot assistance systems. The layout of D-AERO's cockpit is depicted in figure 3.19. Softwarewise, the simulator relies on X-Plane [Lam17], which runs with a proprietary model of the Airbus A320-200 systems and Fly-by-Wire (FBW) logic. The standard display suite depicts independent Primary Flight Displays (PFDs) and NDs for the captain and first officer side, as well the CDU display on the captains side and the Electronic Centralized Aircraft Monitor (ECAM) Engine and Warning Display (EWD) and System Display (SD) on the central displays.

Figure 3.19.: The flight deck of D-AERO [photograph by author]

The CoreFMS needs to be adapted to the simulator structure it is integrated with. As D-AERO uses X-Plane as a backbone, data exchange between X-Plane and the CoreFMS needed to be enabled. For this purpose, a proprietary exchange protocol developed at FSR [Eng01] is used. The same protocol is implemented to enable the exchange of data between simulator hardware and X-Plane, as well as feeding displays with data. This data exchange takes place in the simulator network, as depicted in figure 3.20. Data exchange between the CoreFMS and the EFB takes place in the FMS network, which for the demonstrator is implemented via a wireless network.

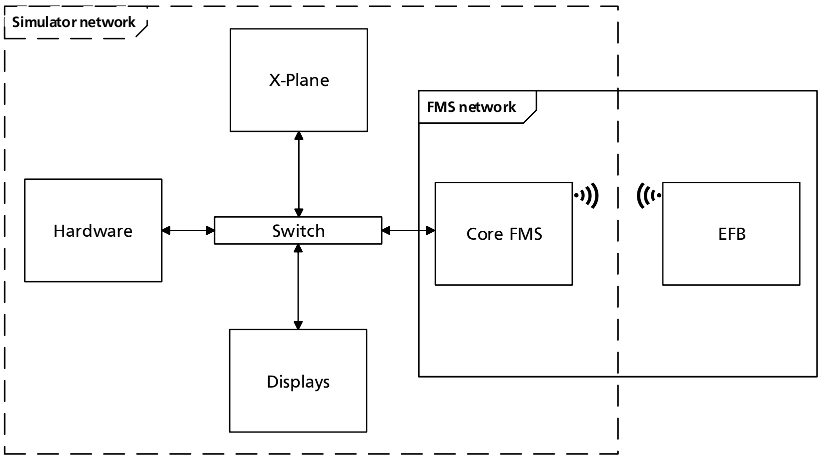


Figure 3.20.: Integration of the demonstrator in D-AERO [illustration by author]

Figure 3.21 shows the setup of D-AERO for demonstration of TEOS. The EFB is placed on the captain's side next to the PFD/ND displays, in a manner that leaves the sidestick movable to its maximum deflections. The wireless connection to the CoreFMS prevents any obstruction by wires in the simulator. For operation of the demonstrator the removal of the EFB from its mount is not intended.

3.6 Summary

A design for a future FMS dubbed TEOS was developed, which addresses shortcomings of traditional FMS as presented in chapter 2. The proposed architecture builds around the concept of shifting functionality from the FMS to the EFB, resulting in a compound of a CoreFMS and the EFB, which are able to exchange data. A conducted FHA revealed that fundamental functionality can be shifted without safety infringements. In further steps, transmittable data and the details of the connectivity were defined. Transmittable data relies on data standards available today such as FIXM and WXXM. To prevent any jamming, the connection between

Figure 3.21.: The EFB mounted in D-AERO [photograph by author]

the CoreFMS and EFB is designed as a wired connection which is using multi-factor authentication and asymmetric as well as symmetric encryption.

A system demonstrator was developed and integrated into a research flight simulator. The demonstrator represents the core capabilities of the system architecture by using a CoreFMS based on an RTOS and an EFB application.

4 Usability Study Based on the Demonstrator

After designing the Trajectory Execution and Optimization System (TEOS) architecture, the following chapters focus on its' evaluation. The developed demonstrator was to be used as a tool to evaluate the system architecture regarding its usability from the perspective of its users, the pilots. This chapter gives information on the concept of usability and structure, conduction and result assessment of a study to evaluate the proposed system's usability.

The analysis of the study results revealed that the system demonstrator is accepted as usable.

4.1 Principles of Usability

The concept of usability is described in ISO/DIS 9241 Part 11 [Int16c], which gives the definition of usability as follows:

> *Usability is the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use.*

In this definition specified users, goals and context define the specific environment the system to be evaluated is used in. Usability is considered to be a suitable measurement to evaluate the developed system architecture from the perspective of a user. When evaluating usability, one should concentrate on three main categories effectiveness, efficiency and satisfaction, see also figure 4.1.

Effectiveness

As the first category of usability, ISO/DIS 9241 Part 11 [Int16c] defines effectiveness in the following way:

> *Effectiveness is the accuracy and completeness with which users achieve specified goals.*

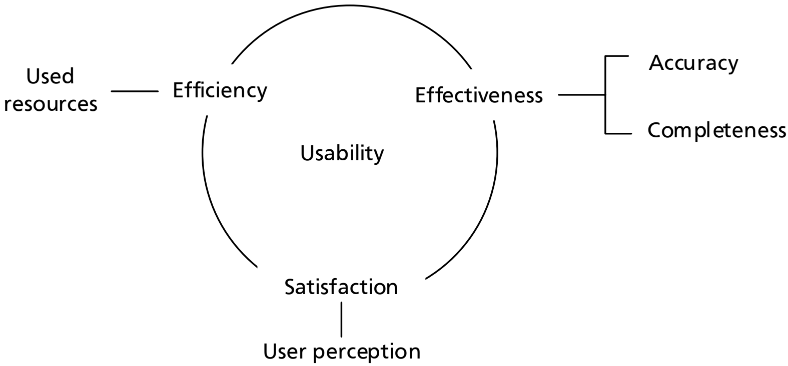


Figure 4.1.: Definition of usability after [Int16c]

By this definition, effectiveness is to be understood as the degree of completion of the intended outcome of the use of the system. Depending on the goal of the executed task, the outcome can be missed which corresponds with a failure in task execution. In this case, the accuracy does not need to be further evaluated.

Efficiency

Following effectiveness, ISO/DIS 9241 Part 11 [Int16c] defines efficiency as:

> *Efficiency is the resources used in relation to the results achieved.*

In the context of usability efficiency is to be understood as the expended resources during task execution. Resources again can be depicted by a variety of different efforts such as temporal, financial, material or cognitive effort invested by the user into solving the task. Efficiency finally depicts the proportion of the results achieved and the expended resources, where it is favorable to achieve the the best results according to the effectiveness measurement using the lowest amount of resources.

Satisfaction

As last category of usability, the definition of satisfaction by ISO/DIS 9241 Part 11 [Int16c] is given below:

> *Satisfaction is a person's perceptions and responses that result from use of a system, product or service.*

In the context of usability, satisfaction is the subjective impression the user gained of the system while trying to achieve his or her goals.

Since the system proposed in this thesis aims to improve the Flight Management System (FMS), the usability of both a traditional FMS and the new system are intended to be measured and compared in this study. The following section describes the design and conduction of study trials, which closely rely on the concept of usability.

4.2 Trial Design and Execution

In this section, the design and execution of the trials for the study are described in detail. Hard- and software setup, flight scenarios as well as the hypotheses to be answered and the recorded indicators are presented.

4.2.1 Concept

The concept of the study is to compare the TEOS architecture to a traditional FMS. To achieve this goal, professional airline pilots were asked to participate in the trials and perform a certain task using a traditional FMS as well as the system demonstrator developed in the scope of this thesis. The studies goal is to evaluate TEOS in a typical operational scenario, as described in section 3.2. As the developed demonstrator focuses on trajectory planning and execution in enroute conditions, a task and scenarios for planning and implementing a diversion trajectory were chosen.

As aircraft regularly encounter adverse weather during the enroute phase [Nat17], the task in the trial was to plan and implement a diversion route around an area of adverse weather defined by a Significant Meteorological Phenomena (SIGMET), or generally around a No Fly Zone (NFZ). The task can be divided into three relevant subtasks:

1. Identify Adverse Weather Area:
The area affected by adverse weather is given as a SIGMET text message. The participant needs to identify this area on a relevant chart in order to plan a diversion route around it.

2. Plan and Enter Route Around Weather Area:
After identifying the area affected by the weather, the participant needs to identify the portion of the active route affected by the weather and plan a diversion route around it. After planning the route, the participant inputs the new route into the respective input device.

3. Review and Activate New Route:
As a last step, the participant reviews the planned diversion route and, if the routes satisfies the needs, activates it for execution.

4.2.2 Simulation Setup

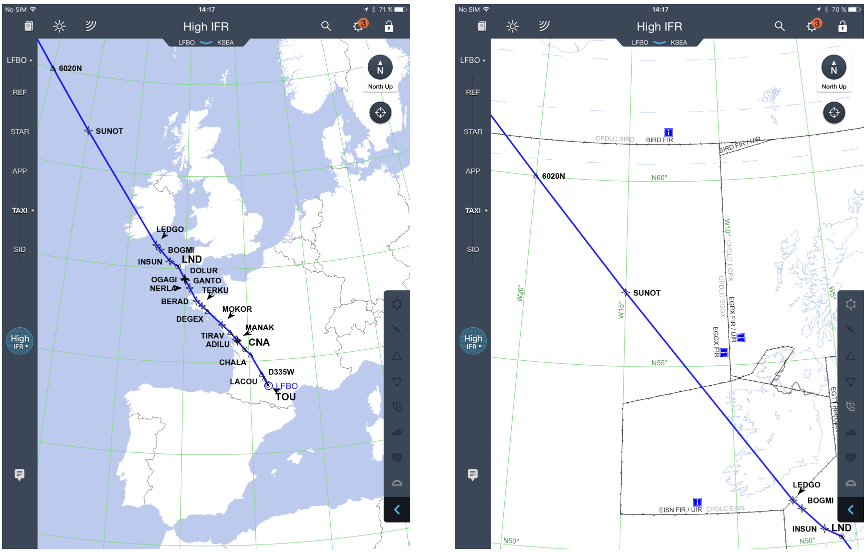
This section describes the simulator setups used to depict the needed environments in Darmstadt Aircraft Environment for Research on Operations (D-AERO) for a traditional FMS as well as the TEOS demonstrator. In the scope of this study, the traditional FMS was labeled "FMS". Both setups share the common display suite of D-AERO consisting of an independent Primary Flight Display (PFD) and Navigation Display (ND) on the captain's and first officer's side as well as the Electronic Centralized Aircraft Monitor (ECAM), Engine and Warning Display (EWD) and System Display (SD) (compare also to section 3.5.4). To deliver the SIGMET text message, a separate display was integrated below the EWD. For both setups, Electronic Flight Bag (EFB) applications were used for charting and route planning purposes, where the EFB was placed on the captain's side next to the sidestick. The general arrangement is depicted in figure 4.2, showing the EFB next to the captain's sidestick and the SIGMET display on the center screen.

Besides the shared elements, the two setups differ in several elements. The EFB application and the Control and Display Unit (CDU) display are specific to each setup.

4.2.2.1 Traditional Flight Management System

In the FMS environment, no connection between EFB and FMS is provided. The EFB charting application is used to plan the diversion route, but it is entered into the FMS interface on the CDU via the Line Select Keys (LSKs) and the alphanumeric keyboard. Serving as a charting application is Jeppesens *Mobile FliteDeck*. *Mobile FliteDeck* offers enroute charting, depiction and altering of flight plans as well as depiction of terminal navigation charts of Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs). Figure 4.3 shows the charting and flight plan depiction in *Mobile FliteDeck*.

Figure 4.2.: Trial setup in D-AERO [photograph by author]



(a) Zoomed out ©Jeppesen **(b)** Zoomed in with higher details ©Jeppesen

Figure 4.3.: Mobile FliteDeck flight plan depiction [screenshots by author]

In the FMS setup the CDU depicts the traditional[1] interface to the FMS. In D-AERO, the display of the CDU is provided by the standard simulator software. Figure 4.4 depicts the flight plan page, on which the currently active flight plan can be reviewed and edited. This is the only page used by the participants during the trials of the study. The participants were free to use any function of *Mobile FliteDeck*.

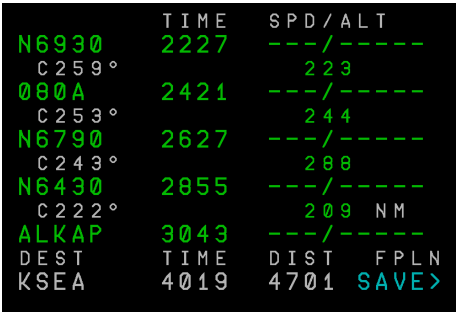


Figure 4.4.: CDU flight plan page [screenshot by author]

Flight guidance along the active flight plan is provided by the standard simulator FMS.

4.2.2.2 Trajectory Execution and Optimization System

The TEOS setup matches with the setup of the demonstrator as described in section 3.5.1. The EFB is placed in the same position as in the traditional FMS setup.

4.2.3 Flight Scenarios

Two flight scenarios were created to give a basis to the task defined in section 4.2.1. The flights chosen are two longhaul flights from Toulouse-Blagnac to Seattle-Tacoma (International Civil Aviation Organization (ICAO) codes LFBO and KSEA) and Toronto-Pearson to Beijing-Capital (ICAO codes CYYV and ZBAA). In the scope

[1] As stated in chapter 2.1.2.8, higher sophisticated interfaces exist. The amount of aircraft in service using such devices are small compared the number of aircraft in service equipped with a CDU. As an example 226 Airbus A380 and 174 Airbus A350 are in service equipped with a Keyboard Cursor Control Unit (KCCU), but 7793 aircraft of the Airbus A320 family are in service equipped with a CDU [Air18a].

of this study the flight scenarios were labeled flight scenario 1 and 2 respectively. The flight plans were computed using Jeppesens *Jetplan* flight planning engine to ensure realistic routing. Figure 4.5 depicts the routes of the flight plans. A full description of both flight plans is found in appendix B.1.

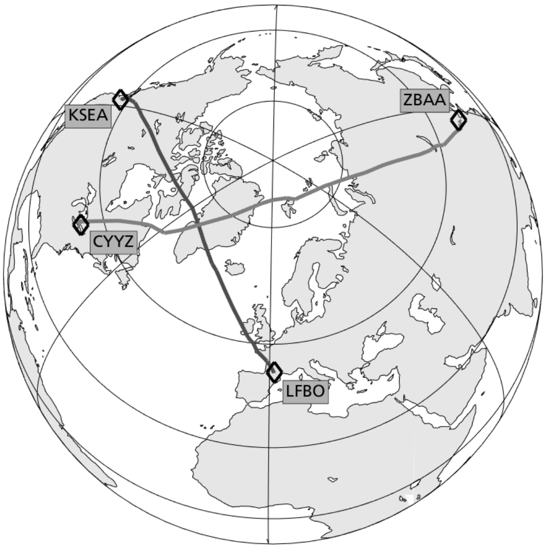
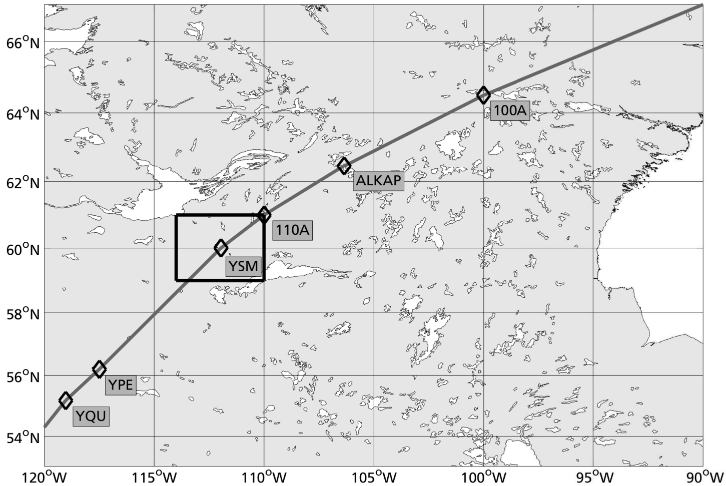


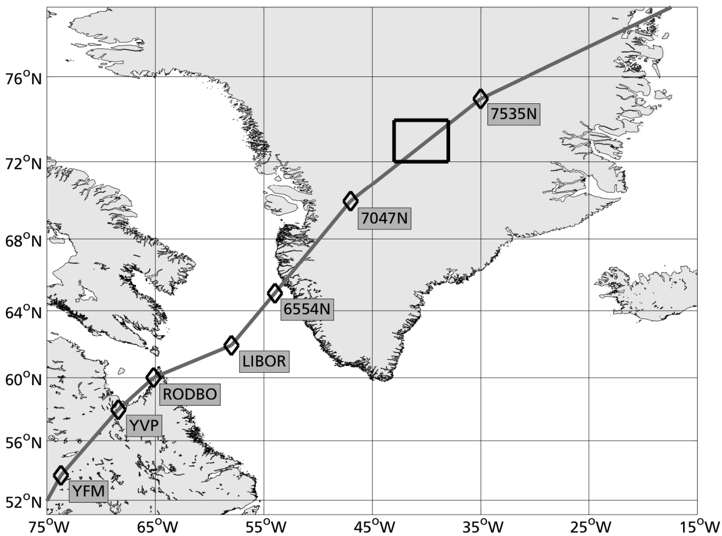
Figure 4.5.: Flight plans of LFBO-KSEA and CYYZ-ZBAA [illustration by author]

The two flights depict a typical westward Atlantic crossing and a northbound polar route. Considering the task to be carried out in the trial, for each route an area containing severe weather phenomena was defined. The areas were considered to be rectangular and were designed to be crossed by the corresponding route. Figure 4.6 depicts sections of both flight plans with area affected by the SIGMET as a rectangle.

The SIGMETs are defined via text messages, which sequence and content is defined in ICAO Annex 3 [Int07]. The actual SIGMET text messages depicted on the display can be found in appendix B.1. In both flights, the starting point of the trial is located well before arriving at the area affected by the SIGMET, in order to depict the scenario of a strategic rerouting. For scenario 1, the starting point is 100NM before arriving at waypoint 100A, for scenario 2 the starting point is directly above



(a) Flight LFBO-KSEA



(b) Flight CYYZ-ZBAA

Figure 4.6.: SIGMET areas for both flights, depicted as black rectangles [illustrations by author]

waypoint YVP (refer to figure 4.6). As can be seen in figure 4.6a, the area to be avoided contains a waypoint of the original route in scenario 1.

The overall concept, task, simulator setups and flight scenarios were shown to and discussed with a commercial pilot experienced on flying Boeing 777 passenger and freighter aircraft. The pilot approved the trial concept to be on a realism level allowing to conduct the intended research.

4.2.4 Hypotheses and Indicators

To evaluate the TEOS architectures usability and to compare it against a traditional FMS, hypotheses were formulated. In order to evaluate these hypotheses, indicators were recorded and collected during the trial execution. This section presents the hypotheses and the indicators used to evaluate them.

4.2.4.1 Hypotheses

The global hypothesis for the usability study was formulated as following:

H1: TEOS shows a higher usability in the task of rerouting a flight around a No-Fly-Zone compared to a traditional FMS.

In order to test this hypothesis, three subhypotheses were formulated, relating to the definition of usability (compare to section 4.1).

H1.1: Using TEOS increases the effectiveness of the pilot when rerouting a flight around a No-Fly-Zone compared to using a traditional FMS.

H1.2: Using TEOS increases the efficiency of a reroute for a flight compared to a traditional FMS.

H1.3: TEOS has a higher perceived usability than a traditional FMS.

The subhypotheses relate to effectiveness, efficiency and subjective usability as defined in section 4.1.

4.2.4.2 Indicators

In order to test and either accept or refuse the hypotheses, indicators were recorded during the trial execution. The indicators include objective values as well as subjective questionnaires filled out by the trial participants. Table 4.1 summarizes which indicators test the respective hypotheses followed by a brief description of each indicator.

Table 4.1.: Indicators used to test the hypotheses

	H1.1	H1.2	H1.3
Objective	1. Violation of NFZ 2. Length of diversion	1. Execution time	-
Subjective	-	1. NASA TLX	1. SUS 2. Likert scale Questionnaire

Violation of No Fly Zone

This value is either true or false and states if any part of the diversion route lies within the NFZ. It is tested for the loxodromes connecting the waypoints of the diversion route. All relevant equations used to evaluate this indicator are given in appendix B.2.1.

Length of Diversion

The value depicts the overall length of the diversion route by adding up the loxodromic distances between all waypoints. It is compared to the length of the original route to determine the effectiveness of the route planning. All relevant equations used to evaluate this indicator are given in appendix B.2.2.

Execution Time

For each trial the time to complete the given task was measured. The values depict the timely effort the participant needed to solve the task.

NASA Task Load Index

The National Aeronautics and Space Administration (NASA) Task Load Index (TLX) was developed by HART ET AL. and STAVENLAND [HS88]. The index is computed out of a questionnaire that the participant fills after completion of the task. The questionnaire rates the subcategories mental demand, physical demand, temporal demand, own performance, effort and frustration on a scale from 0 to 100, which are combined to a single number reflecting the task load the participant experienced during the task execution. The index increases with an increasing task load. For a rapid evaluation, the TLX form was implemented in a spreadsheet and filled out digitally by the participant.

Likert Scale Questionnaire

Likert scales were defined by LIKERT [Lik32] as a tool to measure attitudes. They consist of a five or seven point scale, which typically range from strongly disagree to strong agree. For the study conducted in this thesis, two five point Likert scale questionnaires were developed.

The first questionnaire consists of three statements towards the participant's attitude and usage of mobile electronic devices. This questionnaire was filled out once before the task execution actually begun. The statements are given below:

1. I am using mobile electronic devices in my private life on a daily basis.
2. I am using mobile electronic devices in my professional life on a daily basis.
3. I feel confident in using mobile devices.

The second questionnaire was designed to catch the participant's attitude towards the trial setup and the participant's self assessment on its performance in the trial, which were compared to objective indicators for any systemic disagreement. The statements were formulated as follows:

1. The workflow for solving the task was self-explanatory.
2. I was presented with all relevant information to solve the task.
3. I was able to distinguish if I was working on a certified or a non-certified system at all times.
4. The system design prevents operating errors.

5. The system supported me in solving the task time efficient.

This questionnaire was filled out for both setups, after the task was completed.

System Usability Scale

The System Usability Scale (SUS) as developed by Brook [Bro96] is used to determine the subjective usability of the system under consideration. The usability is determined by rating ten statements on a Likert scale, where the statements remain the same independent on the evaluated system or circumstances. The system usability is not to be understood as an absolute measurement, but rather a tool to compare two systems that were evaluated using the same questionnaire in the same circumstances.

General Information

The participants were asked to give general information in order to evaluate the overall participant group and check connections of the trial results. The information asked were flying hours, active type ratings and the rank of the participating pilot.

Free Comments and Remarks

Additional to all mentioned indicators, the participants were asked to write down free comments, suggestions and criticism. They were specifically asked to include not only the systems under consideration, but also the trial scenario, the simulator setup or any other factor that came to their mind while solving the task. While these comments can not be systematically evaluated, they are valuable to cross check observations made using other indicators and further development of TEOS.

4.2.5 Trial Execution

The order of events while performing the trial as well as information on the participants are given in this section.

4.2.5.1 Order of Events

The order of events for the execution of a trial is depicted in figure 4.7. Each trial was started with a presentation on the goals and basics of the TEOS project and the structure of the trial. The presentation explained the task that needed to be executed and the focus points during task execution. Subsequent to the presentation the general information and Likert scale questionnaire were completed. In order to prevent distorting the results of the study, the order of TEOS/FMS and flight scenarios were randomized.

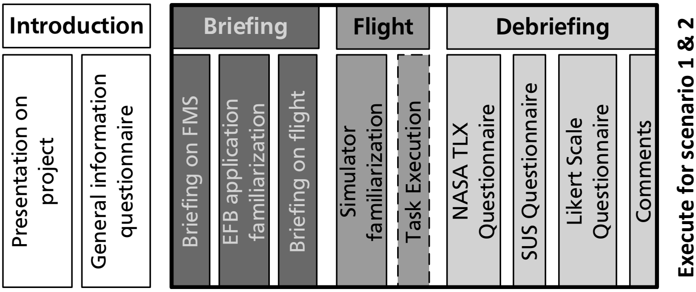


Figure 4.7.: Order of events for the trial execution [illustration by author]

The order of events is the same for both scenarios. Each scenario began with a briefing presentation on the FMS and EFB application that was to be used in the respective scenario. During the presentation the participant was allowed to take notes on the system handling, which could be used during the actual flight. The system briefing was followed by a familiarization phase of the EFB application. For this purpose, an example flight was loaded in the respective application. As a last step, the participant received a briefing for the upcoming flight, which contained a full briefing package of the flight plan and information on the entry point (such as position, altitude and speed).

After walking to the simulator, the participant sat down and was able to adjust the seat, while the simulation was paused. Then the participant was granted a one minute familiarization and orientation phase to the simulator and the flight plan with a running simulation. Beginning with the delivery of the SIGMET message, the time measurement was started and stopped once the diversion route was active.

After returning to the briefing room, the debriefing was started during which the participant filled the relevant questionnaires and noted comments. In the meantime, the simulator was set to the next scenario, which for the participant again began with a system briefing, followed by the same steps illustrated above.

4.2.5.2 Sample Group

A total of ten pilots participated in the study[2]. All pilots hold active commercial pilot licenses, whereas three participants finished training but did not collect any commercial flight hours yet. Table 4.2 gives an overview over the participants, as well as the order of flight scenario and FMS in their trial. S1 and S2 stand for flight scenario 1 and 2 respectively.

Table 4.2.: Information on study participants

Participant #	Rank	Type rating	Flight hours in h	Setup 1	Setup 2
1	SFO	B757/767	4,000	S1/FMS	S2/TEOS
2	FO	A320	5,000	S1/TEOS	S2/FMS
3	SO	A320	-	S2/FMS	S1/TEOS
4	SO	-	-	S2/TEOS	S1/FMS
5	SO	-	-	S1/FMS	S2/TEOS
6	CPT	B747	21,000	S1/TEOS	S2/FMS
7	SFO	A330/340	6,000	S2/FMS	S1/TEOS
8	CPT	A330/340	10,000	S2/TEOS	S1/FMS
9	SFO	B747	5,800	S1/FMS	S2/TEOS
10	CPT	Learjet 60	5,500	S2/TEOS	S1/FMS

The three participants without commercial flight hours gained experience in handling FMS equipped aircraft during their flight training. In total, the commercial flight experience ranges from 0 to 21,000 hours ($\mu = 5730$h, $\sigma = 6267$h). Three participants had the rank of a Captain (CPT), three the rank of a Senior First Office (SFO), one the rank of an First Officer (FO) and three the rank of a Second Officer (SO). SOs are pilots who finished their flight training, but have not finish line training yet. Four participants hold type ratings for Airbus aircraft, three for Boeing aircraft and one for a Learjet. Two pilots have not finish the type rating training for a commercial airliner yet.

The combination of two flight scenarios and FMS/TEOS yield a total of 4 possible combinations, the total number of ten participants allowed to execute 2.5 cycles through the combinations. Shuffling the combinations of scenario and used systems

[2] The usability study intends to gather feedback for the design process with the help of the demonstrator. While the amount of ten participants does not form a fully representative group to evaluate a product, it satisfies the needs of the intended study.

as well as the execution order helps to avoid effects resulting from familiarization. Higher amounts of full cycles through possible combinations let the possibility of those effects decrease.

4.3 Study Results and Discussion

In this section the recorded indicators and their evaluation are presented. The indicators are clustered to the subhypotheses of usability they are representing (compare to table 4.1). Furthermore, the results are discussed and the hypotheses evaluated. Since open feedback given by the participants can not be related to specific hypotheses, relevant feedback is presented where suitable (a complete transcript of the feedback is found in appendix B.3.5).

4.3.1 Effectiveness

This section presents the results obtained while evaluating the indicators for effectiveness and the discussion of these results.

Results

Effectiveness is to be evaluated by task success or failure. A participant failed the task if any point of the activated diversion route lies within the NFZ. As presented in figure 4.8 three participants failed the task in scenario 1 when working with the FMS, where only 1 participant failed using TEOS. In scenario 2, one participant failed the task with each system. In total, the task was failed four times using the FMS and two times using TEOS.

After having determined in which trials the task was failed, all subsequent analysis were conducted only for successful trials. During these analysis it is kept in mind that in scenario 1, when working with the FMS, only two participants executed the task successfully, which represents a rather small sample size.

As second indicator for effectiveness, the difference in length of the diversion route compared to the original route was determined. Figure 4.9 gives an overview over the results of the evaluation.

The means of the added distance through the diversion show little difference for both systems in scenario 1 ($\mu_{1,FMS}$ = 52.58NM, $\sigma_{1,FMS}$ = 56.90NM and $\mu_{1,TEOS}$ = 54.84NM, $\sigma_{1,TEOS}$ = 36.66NM). In scenario 2, the mean of diversion length created using TEOS is lower than the mean of reroutes created using the FMS ($\mu_{2,FMS}$ = 57.36NM, $\sigma_{2,FMS}$ = 28.81NM and $\mu_{2,TEOS}$ = 37.83NM,

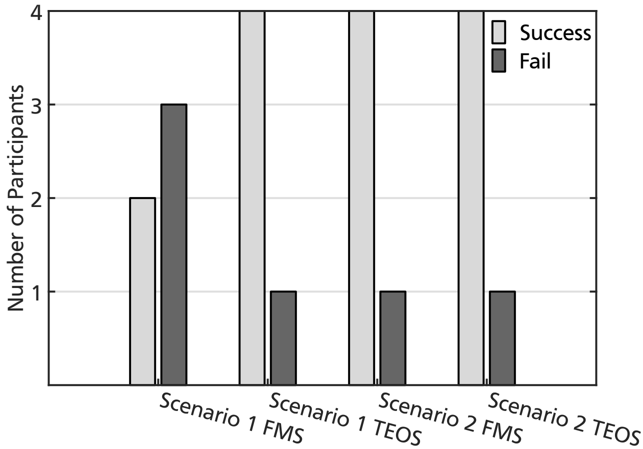


Figure 4.8.: Amounts of successful and failed trials

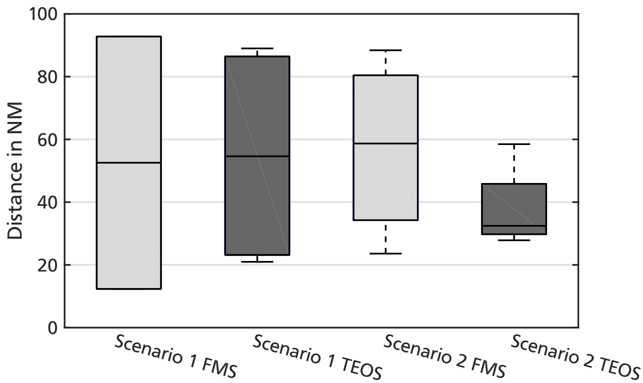


Figure 4.9.: Diversion route length evaluation

$\sigma_{2,TEOS} = 13.98NM$). Additional information on the route length evaluation is provided in table B.1.

Discussion

The FMS shows a higher rate of unsuccessful task execution than TEOS. The failed FMS trials concentrate on scenario 1. An analysis of the diversion routes revealed that the waypoint of the original route located inside the NFZ imposed a problem for the participants. Figure 4.10 depicts two examples for routes that were constructed by participants. Both participants moved waypoints located in front of the NFZ, but forgot about the waypoints on the edges or the center of the NFZ. This error was also not noticed in the review process that followed route construction. As mentioned in section 4.2.2.1, the EFB application used in the FMS setup offered the option to insert custom markings on the map, which could have been used to mark the edges of the NFZ. However, only one out of ten participants made use of this option.

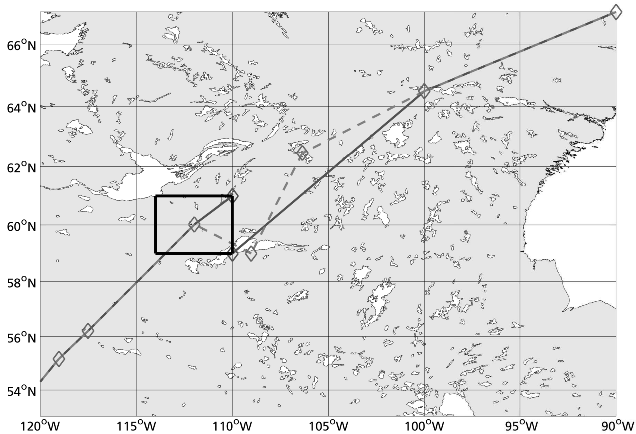


Figure 4.10.: Examples for unsuccessful diversion routes in scenario 1

Regarding the reroute distance, TEOS shows an advantage which is minimal in scenario 1 but more distinctive in scenario 2. The higher failure rate of the FMS and the advantage of TEOS regarding the diversion route distance lead to the acceptance of hypothesis 1.1.

Criticism on Diversion Scenario Due to Weather:
Some participants noted that, even though the trial concept was discussed with a pilot before trial execution, the scenario of a strategical diversion due to a SIGMET report does not depict operations as they are conducted today. Referring to the comments, when receiving a similar SIGMET to the ones used in the trials, the flight deck crew would continue the flight closely monitoring the weather radar. Only if a diversion is indeed necessary, the pilot would contact Air Traffic Control (ATC) to obtain a clearance for a diversion route which would be flown manually or via

dialed autopilot headings instead of being entered into the FMS.

Correlation of Unsuccessful Task Execution and Flying Experience:
Failure and success of the task are not only dependent on the system setup, but also vary with flying experience. Figure 4.11 depicts this correlation, split for both setups but summarizing the scenarios.

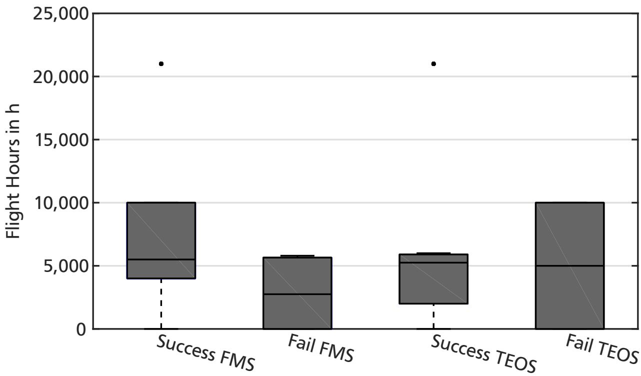


Figure 4.11.: Comparison of flying experience amongst the participants

As can be seen, the median of a successful task execution using the FMS is more than 2,500 flight hours higher than the the median of the failed trials using the FMS. One concludes that the user needs training and experience to operate the FMS. On the other hand, the medians of successful and failed task execution using TEOS differ by 250 hours, which indicates that the system may be easier to operate for inexperienced users.

Self-assessment on Usage of Mobile Devices and Confidence in Using:
The evaluation of the participants' self assessment towards their mobile device usage and confidence in using them revealed no correlation of success or failure with their self assessment. Appendix B.3.4 and figures B.1, B.2 and B.3 present the statements of the participants that succeeded or failed using the respective system. As the figures show, neither does a participant's self assessment of using mobile devices often and feeling confident when using them lead to a successful task execution, nor does a self assessment of merely using mobile devices and not feeling confident using them lead to a failed task execution.

4.3.2 Efficiency

This section presents the results obtained while evaluating the indicators for efficiency and the discussion of these results.

Results

Regarding the efficiency evaluation, the temporal effort (execution time) and the mental effort (TLX) were evaluated. Figure 4.12 summarizes the results obtained from the recordings of the execution time.

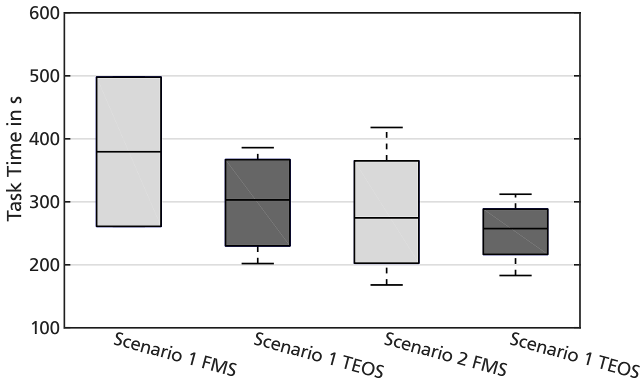


Figure 4.12.: Task time

With respect to scenario 1 one can observe the mean execution times on the FMS are higher than the one on TEOS ($\mu_{1,FMS} = 379.5$s, $\sigma_{1,FMS} = 167.58$s and $\mu_{1,TEOS} = 298.5$s, $\sigma_{1,TEOS} = 83.78$s). Regarding scenario 2 one observes again that TEOS enabled the participants to execute the task faster ($\mu_{2,FMS} = 283.75$s, $\sigma_{2,FMS} = 107.09$s and $\mu_{2,TEOS} = 252.5$s, $\sigma_{2,TEOS} = 53.33$s). Additional information on the evaluation of the task time is found in table B.2. Mental workload was evaluated by the TLX, which survey was filled out after each scenario trial. Figure 4.13 depicts the evaluation of the TLX for the FMS and TEOS. Since the choice of the scenario does not have any impact on the mental workload, the scenarios are not differentiated when evaluating the TLX.

As one observes, TEOS received a lower mean rating than the FMS ($\mu_{FMS} = 51.16$, $\sigma_{FMS} = 11.40$ and $\mu_{TEOS} = 41.10$, $\sigma_{TEOS} = 18.51$). Additional information on the information of the TLX ratings is found in table B.3

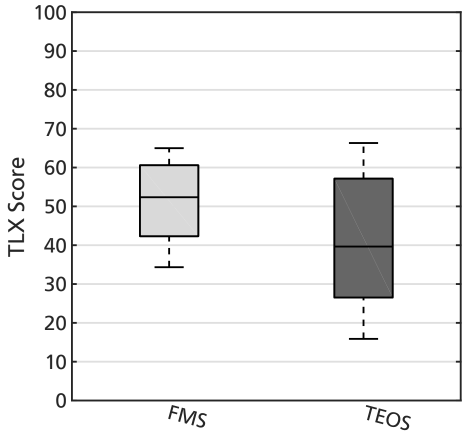


Figure 4.13.: TLX ratings

Discussion

Using TEOS, the participants had less both temporal and mental effort. Figure 4.12 shows a high standard deviation for the FMS trials, which is lower on the TEOS trials. This can be explained, again, by the experience pilots have with using the FMS, as there were participants inexperienced in using all kinds of FMS as well as participants used to fly Boeing aircraft, on which the FMS is operated in a different way then the Airbus FMS depiction used for the trial[3]. Given that TEOS was a new kind of system to all participants, the standard deviation of the execution time is lower when using it. Additionally to experience in handling FMS, the task execution time was influenced by the pilots commenting their actions or the trial itself during task execution. While some pilots commented every step they made during task execution increasing the execution time, others commented less and only spoke when absolutely necessary. The participants were given this option to capture comments that might be forgotten when filling the questionnaire for free comments. Regarding TLX ratings, TEOS shows a ten point lower rating than the FMS.

[3] A participant who obtained his experience flying Boeing aircraft mentally constructed the diversion route correctly, but used the format to enter new waypoints into the flight plan he was used to from Boeing aircraft. Using the correct format for the FMS used in the trial increased the execution time.

Since both task time evaluation and TLX evaluation show advantages of TEOS, hypothesis 1.2 is accepted.

4.3.3 Subjective Usability

This section presents the results obtained while evaluating the indicators for subjective usability and the discussion of these results.

Results

Subjective Usability was evaluated using the SUS questionnaire as well as the custom designed Likert scale questionnaire presented in section 4.2.4. As presented in figure 4.14, one observes that TEOS received higher ratings than the FMS ($\mu_{FMS} = 53.33$, $\sigma_{FMS} = 11.47$ and $\mu_{TEOS} = 77.81$, $\sigma_{TEOS} = 11.37$). Additional information on the evaluation of the SUS ratings is found in table B.4.

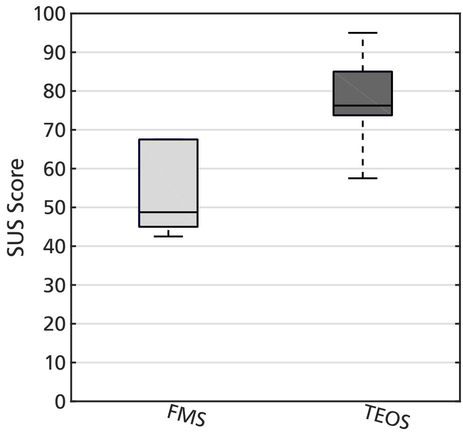
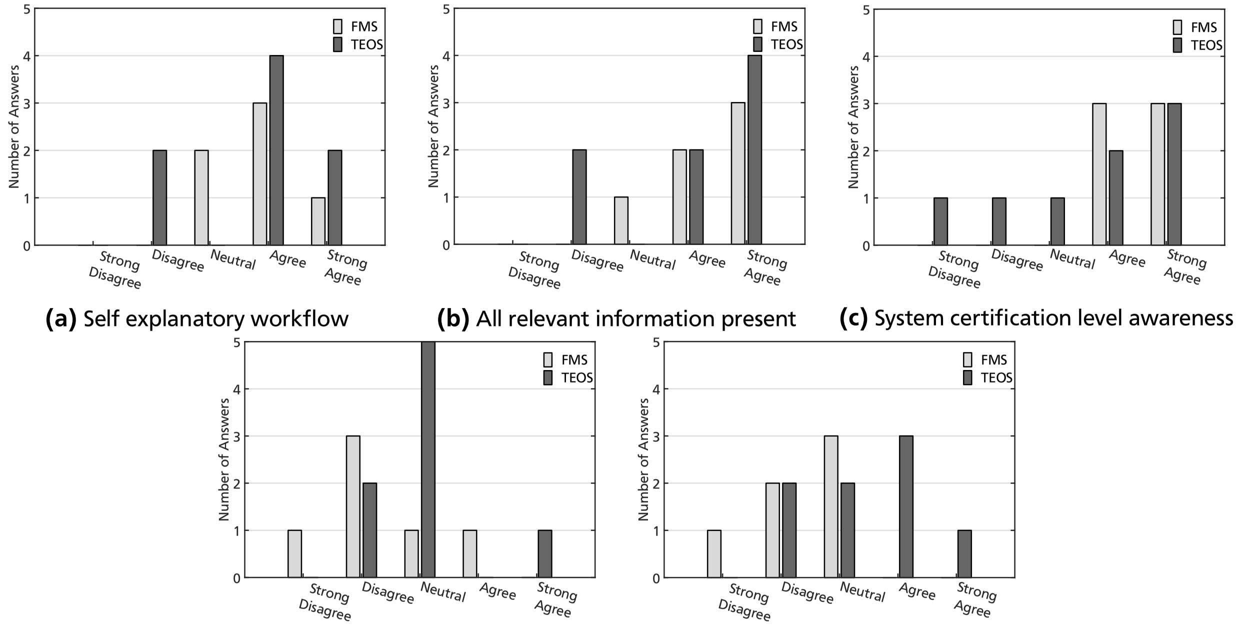


Figure 4.14.: SUS ratings

Additional to the SUS ratings, the Likert scale questionnaire was evaluated. The results for each question are summarized in figure 4.15. A total of four participants agreed to statement 1 (The workflow for solving the task was self-explanatory.) regarding the FMS, where six participants agreed regarding TEOS. One participant showed a neutral position towards the FMS regarding statement 1 and one participant disagreed regarding TEOS.



(a) Self explanatory workflow

(b) All relevant information present

(c) System certification level awareness

(d) Error preventing design

(e) Time saving design

Figure 4.15.: Summarized results of Likert scale questionnaire

With respect to statement 2 (I was presented with all relevant information to solve the task.) a total of 5 participants agreed and one was neutral regarding the FMS, where six participants agreed and 2 disagreed regarding TEOS.

A total of six participants agreed to statement 3 (I was able to distinguish if I was working on a certified or a non-certified system at all times.) regarding the FMS, where only five agreed, one was neutral and two disagreed regarding TEOS.

Answering statement 4 (The system design prevents operating errors.), one participant agreed, one was neutral and four disagreed with regards to the FMS, where one agreed, five were neutral and two disagreed regarding TEOS.

Lastly, when answering statement 5 (The system supported me in solving the task time efficient.) 3 participants were neutral and three participants disagreed regarding the FMS, where four participants agreed, 2 were neutral and 2 disagreed regarding TEOS.

Discussion

The SUS ratings show an advantage of TEOS, having a 24.48 higher mean rating than the FMS. Sauro [Sau11] defines a system usable when having a SUS rating higher than 68. Since the mean SUS rating of the FMS is $\mu = 53.33$ and the maximal given rating is 67.5, the conclusion can be made that the FMS depicted in the trial did not meet a high comparability to real FMS. The expectation was that the FMS would be considered usable by the participants, since they use it in their daily professional life. The assessment might also have been influenced by the fact that the participants are used to other EFB applications than Mobile FliteDeck. However, TEOS received a mean SUS rating of $\mu = 77.81$, leading the conclusion that the system is considered usable by pilots when compared to the FMS.

Evaluation of the Likert scale questionnaires revealed that TEOS received better ratings than the FMS in the respective statements except in the statement "I was able to distinguish if I was working on a certified or a non-certified system at all times.", where the FMS only received "Agree" ratings, where TEOS was also rated neutral and disagree. This indicates that the system boundary between EFB application and CoreFMS needs to be clarified, to ensure the that user is aware of the certification level at all times.

The SUS and Likert scale questionnaire ratings lead to the acceptance of hypothesis H1.3, since TEOS shows higher ratings in both indicators.

4.4 Summary

The trial to compare the usability of TEOS to a traditional FMS was conducted successfully, with ten professional airline pilots participating in the trial. As presented in section 4.3, the three sub-hypotheses H1.1, H1.2 and H1.3 were accepted. By accepting all three sub-hypotheses, the global hypothesis regarding TEOS usability H1 is accepted too. The usability study demonstrated the usability potential of the TEOS architecture compared to FMS.

The amount of failed task executions is considered worrisome both when operating the FMS and TEOS. The failed executions can be tracked two main factors. First, some participants lacked experience in line operating FMS at all[4], or operating Airbus FMS. Second, none of the participants had any experience using the EFB applications used in the trials for flight planning. Even though the participants were granted a familiarization period with each application before the actual trial, the participants did not have the same training with the application as they would have for an application used during their commercial flights.

For future trials, it is recommended to rely on experienced participants as well as to increase the familiarization period granted with the new system. As users would be trained on the system before flying with it, the system does not need to be comprehensive at the first glance.

[4] Depending on their pilot training, trial participants without line experience had no experience on any FMS or only limited simulator experience as they stated in conversations.

5 Development and Evaluation of an Advanced Trajectory Optimization Algorithm

The previous chapter stated that the architecture of the Trajectory Execution and Optimization System (TEOS) has a higher usability than the traditional Flight Management System (FMS), which indicates advantages of TEOS from the user perspective. By offering the functional shifting, TEOS also offers operational advantages, explicitly in trajectory optimizing, compared to the currently implemented Cost Index (CI) method. While traditional FMS have limited support for Required Time of Arrival (RTA) constraints [SB07], no full Trajectory Based Operations (TBO) support is provided. Since TEOS is intended to operate in a TBO environment (compare to section 2.6.3), such functions are required. Additionally, in adherence to the integrated airline concept (compare to section 3.2), airlines strive to optimize the cost of their overall operations rather than single flights. Since this concept is not directly supported by the CI, an advanced trajectory optimization method highlighting advantages of TEOS was designed and evaluated in this thesis[1].

5.1 Approach Towards Advanced Trajectory Optimization

As described in section 2.1.3 and shown in figure 2.5, traditional FMS use the CI method to optimize the flights speed and vertical profile along a given lateral path with respects to time and fuel cost. As shown in figure 5.1 by the solid line, the CI method intends to find the Mach number at which the lowest cost for a single flight occur by determining a balance of fuel and time cost. However, in an integrated airline, the cost function can take a different form. Consider for example a flight carrying a number of transfer passengers. If the flight is delayed, numerous passengers will miss their connecting flights and cause the airline cost in compensation as well as provision of accommodation and meals. However, when

[1] The algorithm presented in this chapter is not intended to be the only algorithm to be used with TEOS, but rather highlights the potential of TEOS' architecture, which allows the deployment of any operational approvable algorithm on the Electronic Flight Bag (EFB).

flying at a higher Mach number, these cost will not occur, which is depicted in figure 5.1 by the dashed line.

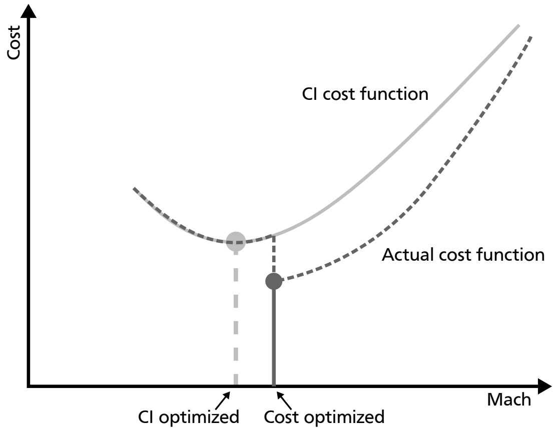


Figure 5.1.: Comparison of cost function used by CI and actual cost function [illustration by author]

A discontinuous cost function as shown in figure 5.1 is not supported by the CI trajectory optimization method, since it intends to find a cost minimum on a continuous function. Therefore, a method was developed in the scope of this thesis to optimize the trajectory with respect to true cost.

5.1.1 Former Efforts to Replace the Cost Index

Several proposals were made and partially implemented to divert the CI method of its intended use to the needs of TBO. Chakravarty [Cha95] proposes a method to iteratively compute a CI which resulting speed profile meets the upcoming RTA. The method needs access to aircraft avionic parameters and an initial CI to compute a CI value that corresponds with a speed profile to meet the RTA. The proposal is meant to retrofit into existing systems, without the need to modify the implemented FMS methods.

The method proposed by DeJonge [DeJ92] needs to interface the FMS to use the already existing trajectory prediction function. The trajectory prediction function is fed with a CI value computed by a CI predictor. Based on the time error between the RTA and the Estimated Time of Arrival (ETA) of the predicted trajectory at the corresponding waypoint, the CI predictor estimates a new CI. This process is iterated until a CI value corresponding with a satisfying ETA is found. To reduce computation time, the CI predictor uses a predefined database of applicable CI values [DeJ88].

Both presented approaches concentrate on adding support of RTA constraints to the FMS, but do not achieve full TBO support. Rather than carrying out an actual trajectory optimization, the CI is used as only available tool to introduce RTA capability to the FMS. Patron and Botez [PB14] on the other hand propose to use genetic algorithms to replace the CI as trajectory optimization method. By assuming a constant Mach number and using detailed weather information and an aircraft performance database, the proposed method calculates a set of alternative trajectories regarding the lateral profile and the vertical profile. Since the speed is held constant during the optimization, this proposal is not capable of incorporating RTA constraints.

5.1.2 Advanced Optimization Concept

Using TEOS allows to propose a new concept for the trajectory optimization method enabling TBO and cost optimization. The function shifting and the defined dataflow enable the deployment of the optimization method onto the EFB to make use of the EFBs computational power and increased amount of available information. To enable a true trajectory cost optimization rather than a CI optimization, the output of the optimization should be a trajectory, which for this purpose is split into a lateral, vertical and speed profile along time, see also equation 5.1.

$$Trajectory = f\big(\lambda(t), \varphi(t), v(t), h(t)\big) \tag{5.1}$$

In equation 5.1 $\lambda(t)$ represents the function of the latitude, $\varphi(t)$ the function of longitude, $v(t)$ the function of the speed profile and $h(t)$ the function of the altitude profile. Since the optimization method designed in this thesis is intended to be used on board and inflight, the lateral path, $\lambda(t)$ and $\varphi(t)$, are considered to be fixed. The optimization method computes the speed and vertical profiles $v(t)$ and $h(t)$, along a lateral path defined by waypoints and imposed with RTA constraints.

Several boundary conditions need to be adhered by the optimization to make sure the trajectory is acceptable by the pilot, the Air Navigation Service Provider (ANSP) and the airline. Three levels of boundary conditions are defined below.

Level 1: Physical Boundary Conditions:
The flight envelope of the aircraft must not be violated at any point along the tra-

jectory to ensure a safe flight inside the certified operational limits. The envelope is defined by minimum and maximum operating speeds and altitudes.

Level 2: ANSP Boundary Conditions:
The solution trajectory must conform with the imposed constraints on altitude, speed and time in line with the TBO concept. If no solution can be found without violating the flight envelope, the optimization ceases without result. When the optimization failed, constraints need to be renegotiated appropriately. Additionally, the solution should maintain a form that is acceptable by ANSP controllers and conforms with operational standards, e.g. using the step climb concept instead of flying at a constant climb rate.

Level 3: Airline Boundary Conditions:
In addition to ANSP constraints, airlines have their own requirements regarding their operations as explained in the integrated airline concept in section 3.2. Depending on each flight and the circumstances on the day of operations, these requirements vary. Examples for those requirements are speeding up an aircraft inside the allowable limits to allow passengers to catch their connection flights, or noise restriction at certain airports. Generally, the interest of the airline is to keep its overall operation on the lowest possible cost. The architecture of TEOS and the deployment of the method on the EFB allow the adaption of optimization methods to those needs without costly recertification.

5.2 Optimization Algorithm Development

Based on the requirements and boundary condition stated in section 5.1, an optimization method was designed and exemplary implemented to allow an evaluation. This section describes the development of the algorithm.

5.2.1 Algorithm Functionality

The optimization algorithm used to analyze advantages of the TEOS architecture was developed by Sprengart in [Spr16] under supervision of the author of this thesis and adapted by Sprengart, Schulze and Westphal in [SSW17] to the needs of this work. The algorithm was implemented in the C++ programming language. This section summarizes the functionality and capabilities of the algorithm.

Basic Concept

As the requirements stated in section 5.1 demand, the output of the optimization must be a trajectory that adheres to the boundary conditions. Since path finding algorithms are designed to find an optimal path through a discretized environment, a path finding algorithm is suitable to solve the problem at hand. The airspace and the time domain the trajectory is located in can be represented by a search graph discretizing the environment. Such a graph, also referred to as grid, consists of nodes and weighted edges connecting the nodes. In this thesis, the weights depict the cost of traveling along the corresponding edge[2], corresponding to the level 3 boundary conditions stated in section 5.1.

As an algorithm that by design guarantees to find the optimal solution, the widely used [LaV06] A^* algorithm was chosen in this thesis. The A^* algorithm was described by HART ET AL. in [HNR68] and is based on DIJKSTRAS algorithm [Dij59]. A^* is an informed path finding algorithm. Following, the method of A^* and its application in this thesis are briefly outlined.

The path finding process starts with only the beginning and end node known to the A^* algorithm, nodes in between are explored during the process. Nodes that already have been explored are put on a closed list, nodes not explored yet are held in an open list. The search continues until the end node is about to be explored or until the open list is empty. Exploring the end node corresponds with finding a solution, where removing the last node from the open list without reaching the end node means that no solution can be found.

The herein used implementation of the A^* algorithm maintains a third list, on which blocked nodes are saved. Blocked nodes are nodes that are not reachable due to aircraft performance limits (level 1 boundary conditions) or time and altitude constraints (level 2 boundary conditions), hence do not need to be expanded further in the path finding process. Aircraft performance is depicted by the Base of Aircraft Data (BADA) library compiled by European Organization for the Safety of Air Navigation (EUROCONTROL) [Nui15]. The introduction of blocked nodes also introduces the possibility that no solution at all is found, if all instances of a node are blocked. To improve the speed of the path finding process, the algorithm uses a heuristic to estimate edge weights and explore promising paths first[3].

[2] In an actual application to find the shortest path, the edge weights would depict the distances between the nodes.

[3] In the scope of this thesis no valid heuristic to be used was found, which means the achieved computational times have potential to be improved.

Algorithm Process

The general process of the path finding is driven by its programmed priorities. The pillars of those priorities are safety and mission success. The first priority is to never exceed any aircraft performance limit during flight conduction. Next priority is the compliance with time and altitude constraints within their limits at waypoints imposed with such, which is followed by finding the solution producing the minimum cost. Figure 5.2 depicts the general process of the algorithm. As presented, the first step is to remove a node from the open list for evaluation and compute V_{min} and V_{max}. Next, the range between V_{min} and V_{max} is evaluated by checking if any limitations, aircraft performance or time constraint, are violated using the specific speed. If limitations are violated the node is moved to the blocked list, if no limitations are violated the cost of the edge is computed and stored and the next node is being taken from the open list.

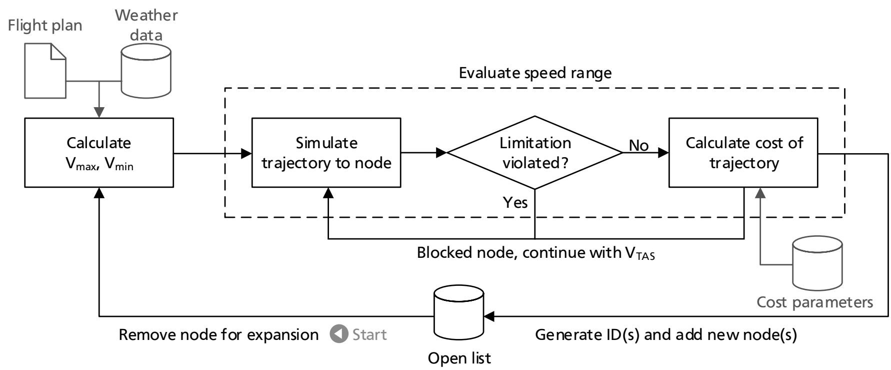


Figure 5.2.: Pathfinding algorithm process overview after [SSW17]

The concept of blocked nodes yields the possibility that no solution to the given combination of flight plan, weather and constraints can be found due to limits in aircraft performance[4]. If a time or altitude constraint at any waypoint cannot be met (corresponding with all combinations of the waypoint were put on the blocked list), the algorithm aborts its computation. Non-achievable constraints may be based on coarse or incomplete knowledge of aircraft performance and weather when computing constraints. The algorithm is also able to produce a solution

[4] It may be not possible to meet a constraint if maximum or minimum speeds or vertical speeds need to be exceeded in order to do so.

which will prioritize reaching time constraints at a minimum of deviation to the RTA over cost efficiency for comparison reasons.

Grid Generation

As described above, nodes and edges need to be constructed to let the algorithm search for a path. This grid is finite and computed before the path finding process begins. In the scope of the implementation for this work, the spatial grid was defined along a predefined lateral path. The lateral grid corresponds with the waypoints defined in the flight plan, where vertical grid points are spaced in 200m intervals. To reduce computation time, the vertical nodes are constrained by a boundary. This boundary extends to a minimum[5] of 1400m only in a vicinity of 250NM to the departure and arrival airport and is located at 9,000m for the remainder of the nodes (see also figure 5.3). It is assumed that the optimal trajectory will not be located at lower altitudes. The upper boundary is defined by the maximum operating altitude of the respective aircraft h_{MO}.

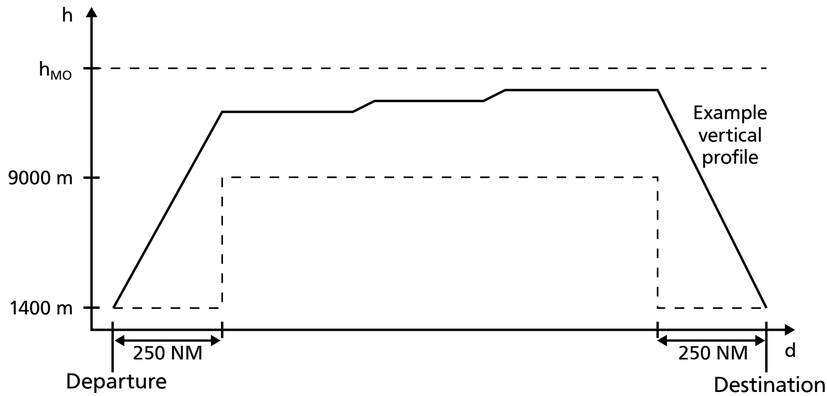


Figure 5.3.: Altitude limits for the generation of nodes in vertical direction [illustration by author]

Additional to the spatial nodes, time spans a third dimension. Since the aircraft is able to travel along the edges at a variety of speeds[6], the edge weights differ

[5] Altitude as well as speed constraints on the Standard Instrument Departure (SID) and Standard Terminal Arrival Route (STAR) are considered to prohibit any optimization potential on lower altitudes.

[6] The aircraft True Airspeed (TAS) is limited by minimum speed V_{min} and maximum speed V_{max} defined in the BADA.

with each speed. For each speed step another node is added. So each node, having a fixed spatial location, exists several times in the time dimension which results in edges with different weights depending on the flown speed and therefore fuel consumption.

Edge Weight Computation

The weight of the edges depicting the cost to travel along them is computed by taking into account several factors:

Aircraft Performance:
Aircraft performance determines the fuel consumed while traveling along an edge. The computation takes into account climbs and descents as well, where fuel consumption increases and decreases respectively[7].

Weather:
Weather data published by the United States National Oceanic and Atmospheric Administration (NOAA) in the Gridded Binary (GRIB)[8] format is used to determine the weather condition at each node. Interpolation methods are employed to compute the condition along the edges. Weather information consists of winds in lateral directions and temperatures. The data is published for four six hour intervals each day, the intervals begin at 00:00 Universal Time Coordinated (UTC), 06:00 UTC, 12:00 UTC and 18:00 UTC.

Cost Function:
In order to depict level 3 boundary conditions, a cost function was developed by Schrader [Sch17], supervised by the author of this thesis, that incorporates all elements of airline cost while operating a flight. Figure 5.4 depicts the elements represented by the cost function, which on a first level is split into time-dependent and time-independent cost. Time-dependent cost are further split into direct operational cost of operating the aircraft such as flight operations and maintenance, while indirect operational cost occur e.g. for ground services at the airport or

7 The BADA manual [Nui15] states that fuel consumptions computed using BADA equations are only meant to be used for comparing scenarios operated with the same aircraft type. The computed fuel consumptions do not depict a realistic fuel consumption and are also not intended to compare different aircraft types.

8 The GRIB format provides weather on a grid with a resolution of 0.5 degrees for both longitudes and latitudes on fixed altitudes.

develop with passengers satisfaction or dissatisfaction, so called soft factors[9]. Example for time-independent cost are ANSP overfly fees, which often depend on the aircrafts Maximum Take Off Mass (MTOM) and flown ground distance or taxes which are computed by fixed rates [EUR18b; Fed18].

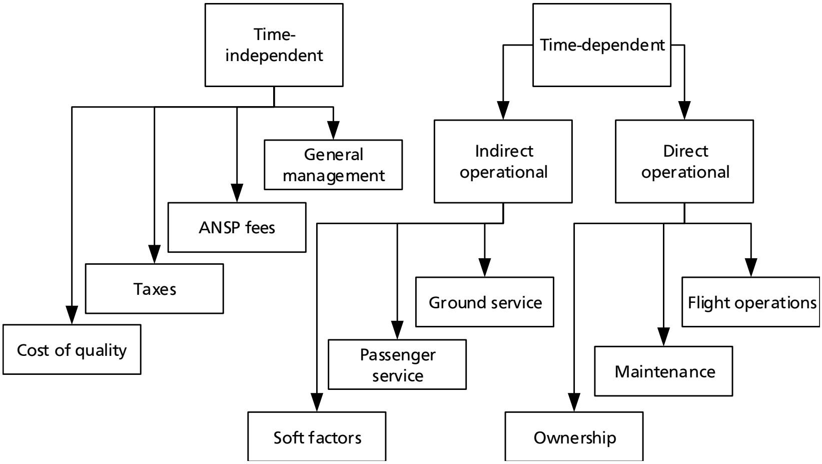


Figure 5.4.: Cost elements for operating a flight, after [Sch17]

In the scope of this thesis, three cost elements were implemented for the edge weight computation. The time-dependent cost of fuel, crew and engine maintenance were chosen to be implemented, since they can be seamlessly computed and show variations along with changes in the trajectory. Fuel consumption is computed by the BADA aircraft performance model where regression models are used for crew and maintenance cost. Crew cost are modeled after an approach by Roskam [Ros15], while a model created by Liebeck et al. [LAC+95] was used to depict engine maintenance wage cost in dependence of produced engine thrust.

5.3 Optimization Algorithm Evaluation

The algorithm described in section 5.2 was evaluated in order to determine the rate of success when optimizing trajectories and the trajectories deviation from the imposed constraints. In this scope, finding of a trajectory that complies with the

9 It is assumed that when building up delay passenger satisfaction decreases. Along with entitled compensations, the airline might face additional losses when passengers discourage other potential customers of booking flights with the airline.

imposed constraints is deemed a success, where a failure is the inability of the algorithm to find a solution (compare to section 5.2.1). For this purpose, city pairs were determined which are connected by airlines in day-to-day operations and trajectory optimizations were performed simulating flights throughout the year, to catch effects of changing weather. This section presents the evaluation study structure and results, as well as discussing them.

5.3.1 Study Structure

This section presents the structure of the optimization algorithm evaluation and the programs implemented to support the evaluation process.

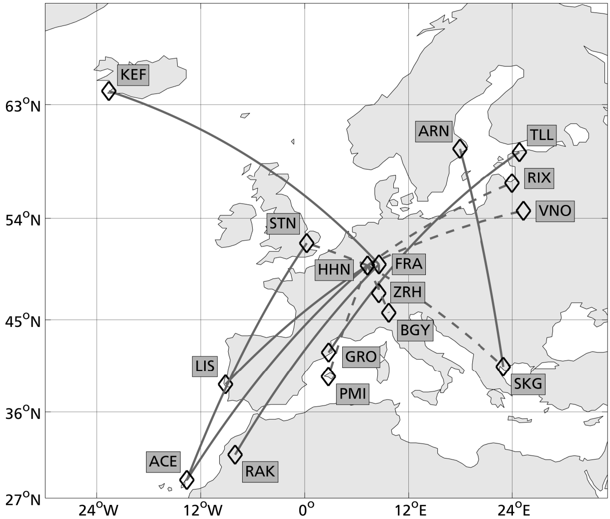
5.3.1.1 Simulation Input

Various input is needed to start the optimization. This section presents how the input data was generated in the scope of the evaluation study.

City Pairs and Flight Plans

City pairs were picked to represent actual airline operations on a variety of route lengths, as well as to capture meteorological effects such as the jetstream. A total of seventeen city pairs were chosen to depict shorthaul routes, flown with a Boeing 737-800 and five routes to depict longhaul routes flown with a Boeing 777-200LR. City pairs for shorthaul routes are located in Europe, longhaul flights take place between Europe, North America, South America, the Middle East, the Far East and Australia. Figure 5.5 presents the simulated routes, shorthaul routes shorter than 250NM are omitted in the figure. These routes are Frankfurt (FRA) - Dusseldorf (DUS), Frankfurt - Nuremberg (NUE) and Lisbon (LIS) - Porto (OPO). In figure 5.5a, routes plotted in a dashed line have a length between 250NM and 1000NM (compare to table 5.1). Flight Plans were acquired from Jeppesens *Jetplan* flight planning engine, using the above mentioned aircraft types and International Standard Atmosphere (ISA) weather conditions. By computing flight plans in ISA conditions the influence of wind on the lateral route planning is eliminated. Keeping the lateral route unchanged over all simulated weather days ensures comparability of the results.

Depending on the length of the routes, one, two or three waypoints of the route were designated to be imposed with time constraints. Table 5.1 depicts number and position of time constrained waypoints dependent on the overall route length.



(a) Shorthaul, routes shorter than 250NM omitted

(b) Longhaul

Figure 5.5.: Simulated routes [illustrations by author]

Table 5.1.: Route length, number of RTA waypoints and their positions

Route length d	RTA 1	RTA 2	RTA 3
$d < 250$ NM	TOD	-	-
250 NM $< d < 1{,}000$ NM	Mid of cruise	TOD	-
$d > 1{,}000$ NM	TOC	Mid of cruise	TOD

TOC, mid of cruise and TOD were determined from the generated flight plans. All flights were computed estimating a 75% payload for the flight, measured by the maximum payload defined in the BADA[10]. Finally, the amount of fuel was also taken from the computed flight plan but added with a reserve of 70% or 30% for long and shorthaul flights respectively to accommodate for the fact that the flight plans were computed with ISA conditions[11].

Weather Selection

The days on which the flights were simulated were chosen to represent the weather in all seasons at the airports and along the route. Weather data was retrieved from the NOAA for the year 2016. Flights were scheduled for every other month beginning at February and every third day of each month, resulting in a total of 84 flights per route. The retrieved weather data contained forecasts as well as measurements of the actual weather, which are both used during the simulation process.

Since both weather forecast and actual weather description have a validity period of six hours, data needs to be merged when the flight lasts longer than six hours. Since the GRIB format describes weather on a fixed grid of altitudes and longitudes, a blending method was implemented to blend two weather files at the location the aircraft is expected to have reached after six hours. Care was taken to ensure a smooth transition between the two files (compare to appendix C.1 for details on the blending method).

[10] This corresponds to a payload of 51,693kg on the 777-200LR and a payload of 15,225kg on the 737-800.

[11] Under ISA conditions no wind is present, which strongly influences fuel planning. Care was taken not to let the aircraft exceed its MTOM.

Computation of Time and Altitude Constraints

In the future Air Traffic Management (ATM) system (compare to section 2.6), time constraints will be imposed by the ANSP [SES12c]. For computing the constraints, ANSPs use weather forecasts and estimates of aircraft performance and weight. By doing so, the computed RTAs will contain uncertainties which in worst case cause the trajectory optimization to abort if no solution can be found. The RTA computation for this study intends to depict such uncertainties and therefore uses average aircraft performance and weather forecast data. In the following the computation process is outlined.

For each simulation day RTAs at the identified waypoints are computed based on the retrieved weather forecast. The computation takes into account the climb after the take off by using average Rate of Climbs (ROCs) and winds at passed altitudes, but since altitudes during the enroute phase are subject to the optimization itself, no fixed altitudes and the prevailing weather condition can be used. Instead an average wind over an altitude band is estimated for the enroute portion of the flight. Since it is expected that the optimization will favor altitudes offering tailwind over those offering headwinds, tailwinds are weighed higher when estimating the average to move it closer to the winds experienced on the actual flight (compare to appendix C.2 for details on RTA computation).

Similar to altitudes, the TAS at which the aircraft will travel is unknown and is estimated as an average over typical TAS values at an altitude band taken from the BADA library as well. The RTAs values computed in this manner are passed as input to the algorithm, which intends to meet the constraints within the limit of $\pm 30s$.

Altitude constraints are not dynamically computed, since fuel consumption and step climb behavior are subject to the optimization. Instead, estimated altitudes are taken from the computed flight plan and are reduced according to the added fuel reserves. This builds the risk of forcing the trajectory onto non optimal altitudes and to produce vertical profiles characterized by abnormal climbs or descends.

5.3.1.2 Simulation Process

A framework in MATLAB was programmed to accommodate the computations of the simulation input as described in section 5.3.1.1 and to call the optimization routine. The process is outlined in figure 5.6.

The process begins with checking the input files of flight plan, list of RTA constrained waypoints and simulation day schedule for validity. This step is followed by blending weather files where necessary and computing the actual RTAs. This process is repeated for every day to be simulated. To increase the speed of the

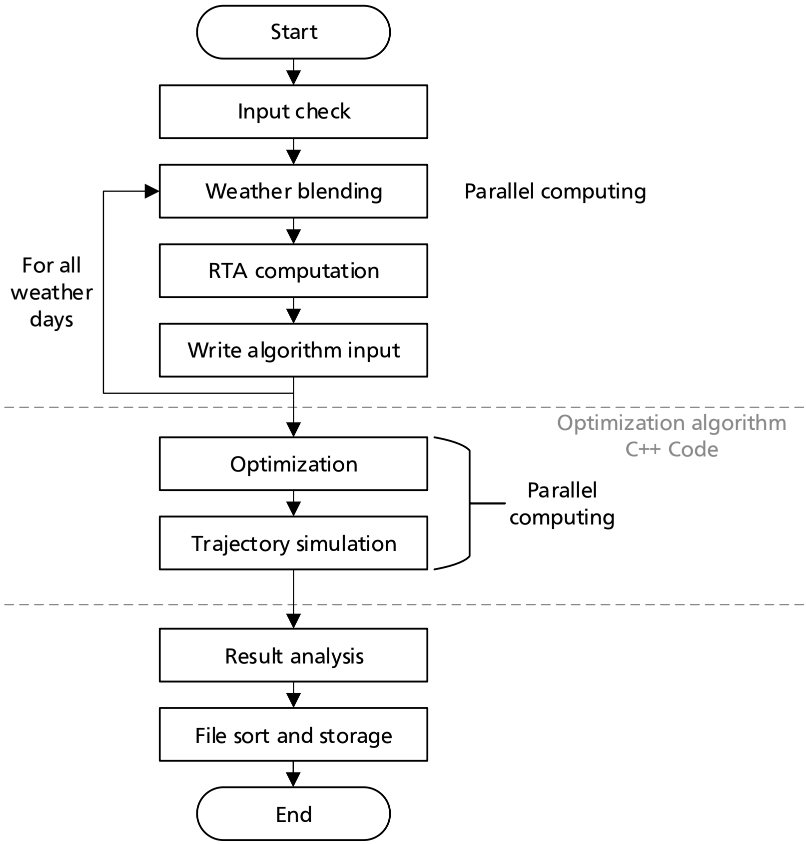


Figure 5.6.: Simulation process [illustration by author]

computations, the blending process is paralleled using MATLAB tools. When the input for all days are prepared, the optimization algorithm is called, paralleled as well, for all days to be simulated. When all days have been cycled, the result files are sorted and analyzed. The process begins again for the next flight plan, if any exists.

5.3.1.3 Computation Parameters

Computations were carried out on a Commercial off the Shelf (COTS) machine, which used an intel i7-930 Central Processing Unit (CPU), 18GB of memory and a Windows 7 Professional 64bit Operating System (OS). As the CPU offers four kernels, all paralleled tasks run in four instances.

The computation time needed to finish the simulation for a single flight plan on all simulation days depends on if the weather needed to be blended, the number of RTA constrained waypoints, the length of the route and the success rate. If no trajectory is found already to the first time constrained waypoint, the optimization aborts at an early stage and computation time is reduced. Table 5.2 gives an overview of examples for computation times, carrying out 84 flights.

Table 5.2.: Computation time examples

Route	Distance in NM	Number of RTAs	Computation time in min
FRA - DUS	153	1	44
HHN - BGY	363	2	545
HHN - ACE	1,650	3	449
FRA - GRU	5,370	3	3,731

As can be seen the computation time increases over route length and number of RTA waypoints, most drastic when weather files needed to be blended. During the computation of the Frankfurt - Sao Paulo route, 60% of the computation time was needed for weather blending alone. The computation time for the route Hahn - Arrecife is lower then the one of Hahn - Bergamo, even though the route is longer and imposed with three instead of two time constrained waypoints. Multiple factors are responsible for the lower computation time. First, routes with two time constrained proved to have a higher success rate than routes with three. This means less optimizations abort with no solution found. Second, the portion between the take off and the mid of cruise contains an increased number of nodes (compare to section 5.2.1: Grid Generation.) and needs more computation time to be expanded. On routes with three time constrained waypoints, this portion of the flight is separated in two parts by the TOC, which is also time constrained. This separation reduces the computation time.

5.3.2 Study Results and Discussion

In this section, the results of the simulation are presented and the findings are discussed.

Success Rate

This section presents and discusses the success rates of the trajectory optimization. As it is possible that the optimization algorithm does not find a solution, it is first examined how often the optimization fails and possible reasons for the failure are determined. In a first attempt, the flights were ordered by their duration, where the success rates are depicted in figure 5.7.

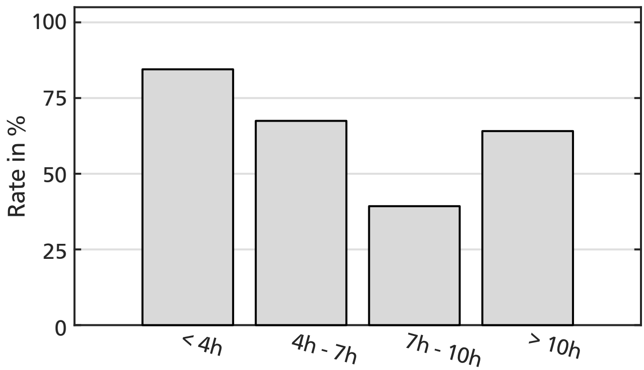


Figure 5.7.: Success rate in dependence of flight duration

As can be seen, flights with a duration of less than 4 hours show the highest success rates, whereas flights with a duration between seven and ten hours show the lowest. In the following, the analysis is conducted based on the differentiation between shorthaul and longhaul flights as described in section 5.3.1.1.

Longhaul Flights:
For the ten longhaul flights, a solution was found for 63% of all simulated days. As figure 5.8 presents, the success rate varies with the month the simulation was carried out for.

A general drop in success in August is observed. The longhaul flights depart at airports located in areas of strong climatic differences and lead through areas

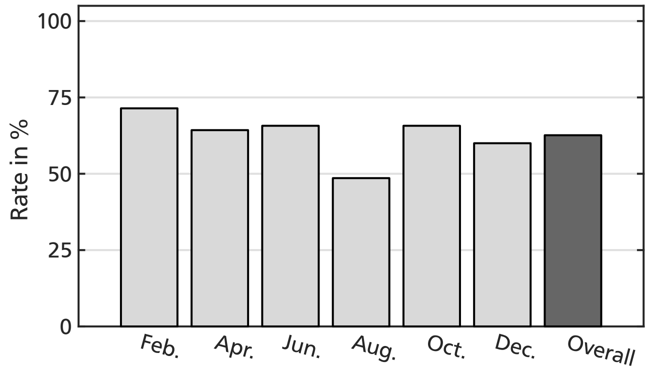


Figure 5.8.: Success rate in dependence of months of longhaul flights

affected by weather phenomena such as the jetstream[12]. As figure 5.9 depicts, flights departing from Dubai to Frankfurt have the lowest success rate of 0% in the summer month August, during which climb performance is limited due to higher temperatures[13].

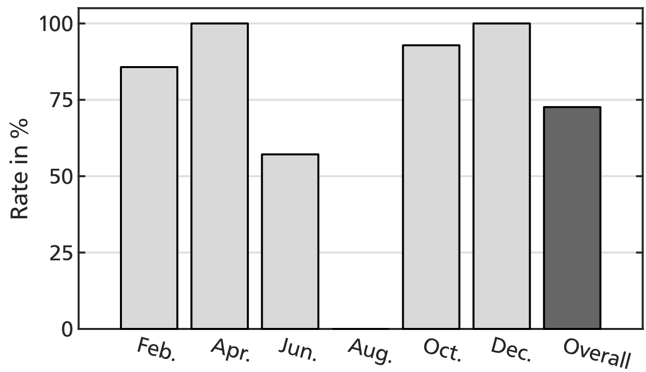


Figure 5.9.: Success rate in dependence of months of the route DXB - FRA

[12] Jetstreams are atmospheric winds moving in eastern direction in high altitudes caused by temperature differences of air masses. Two main jetstreams, the polar-front and the subtropical jetstream, exist [Mor17].

[13] August shows the highest average temperature of all months at DXB for the period 1977-2017 [Uni18].

As an additional analysis found, the optimization of the flights on the route DXB - FRA conducted in August terminated at the first time constrained waypoint in all cases, leading to the assumption that the combination of altitude and time constraints could not be met due to insufficient aircraft performance in hot weather conditions[14]. Since the altitude constraint was not computed individually for each simulated day, weather conditions such as high temperatures have strong impact on the success rates of flights which route is altitude constrained at the TOC. In addition, long haul flights were computed with a high fuel reserve, which again decreases aircraft climb performance.

In difference to high temperatures in Dubai, figure 5.10 depicts the influence of the jetstream on the flight from Frankfurt to New York - JFK. Since the route was computed for a flight in ISA conditions, the daily change of the jetstream's lateral dispersion can not be taken into account by the optimization.

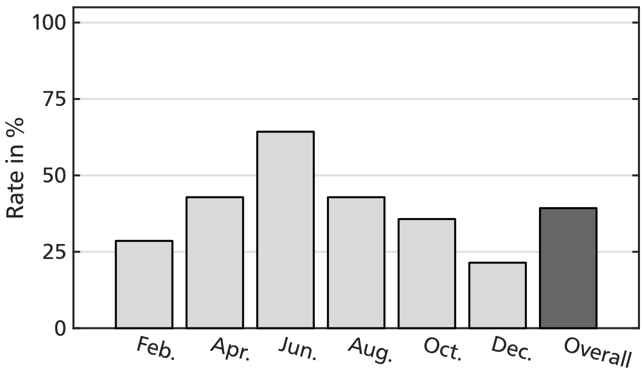


Figure 5.10.: Success rate in dependence of months of the route FRA - JFK

As one can see, the success rates do not drop as low as 0%, but the overall success rate is below 50%. Since the polarfront jetstream is flowing in an eastern direction, it has strong influences on the westward flight from Frankfurt to New York. The jetstream's lateral and vertical positions are bounded by defined borders, making it difficult for the time constraint computation to catch its effects, since the wind average over an altitude band is used.

[14] Temperature was not considered when computing RTAs and defining altitude constraints. Reducing the altitude constraint at the first waypoint by 400m led to an increased success rate of 50% in August on the route DXB - FRA.

Shorthaul Flights:
For the shorthaul flights, the optimization found a solution in 85% of all cases. As the amount of time constrained waypoints differ with the route length, a further categorization by amount of time constrained waypoints is done which is presented in figure 5.11.

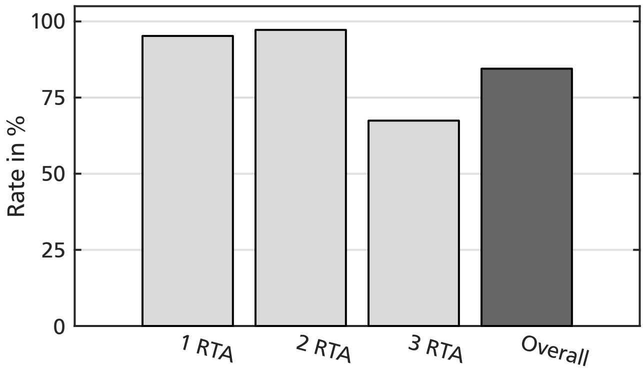


Figure 5.11.: Success rate in dependence of amount of RTA waypoints of shorthaul flights

As one observes, flights imposed with two time constraints show a success rate of 97%, followed by flights with one constraint and a success rate of 95% and ended up with flights having three constraints and a success rate of 67%. This decrease in success when adding a third RTA is explained with the position of the time constrained waypoint at the TOC. The uncertainty of the RTA is having the highest impact on time constrained waypoints positioned after the climb, since aircraft performance limitation leave less room for optimization during the climb.

Categorized by months, the results are presented in figure 5.12.

Having the highest rate of success in June with 89%, the rates of the other months drop lowest in December to 80%. The distribution does not show a drop such dramatic as the distribution for longhaul flights in August. Generally, the shorthaul flights operate on shorter distances which leaves less room for weather phenomena to adversely influence the optimization process.

RTA Compliance and Deviation

The previous section presented the success rate of the trajectory optimization. This section focuses on the compliance with the imposed time constraints. First, it is

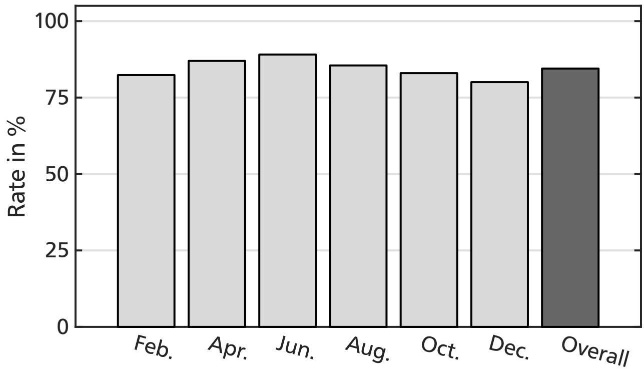


Figure 5.12.: Success rate in dependence of months of shorthaul flights

evaluated if, even though a solution was found in the trajectory optimization, a time constraint was not met when simulating the found trajectory. This was the case in 2.3% of the successful longhaul optimizations and 0.8% of the successful shorthaul optimizations. Following, the results are presented and discussed separately for longhaul and shorthaul flights. A complete presentation of the results of the RTA deviation is found in appendix C.3.

Longhaul Flights:
Figure 5.13 depicts the overall deviation from time constraints for all longhaul flights. As can be seen, the deviations are the largest at the first time constrained waypoint located at the TOC ($\mu_{\mathrm{RTA1}} = -13.1$s, $\sigma_{RTA1} = 18.3$s).

This behavior shows the struggle of the optimization algorithm to find a solution for the first waypoint. Again, this is explained by the fixed altitude constraint at the TOC and the uncertainties when computing the time constraint at this waypoint. Further a behavior of the algorithm is evident to compute solutions that tend to the lower end of the time constraint limits of −30 seconds ($\mu_{\mathrm{RTA2}} -27.3 =$s, $\sigma_{RTA2} = 2.6$s and $\mu_{\mathrm{RTA3}} = -26.9$s, $\sigma_{RTA3} = 3.6$s). The fuel price being the dominating factor in the cost representation, the optimization with the goal of the lowest overall cost tends to fly slower and therefore reduce fuel burn. It is envisioned that in the future cost structures are not implemented static, but are dependent on the actual present situation, where arising time cost might outgo fuel cost by far[15]. Such a scenario could be e. g. a foreseen late arrival of a flight which causes con-

[15] To exemplarily depict a similar scenario, the flight HHN - PMI was optimized again for a single day with time dependent cost increased by a factor of 1,000. While the simulation with lower time cost met the RTAs at −30s and −27s respectively, the simulation with higher modeled time

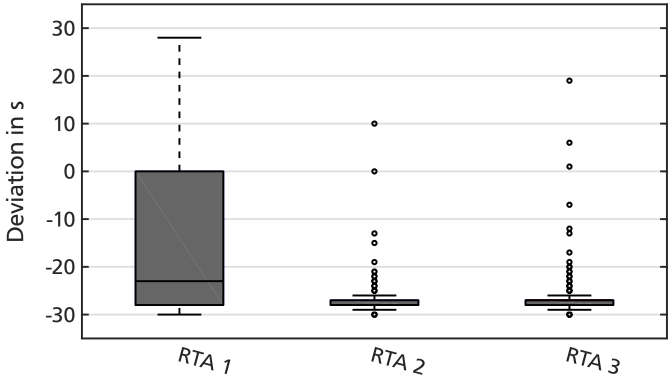


Figure 5.13.: Deviation from RTAs for all longhaul flights

necting passengers to miss their flights which in turn forces the airline to provide a hotel and meals for the affected passengers.

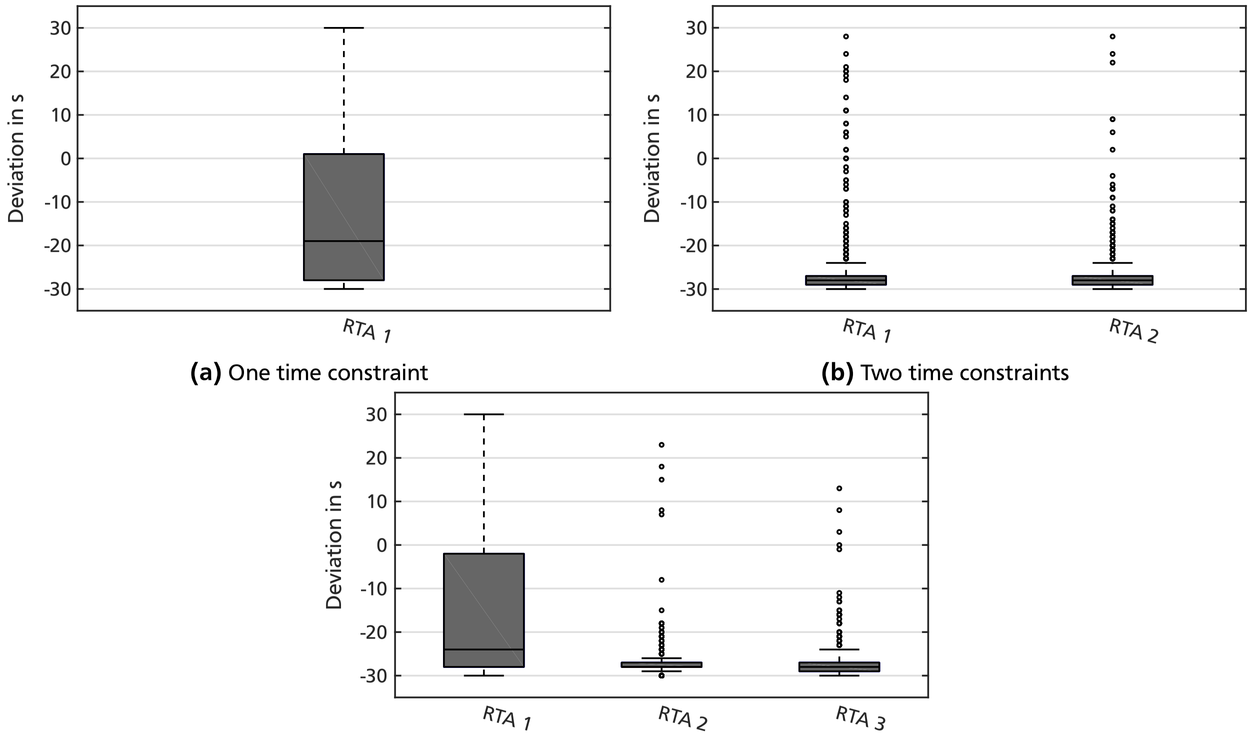
Shorthaul Flights:
Shorthaul flights are evaluated separately categorized by their amount of time constrained waypoints. Figure 5.14 presents the deviations from the time constraints for the three cases.

As can be seen, flights with two RTAs tend towards the lower end of the allowable deviation limit ($\mu_{\mathrm{RTA1,2}} = -26.5\mathrm{s}$, $\sigma_{RTA1,2} = 6.5\mathrm{s}$ and $\mu_{\mathrm{RTA2,2}} = -26.9\mathrm{s}$, $\sigma_{RTA2,2} = 5\mathrm{s}$). Flights with one RTA tend to use the full spectrum of the limits ($\mu_{\mathrm{RTA1,1}} = -12.7\mathrm{s}$, $\sigma_{RTA1,1} = 17.5\mathrm{s}$). Flights imposed with three time constraints show, similar to the longhaul flights, a use of the full spectrum of the limits on the first constrained waypoint and tendencies to the lower limit on the two subsequent constraints ($\mu_{\mathrm{RTA1,3}} = -14.1\mathrm{s}$, $\sigma_{RTA1,3} = 18\mathrm{s}$ and $\mu_{\mathrm{RTA2,3}} = -27.3\mathrm{s}$, $\sigma_{RTA2,3} = 4\mathrm{s}$ and $\mu_{\mathrm{RTA3,3}} = -27.6\mathrm{s}$, $\sigma_{RTA3,3} = 3.6\mathrm{s}$).

Comparison of cost priority and time priority

Selected city pairs were simulated with the optimization focusing on minimizing the deviation from the imposed time constraints rather on minimizing the cost of

cost met the RTAs at −29s and 11s. The small difference at the first of waypoint of $\Delta t = 1\mathrm{s}$ is explained with the combination of altitude constraint and time constraint, which can not be met by arriving earlier, where the difference at the second constraint of $\Delta t = 38\mathrm{s}$ shows the influence of increased time cost, which forces the optimization to arrive at the waypoint earlier.



(a) One time constraint

(b) Two time constraints

(c) Three time constraints

Figure 5.14.: Deviation from RTAs for all shorthaul flights

the flight. The city pairs were chosen to represent each category of flights, therefore one longhaul flight (FRA - NRT) and three shorthaul flights (FRA - DUS, HHN - BGY and HHN - LIS) were simulated. This section presents the results and their comparison to the results of the cost optimization. All routes were computed for an outbound and inbound flight, where the results are combined in this evaluation.

First, the success rates of cost and time priority were compared. Success rates differ only in the range of two simulation for two of the routes, for all other routes the success rates remained the same. Second, the deviations from the time constraints were evaluated, they are depicted for the flight FRA - NRT in figure 5.15.

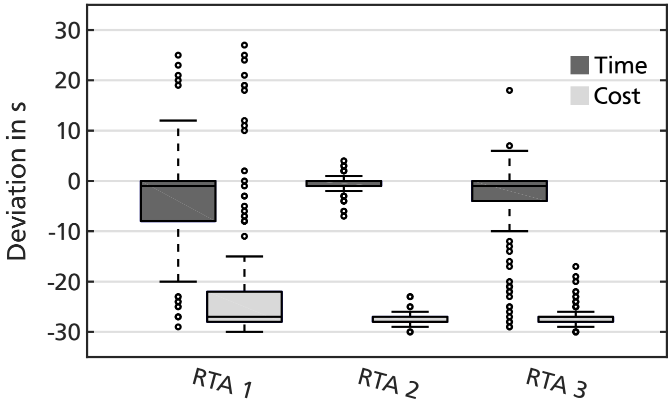


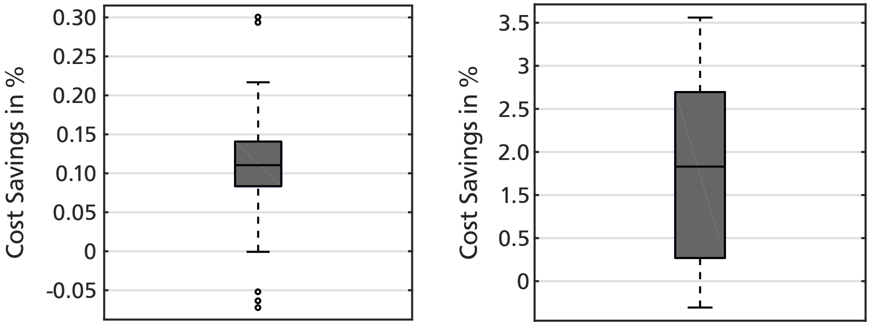
Figure 5.15.: Deviation from RTAs compared for cost and time priority of the route FRA - NRT

The simulation computed under time priority shows less deviation from the time constraint, the first waypoint still shows stronger deviations ($\mu_{\mathrm{RTA1,3}} - 4.3 =$s, $\sigma_{RTA1,3} = 9.7$s). The middle constraint was met with a mean precision of less than 1 second ($\mu_{\mathrm{RTA2,3}} = -0.6$s, $\sigma_{RTA2,3} = 1.5$s), where the constraint located at the TOD was met with similar precision as the first one ($\mu_{\mathrm{RTA3,3}} = -4$s, $\sigma_{RTA3,3} = 8.6$s).

Following, the total occurred cost[16] are compared exemplary on the routes FRA - NRT and FRA - DUS. The results for all routes are found in appendix C.3.0.1. Figure 5.16 depicts a comparison of the cost savings the cost priority computation was able to achieve compared to the time priority computation. Negative savings indicate that the cost priority actually had higher cost than the time priority. For both flights, the cost optimization was able to reduce the average cost compared to the computation in time priority. For the route FRA - NRT, mean

[16] Cost are depicted using a nondimensional cost unit that is not connected to any actual currency.

cost savings of 0.13% were accomplished ($\mu_{CP} = 350{,}915$, $\sigma_{CP} = 5{,}149$ and $\mu_{TP} = 351{,}365$, $\sigma_{TP} = 5{,}167$) and for the route FRA - DUS mean cost savings of 1.3% were achieved ($\mu_{CP} = 7{,}220$, $\sigma_{CP} = 602$ and $\mu_{TP} = 7{,}315$, $\sigma_{TP} = 617$).



(a) Flight FRA - NRT

(b) Flight FRA - DUS

Figure 5.16.: Cost savings of cost priority over time priority

As the optimization goal was to arrive at the time constrained waypoints within a limit of ±30s, the optimization was left with little space to achieve higher savings.

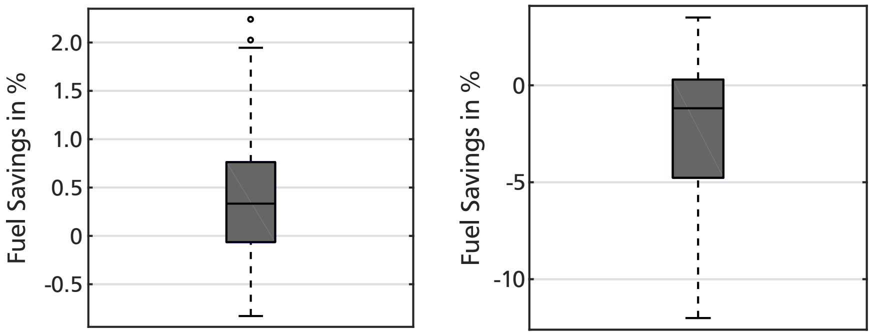
On shorter routes, time cost are the dominating cost factor, where as on longer routes consumed fuel dominates over time cost. Figure 5.17 presents this fact in form of fuel savings[17], where one notices that on the route FRA - NRT the flight under time priority consumed an average of 0.36% more fuel than the flight under cost priority ($\mu_{CP} = 77{,}149$kg, $\sigma_{CP} = 2{,}193$kg and $\mu_{TP} = 77{,}425$kg, $\sigma_{TP} = 2{,}090$kg), where on the route FRA - DUS the opposite is noticed and the cost priority flight consumed 2.16% more fuel the time priority flight ($\mu_{CP} = 1{,}403$kg, $\sigma_{CP} = 84$kg and $\mu_{TP} = 1{,}373$kg, $\sigma_{TP} = 86$kg).

5.4 Summary

To showcase the feasibility and potential of trajectory optimization algorithms running on an EFB, an exemplary algorithm was developed and implemented. To evaluate this algorithm, an evaluation concept and software framework were developed which supported the execution of the simulation.

The evaluation of the optimization algorithm shows that a four dimensional trajectory optimization carried out on COTS hardware is possible. Both success rates

[17] Again, negative savings represent that the cost priority consumed more fuel than the time priority.



(a) Flight FRA - NRT

(b) Flight FRA - DUS

Figure 5.17.: Fuel savings of cost priority over time priority

and computation time lag behind the expectations. The cause for low success rates though is considered to be the coarse specifications of time and altitude constraints rather than the performance of the optimization algorithm itself. To include expected uncertainties that arise when ANSPs compute RTAs, constraints were computed by using averaged values for aircraft performance and coarse weather information, which inevitably decreases the accuracy of the results. This emphasizes the importance of developing advanced flight planning tools which are able to compute routes along with corresponding time and altitude constraints that are flyable by the intended aircraft. Optimization algorithms running on an EFB can then be used to build and optimize the actual trajectory during the flight and send it to the CoreFMS for execution.

To use advanced optimization algorithms on an EFB, computation time needs to be reduced compared to the ones achieved by the exemplary implementation evaluated in this thesis. The algorithm evaluated in this thesis shows potential to further decrease computation time by several measures. First, it is expected that weather data is provided in a format that does not need any blending on the EFB, which could reduce computation time on longhaul routes by more than 50%. Second the speed of the algorithm itself can further be increased by reducing nodes on the computational grid and the implementation of a valid monotonic heuristic. Further, a professional implementation having the target hardware in mind will be able to decrease computation time.

6 Summary and Outlook

After presenting the conceptual design and evaluation of the Trajectory Execution and Optimization System (TEOS), a final summary is given in this chapter. An outlook on envisioned future works resulting from the research conducted follows.

6.1 Summary

The research conducted was motivated by the shortcomings of current Flight Management Systems (FMSs) with respect to their support for future Air Traffic Management (ATM) systems and integrated airline operations. The aim was to provide a system architecture that facilitates both support for Trajectory Based Operations (TBO) and for an increase in airline operations efficiency.

6.1.1 Architecture Concept

The concept of shifting functionality from the certified FMS to the Electronic Flight Bag (EFB) was the driving factor leading to the proposal of the TEOS architecture. The architecture reduces the functionality of the FMS, which is stripped down to the CoreFMS, and puts functionality onto the EFB, which grants higher computation power, data storage volume and connectivity. The proposed architecture was examined through a Functional Hazard Analysis (FHA), to ensure that no safety critical function resides on the EFB. The FHA shows that 42% of the analyzed functions can be shifted to the EFB. In addition, the connection between the EFB and the CoreFMS was designed with regards to security requirements to prevent malicious activity by third parties. The connection was designed as a wired connection to prevent possible jamming of wireless networks, which was identified to be a risk of high potential. Furthermore, installation cost and maintainability were considered in the connection design.

The effort to achieve certification for a system depends, amongst other factors such as project complexity and staff experience, on the amount of code lines. As the amount of code lines of the CoreFMS is expected to decrease using the TEOS architecture, an analysis of cost per code line was conducted and found that up to 12.6% of certification cost depending on the amount of code lines can be saved. As

TEOS is a new system architecture, experience in certifying such a system is low and reuse of previous software code is limited.

A demonstrator for the architecture design was developed and integrated into a research flight simulation environment. The demonstrator features the core capabilities of TEOS including an exemplary application running on an EFB. The demonstrator's CoreFMS was implemented to run on a Real Time Operating System (RTOS), simulating the operating environment on an aircraft.

6.1.2 Architecture Evaluation

The demonstrator was used to evaluate the architecture regarding its usability. Usability consists of the three factors effectiveness, efficiency and subjective usability. Corresponding hypotheses were formulated in order to test the TEOS architecture with regards to all three factors. A study was designed to assess the usability of the TEOS architecture in comparison to a traditional FMS. The study was built around the task of planning and implementing a route change due to an area of severe weather intersecting with the planned route. Operations using the traditional FMS were simulated by the standard simulator FMS together with a charting application on an EFB. No connection existed between FMS and EFB.

Ten participants took part in the study, representing a mixture of flying experience and aircraft type ratings. For each participant, objective and subjective indicators were recorded and evaluated. Regarding effectiveness, an evaluation of successful task execution and the diversion route length showed better values for TEOS. While four participants failed the task using the FMS, two failed using TEOS. For the second scenario, reroutes created using TEOS showed shorter routes with mean difference of 19.55NM compared to routes created using the FMS. With temporal effort represented by task time and mental effort represented by the National Aeronautics and Space Administration (NASA) Task Load Index (TLX) score, TEOS received higher ratings with regards to efficiency in terms of effort to solve the task, too. For scenario one and two, mean time savings of 81s and 31.25s were achieved respectively, where the mean overall TLX rating of TEOS was 10.36 points lower than the one of the FMS. Subjective usability was evaluated by obtaining a System Usability Scale (SUS) score and the participants' answers on a Likert scale questionnaire. Both showed that the participants favored TEOS over the traditional FMS, where the SUS score of TEOS was 24.48 points higher then the score of the FMS.

6.1.3 Trajectory Optimization Algorithm Evaluation

An example for the application of the TEOS architecture was intended to be given in this thesis in order to depict the possibilities a system designed according to the TEOS architecture offers. It was chosen to design and implement a trajectory optimization algorithm for an EFB, which is able to optimize the speed and vertical profile of a trajectory with respect to temporal and altitude constraints. The informed search graph approach A^* was chosen for the optimization. The algorithm was designed to be able to find a cost optimal solution within the boundaries of time constraints as well as to find a solution to meet time constraints as precisely as possible. cost were characterized by fuel cost and a cost function representing other time dependent cost fractions. The definition of a cost function on the EFB allows airlines to implement custom optimization specifications instead of using the simple Cost Index (CI) method employed on traditional FMSs.

A study was designed to evaluate the capabilities of the algorithm with respect to success rates of finding a solution, precision of meeting temporal constraints and cost. Ten longhaul and thirty four shorthaul flights were chosen to represent the variety of today's airline operations. Shorthaul flights were simulated using the aircraft performance of a Boeing 737-800, a Boeing 777-200LR was used for the longhaul flights. Depending on the route length, the flights were imposed with up to three time constraints along the route each with boundaries of ±30s. The flights were simulated on a total of eighty four days spread evenly over the year 2016. Time constraints were computed individually for each day, taking into account a possible defective computation by the Air Navigation Service Provider (ANSP) by using average aircraft performance and weather data.

The simulation results showed success rates of 63% and 85% for longhaul and shorthaul flights respectively. The rough computation of temporal constraints showed to have strong impact on the ability of the algorithm to find a solution within the given boundaries. In addition to average wind, no temperature data was used for the determination of time constraints, which has strong effects on aircraft performance. The results emphasize the need for a potent trajectory computation algorithm employed by the ANSP and collaborative decision making regarding constraints in order to issue flyable constraints to aircraft. With regards to precision of meeting time constraints, the evaluation found that if a solution was found only in 2.3% and 0.8% of the flights for longhaul and shorthaul flights respectively time constraints were not met. When optimizing to achieve a cost optimal solution, the solution trajectory tended to an arrival towards the later time limit except for time constraints located at the Top of Climb (TOC). When comparing optimizations computed for minimal cost to those computed for a precise arrival at the time constraint, the cost optimal solution showed lower cost. When being able to only optimize inside the limits of the time constraints of ±30s, cost savings are limited. When comparing long and shorthaul flights, the dominance of time cost, depicted by the cost function, during the latter became evident. While still saving cost compared to a precise arrival, the cost optimal solution consumes more fuel.

6.2 Outlook

The work presented in this thesis lays the foundation for future research. Future work will gain further understanding of the matter as well as bring more detail to the proposed system architecture. Assumptions and simplifications presumed in this thesis need to be eliminated.

Regarding the FHA, its focus needs to be expanded in several ways. First, the system boundaries of the FHA should be expanded to analyze the impact of the function shift on a broader level of aircraft functions. The analysis should be conducted not only for the enroute phase but for all flight phases that can occur during flight operations, including abnormal operations. Second, the analyzed functions should be formulated on lower system levels to allow more detailed definitions of shiftable functions. Along with the finer definition of shiftable functions, exact message protocols to exchange data between the FMS and the EFB can be developed and evaluated regarding their completeness and achievable transmission rates via the chosen connection medium.

Having in mind the development of new aircraft models, an adapted design for an Human Machine Interface (HMI) to the CoreFMS should be considered. The introduction of new aircraft models hold the chance to introduce innovations to the flight deck such as touchscreens [Boe16] or synthetic vision [Air18b]. Further research into the CoreFMS HMI will help to leverage the full potential of TEOS by designing new and efficient cockpit workflows.

The efficiency gains achieved by airlines when using TEOS regarding integrated operations need to be analyzed further, for example in terms of financial or passenger satisfaction gains. The analysis should consider a detailed data exchange model, tailored to an airline needs, as well as an examination of the financial and technical effort of data transmission between air and ground. Several factors comprise the effort of data transmission, such as installation of required technical equipment and data transmission fees.

As the evaluation of the trajectory algorithm showed, the principle of an algorithm deployable on Commercial off the Shelf (COTS) hardware works in general. Future implementation should be carried out with the focus on reducing the computation time, having the target hardware and use cases in mind. The success rate of the solution finding process could be further increased by improving the constraint computation. This emphasizes the need to conduct general research in the field of trajectory building, where ANSPs are responsible for computing conflict free trajectories for all participants in air traffic.

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A Considerations for the Conceptual Design

This appendix lists additional information on the considerations made for the conceptual design of Trajectory Execution and Optimization System (TEOS).

A.1 Functional Hazard Analysis Results Table

This section presents detailed results of the Functional Hazard Analysis (FHA) as mentioned in 3.4.1.2.

Function	Failure Condition	Phase	Effect	Classification	Verification and Supporting Material
CoreFMS Functions					
Navigation Functions					
Determine Current Position	a. Current Position is computed false	Cruise	Position needs to be determined manually in alternative way, significant increase of workload.	Major	
	b. Total failure of Position Determination	Cruise	Position needs to be determined manually in alternative way, significant increase of workload.	Major	
Send Current Position Data to the Navigation Display (ND)	a. Position Data with false values is send to the ND but Navigation Computations use correct values.	Cruise	The crew notices the failure and needs to be vectored by Air Navigation Service Provider (ANSP). Mobile Device serves as backup.	Major	Mobile Device needs to be redundant.
	b. Total Failure of Sending Position Data to the ND	Cruise	The displays receive no navigation data from the Flight Management System (FMS). The crew uses the mobile device as backup. Slightly increased crew workload.	Minor	Mobile Device needs to be redundant.
Send Current Position Data to Mobile Device	a. Position Data with false values is send to Mobile Device	Cruise	The crews primary source of Position Data are the Primary Flight Display (PFD)/ND.	No Safety Effect	
	b. Total Failure of Sending Position Data to mobile device	Cruise	The crews primary source of Position Data are the PFD/ND.	No Safety Effect	
Guidance Functions					
Trajectory Generation	a. Trajectory is generated false unnoticed by crew	On Block / Cruise	With automatic guidance the aircraft will follow the generated trajectory into possible hazardous situations	Hazardous	
	b. Trajectory generated false noticed by crew	On Block / Cruise	The crew notices the false trajectory and switches to manual controlled flight and Air Traffic Control (ATC) vectoring. Significant increase of workload	Major	
	c. Failure of trajectory generation	On Block / Cruise	No trajectory can be generated from an entered flight plan. The crew uses manual flight and requests ATC vectoring	Major	
Control Lateral Flight Path	a. Control Value for Lateral Flight Path is computed with an Offset Too High/Low (noticed by crew on displays)	Cruise	Lateral Flight Path needs to be controlled selected/manually, significantly increased workload for pilots	Major	
	b. Total Failure of Controlling the Lateral Flight Path (noticed by crew on displays)	Cruise	Lateral Flight Path needs to be controlled selected/manually, significantly increased workload for pilots	Major	

Function	Failure Condition	Phase	Effect	Classification	Verification and Supporting Material
Control Vertical Flight Path	a. Control Values for Lateral Flight Path are computed with an Offset Too High/Low (noticed by crew on displays)	Cruise	Too High/Low Vertical Speeds endangering the aircraft are prohibited by Envelope Protection. Significantly increased workload due to controlling the Vertical Flight Path selected/manually.	Major	
	b. Total Failure of Controlling the Vertical Flight Path	Cruise	Vertical Flight Path needs to be controlled selected/manually, results in significantly increased workload for the crew.	Major	
Control Speed	a. Control Value for Speed is computed with an Offset Too High/Low unnoticed by crew	Cruise	Waypoints are reached too late/early, resulting in possible conflicts with other traffic. Speed commands endangering the aircraft are prohibited by the Envelope Protection.	Major	
	b. Control Value for Speed is computed with an Offset Too High/Low noticed by crew	Cruise	The Crew needs to control the speed commands manually/selected, slightly increased workload. Speed commands endangering the aircraft are prohibited by the Envelope Protection.	Major	
	c. Total Failure of Speed Control	Cruise	The Crew needs to control the speed commands manually/selected, slightly increased workload. Speed commands endangering the aircraft are prohibited by the Envelope Protection.	Major	
Flight Plan Handling					
Activate initial flightplan	a. Inadvertent activation of initial flightplan	On Block	The flightplan can be changed if the activated one contains errors. Slight increase in workload	Minor	
	b. Failure of activating the inital flightplan	On Block	The flight will be held back	No Safety Effect	
Activate flightplan update	a. Inadvertent activation of an updated flightplan	Cruise	The crew inadvertent activates a proposed updated flightplan. The previous active flightplan is stored, changing back to it needs to be negotiated with Airline Operations Center (AOC)/ANSP. Slight increase of workload	Minor	Crew procedure: Negotiate with AOC/ANSP to activate previous flightplan
	b. Inability to activate updated flightplan	Cruise	An updated flightplan can not be activated by the crew. The flightplan might have been updated due to safety reasons, the inability to activate it leads to an increased workload and reduced safety margins	Minor to Major	
Decline updated flightplan	a. Inadvertent Decline of Flightplan	Cruise	The updated flightplan is stored in the system. The review page of the update offers the ability to activate again	No Safety Effect	
	b. Inability to Decline Flightplan	Cruise	Flightplan will not be accepted automatically, no effect on crew or aircraft	No Safety Effect	

Function	Failure Condition	Phase	Effect	Classification	Verification and Supporting Material
Check for updated flightplan	a. Inability to Check for an Updated Flightplan unnoticed by crew	Cruise	The crew will not be noticed if an updated flightplan is sent by AOC/ANSP while the crew is unaware of the function failure. If a flightplan update was sent due to safety reasons, safety margins may be reduced	Major	
	b. Inability to Check for an Updated Flightplan noticed by crew	Cruise	The crew identifies the system failure and informs the other participants of the trajectory negotiation. The system is unable to use an updated flightplan for computations of commands or visualization on displays, the aircraft needs to be vectored by ANSP. Significant increase in workload.	Major	Crew procedure: Request vectoring by ANSP.
Receive flightplan update	a. Inability to receive flightplan updates noticed by crew	Cruise	Crew advises AOC/ANSP of their inability t oreceive updated flightplans. ATC vectoring might be needed. Slight increase in workload	Minor	
	b. Inability to receive flightplan updates unnoticed by crew	Cruise	Crew is notified on the failure by the sender	Minor	
Buffering of flightplan updates	a. Failure of flightplan buffering	Cruise	Received flightplan updates are not buffered, but always overwritten. Earlier sent updates are no longer available from the list.	Minor	
Notification of full flightplan update buffer	a. Misleading notification of full flightplan buffer	Cruise	Pilots could delete existing updates upon receiving the notification, even if buffer is not full. If needed, updates can be resent.	Minor	
	b. Failure of notification	Cruise	Pilots are unaware of a full flightplan update buffer. No updates can be received	Major	
Delete updated flightplan	a. Inadvertent deletion of updated flightplan before activation.	Cruise	The crew communicates with AOC/ANSP to have the flightplan resent. Slight increase in workload.	Minor	
	b. Inadvertent deletion of updated flightplan after activation.	Cruise	The updated flightplan is still active. When updating with another flightplan, it is swapped to the secondary flightplan and still accessible.	No Safety Effect	
	c. Failure to delete updated flightplan	Cruise	Flightplan update remains in buffer, which might be saturated. No more updates possible. ATC vectoring needed if the flightplan is changed. Significant increase in workload	Major	
Send Flightplan Information to ND	a. False Flightplan Information are sent to the Displays	Cruise	The crew relies on the displayed flightplan informations and bases their decisions on them, which might lead to false course corrections. Mobile Device is used as backup.	Major	Redundancy of Mobile Device
	c. Total Failure of Sending Flightplan Information on the Displays	Cruise	No flightplan information is shown on the displays, the crew uses the mobile device as backup. Slightly increased crew workload	Minor	Redundancy of Mobile Device

Function	Failure Condition	Phase	Effect	Classification	Verification and Supporting Material
Activate Secondary Flightplan	a. Inadvertent activation of secondary flightplan unnoticed by crew	Cruise	The crew inadvertent activates the secondary flightplan and changes back to primary after noticing/being noticed of the failure.	Minor	Crew procedure: Negotiate with ANSP to change back to previous flightplan.
	b. Inadvertent activation of secondary flightplan noticed by the crew	Cruise	The crew immediately changes back to primary flightplan	No Safety Effect	Crew procedure: Negotiate with ANSP to change back to previous flightplan.
	c. Failure to activate secondary flightplan	Cruise	The secondary flightplan can not be activated and the crew needs to change to selected/manual flying, which results in a slightly to significantly increased workload. Alternatively, ANSP can send the wanted flightplan upon request.	Minor to Major	Crew procedure: Request the required flightplan at ANSP to be send as an update.
Swap primary to secondary flightplan upon update activation	a. Failure of swapping unnoticed by crew	Cruise	Primary flightplan is lost and not longer available for reactivation from the secondary flightplan page. When reactivation is desired, workloads increases slightly.	Minor	
Swap primary to secondary flightplan upon secondary activation	a. Failure of swapping unnoticed by crew	Cruise	Primary flightplan is lost and not longer available for reactivation from the secondary flightplan page. When reactivation is desired, workloads increases slightly.	Minor	
Mobile Device Functions					
Flightplan Handling					
Edit Flightplan	a. Inadvertent Editing of the Flightplan	Cruise	Inadvertent edited flightplan can be declined via the Control and Display Unit (CDU)	No Safety Effect	
	b. Inability to edit flightplan	Cruise	Intended changes in the flightplan can not be carried out using the mobile device. Intended changes need to be communicated to AOC/ANSP to be entered and uploaded. Slight increase of workload.	Minor	Crew procedure: Request flightplan changes at AOC/ANSP.
Send Flightplan from Mobile Device to CoreFMS	a. Inadvertent sending of Flightplan	Cruise	The inadvertent sent flightplan can be rejected via the CDU	No Safety Effect	
	b. Inability to upload flightplan	Cruise	A changed flightplan can not be send to the CoreFMS. Intended changes need to be communicated to AOC/ANSP to be entered and send. Slight increase of workload.	Minor	Crew procedure: Request flightplan changes at AOC/ANSP.
Display Functions					

Function	Failure Condition	Phase	Effect	Classification	Verification and Supporting Material
Display Information	a. Partial Loss of Capability to display information	Cruise	The display of the mobile device is only partial functional. PFD/ND are used as primary source for navigational information. If portions of the display which support editing/uploading the flight plan are not functional, safety margins may be reduced and the crew workload will increase slightly to significant.	Minor to Major	
	b. Total Loss of Display Capabilities (black display)	Cruise	Nothing is shown on the display of the mobile device which effectively puts it out of use. Requests for editing the flightplan need to be communicated to ANSP, slight increase of workload	Minor	Crew procedure: Request flightplan changes at AOC/ANSP.
Touch Display Functions	a. Inadvertent input via touch	Cruise	All changes to the flightplan made inadvertent need to be accepted first via CDU.	No Safety Effect	
	b. Inability to use touch	Cruise	While the display still shows information, no inputs can be made. Flightplan can not be edited and uploaded by the crew, intended changes need to be communicated to AOC/ANSP to be entered and uploaded. Slightly increased workload.	Minor	Crew procedure: Request flightplan changes at AOC/ANSP.
Optimization Functions					
Optimize Vertical Profile	a. Optimize vertical profile with false (not compliant to aircraft performance) outputs	Cruise	Trajectory construction function and aircraft envelope protection will prohibit any commands endangering the aircraft	No Safety Effect	
	b. Failure of vertical profile optimization	Cruise	Trajectory construction function and aircraft envelope protection will prohibit any commands endangering the aircraft.	No Safety Effect	
Optimize Speed Profile	a. Optimize speed profile with false (not compliant to aircraft performance) outputs	Cruise	Trajectory construction function and aircraft envelope protection will prohibit any commands endangering the aircraft	No Safety Effect	
	b. Failure of speed profile optimization	Cruise	Trajectory construction function and aircraft envelope protection will prohibit any commands endangering the aircraft.	No Safety Effect	

B Additional Information on Usability Study

B.1 Flight Scenario Description

The lateral routes of the flight plans used in the simulator study are given in this section. Even though computed, any altitude and speed predictions are irrelevant for the study, since the aircraft used to compute the flight plans (Boeing 777F) does not match the aircraft simulated in Darmstadt Aircraft Environment for Research on Operations (D-AERO). The actual briefing packages provided to the participants are omitted in this appendix due to their comprehensive extent.

B.1.1 Flight 1: LFBO - KSEA

The flight from Toulouse to Seattle consisted of the waypoints:

LFBO - TOU - D335W - LACOU - CHALA - CNA - ADILU - MANAK - TIRAV - MOKOR - DEGEX - TERKU - BERAD - NERLA - GANTO - OGAGI - DOLUR - LND - INSUN - BOGMI - LEDGO - SUNOT - 6020N - ELREX - 6430N - 6740N - 6950N - 7060N - ADSAM - 070A - 080A - 090A - 100A - ALKAP - 110A - YSM - YPE - YQU - HOWSE - WALUP - YWL - WIGHT - GABAL -YYJ - ORCUS - MARNR - PNELA - VEGGN - UNITT - WUBET - SHIPZ - EMMSS - KSEA

The corresponding Significant Meteorological Phenomena (SIGMET) message for this scenario is:

WSCN31 CYYC 232315 CYEG SIGMET 1 VALID 232320 / 240530 CYYC-CYEG EDMONTON FIR +TS FCST AT 232320Z WI N061 W114 - N059 W114 - N061 W110 - N059 W110 TOP FL380 STNR NC=

B.1.2 Flight 2: CYYZ - ZBAA

The flight from Toronto to Beijing consisted of the waypoints:

CYYZ - MOBEL - DUSEK - VIDRA - ANCOL - LETOR - SEVBI - DERLO - ETBOX - KAPUX - YVO - YFM - YVP - RODBO - LIBOR - 6554N - 7047N - 7535N - 8013N - 8100N - 8120E - 8030E - PIREL - ANODI - MELAM - TINEM - DOSON - RIVAS - ROKDI - TESLA - SAKAT - OKASA - KOSUM - GISAL - BRT - DITUS - LIDKA - RUSAM - CS - TEKRO - NH - GEKMA - PEMAL - USONA - LAMIR - SERNA - BUGAN - SANOT - VIZOT - SUMOR - INTIK - ESMEP - LHT - TMR - TZH - KM - CD - JR - D109G - D189Z - ZBAA

The corresponding SIGMET message for this scenario is:

WSCN46 CYVP 252030 BGSF SIGMET 1 VALID 252035 / 260630 CYVP-BGSF SONDRESTROM FIR +TS OBS AT 252035Z WI N074 W043 - N072 W043 - N074 W038 - N072 W038 TOP FL380 STNR NC=

B.2 Diversion Route Evaluation

This section describes the mathematical equations used to evaluate the diversion routes resulting from the participant trials. In the equations mentioned in this section, λ denotes latitudes, where φ denotes longitudes. The equations used in the evaluation consider the earth as a sphere with the fix radius $R_{\oplus} = 6378137m$. Coordinates λ and φ are always given in radians and can be converted to degrees using $R_{\oplus}$. Equations were taken and developed from Schuppar [Sch16].

B.2.1 Evaluation of No Fly Zone Violation

The diversion routes were evaluated to test if any point locates inside the No Fly Zone. in order to do that, the routes discretized in portions not longer than 1 NM. To do so, first the distance of all legs in NM between their start waypoint (index 1) and end waypoint (index 2) was determined via equation B.1

$$d = \sqrt{((\lambda_2 - \lambda_1)^2 + q^2 \cdot (\varphi_2 - \varphi_1)^2)} \cdot R_{\oplus}/1852 \tag{B.1}$$

in which q is determined via equation B.2.

$$q = \begin{cases} cos(\lambda_1) & \text{for } \lambda_1 = \lambda_2 \\ \frac{(\lambda_2-\lambda_1)}{log\left(\frac{tan(\lambda_2/2+\pi/4)}{tan(\varphi_1/2+\pi/4)}\right)} & \text{for } \lambda_1 \neq \lambda_2 \end{cases} \tag{B.2}$$

All legs longer than 1NM were cut in half by placing an artificial waypoint in the middle of the leg. The coordinates of the artificial waypoint were computed by equations B.3 and B.4, which use the coordinates of the starting point of the leg λ_1 and φ_1, the legs bearing θ, the intended distance of the new point along the tracks course $d_m = d_{leg}/2$ and $d_{rad} = d_m/(R_{\oplus}/1852)$.

$$\lambda_m = asin\left(sin(\lambda_1) \cdot cos(d_{rad}) + cos(\lambda_1) \cdot sin(d_{rad}) \cdot cos\left(\frac{\psi\pi}{180}\right)\right) \tag{B.3}$$

$$\varphi_m = \begin{cases} \varphi_1 & \text{for } cos(\varphi_1) = 0 \\ mod\left(\varphi_1 - asin\left(\frac{sin\left(\frac{\psi\pi}{180}\right) \cdot sin\left(d_{rad}\right)}{cos(\varphi_1)}\right) + \pi, 2\pi\right) - \pi & \text{else} \end{cases} \tag{B.4}$$

The legs heading ψ is computed by equation B.5.

$$\psi = atan2\left(log\left(\frac{tan\left(\varphi_2/2+\frac{\pi}{4}\right)}{tan\left(\varphi_1/2+\frac{\pi}{4}\right)}\right), \lambda_2 - \lambda_1\right) \tag{B.5}$$

The procedure of cutting legs in half, including legs by artificial waypoints, is repeated until no leg is longer than 1 NM. Following, the coordinates of all waypoints are checked wether they lie within the No-Fly-Zone.

B.2.2 Evaluation of Diversion Route Length

The length of the diversion route is computed by equation B.1 and compared to the length of the original route.

B.3 Additional Indicator Results and Discussion

B.3.1 Effectiveness Evaluation

Table B.1 presents detailed information on the results obtained while evaluating the diversion route length.

Table B.1.: Diversion route length evaluation

	S1 FMS	S1 TEOS	S2 FMS	S2 TEOS
Min in NM	12.36	21.00	23.61	27.86
Max in NM	92.83	89.06	88.47	58.52
μ in NM	52.58	54.84	57.38	37.83
σ in NM	56.90	36.66	28.81	13.98

B.3.2 Efficiency Evaluation

Table B.2 presents detailed information on the results obtained while evaluating the execution time.

Table B.2.: Execution time evaluation

	S1 FMS	S1 TEOS	S2 FMS	S2 TEOS
Min in s	261	202	168	183
Max in s	498	386	418	312
μ in s	379.5	298.5	283.75	252.5
σ in s	167.58	83.78	107.09	53.33

Table B.3 presents detailed information on the results obtained while evaluating the Task Load Index (TLX) ratings.

Table B.3.: Task Load Index evaluation

	FMS	TEOS
Min	34.34	15.88
Max	64.99	66.32
μ	51.16	41.10
σ	11.40	18.51

B.3.3 Subjective Usability Evaluation

Table B.4 presents detailed information on the results obtained while evaluating the System Usability Scale (SUS) ratings.

Table B.4.: System Usability Scale evaluation

	FMS	TEOS
Min	42.5	57.5
Max	67.5	95
μ	53.33	77.81
σ	11.47	11.37

B.3.4 Mobile Device Statements Results

This section gives the results of the statements towards the attitude and usage of mobile devices of the trial participants as they are presented in section 4.2.4.2. Figures B.1, B.2 and B.3 compare the answers of participants that succeeded or failed in the trial task using the respective system. Special attention was given to failed task executions, to determine if the participants performance can be correlated to their own assessment of mobile device usage and their confidence in using them.

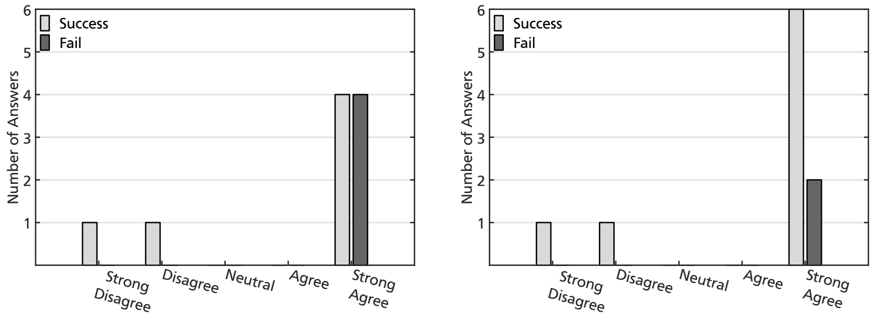
B.3.5 Free Comments and Remarks

This section presents the complete comments and remarks the trial participants provided. Some of the comments were given in german, for which both the original statement and an translation in english is given. Translations are given in an italic font which follows directly to the original statement. The statements are quoted as given by the participants without any editing.

Participant 1

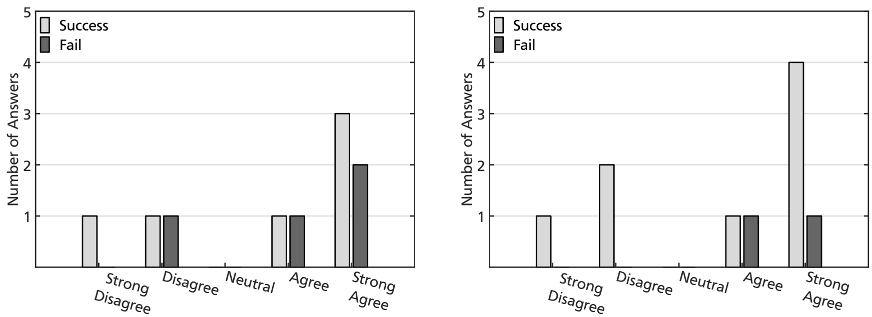
Scenario 1:

- Import von Sigmet von Uplink auf EFB wäre hilfreich.
  Import of SIGMET from Uplink to Electronic Flight Bag (EFB) would be helpful



(a) FMS **(b)** TEOS

Figure B.1.: Results for statement 1: I am using mobile electronic devices in my private life on a daily basis.



(a) FMS **(b)** TEOS

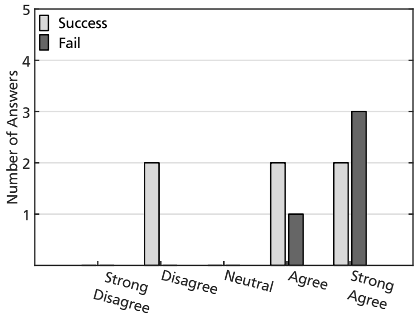
Figure B.2.: Results for statement 2: I am using mobile electronic devices in my professional life on a daily basis.

- Übertragung der Daten fehleranfällig.
  Transmission of data is error-prone

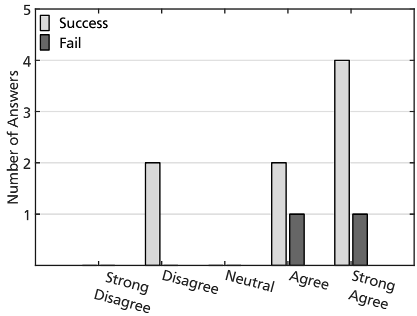
Scenario 2:

- Übertragung der Daten fehleranfällig.
  Transmission of data is error-prone

- Man muss sich das SIGMET im Kopf merken, um Ausweichroute zu wählen.
  You have to remember the SIGMET in order to choose an alternative route



(a) FMS



(b) TEOS

Figure B.3.: Results for statement 3: I feel confident in using mobile devices.

Participant 2

Scenario 1:

Besser:

Geographische Einblendung des Schlechtwetter-Gebiets in der Moving Map des EFB wünschenswert, nicht nur reine Textinformation.
Better: Geographical implementation of the bad-weather-area in the moving map of the EFB is preferable, not only sole text information

Zu Jeppesen:

- Wünschenswert wäre Skalierbarkeit während der Planungsphase - derzeit nicht möglich.
  Scalability during the planning phase is desired, currently not possible
- Umschaltung zwischen Planungsphase und Aktivierungsphase per "Backspace" (Pfeiltaste zurueck) mit Auswahl einer neuen Oberfläche ("Flight"?) nicht intuitiv
  Switch between planning phase and activation phase via backspace while choosing a new surface ("flight"?) is not intuitive
- Rückmeldung, ob neuer Flugplan ans FMS gesendet wurde wünschenswert. Bspw.: **New FPL has been sent to FMS**
  Feedback, whether new flight plan was transmitted to FMS preferable, for example: ***New FPL has been sent to FMS***

Schwierig ist die Überprüfung, ob das FMS die neuen FPL-Daten aus EFB richtig übernommen hat. Bspw wäre schön, wenn man als "weiße Linie" den alten FPL

(quasi in Secondary) angezeigt bekäme und den neuen FPL wie gewohnt als "grüne Linie". Dann wäre die Situational Awareness höher und die Überprüfung leichter.
Check, whether FMS has correctly accepted the new FPL-data from the EFB. For example a "white line" representing the old FPL (as a secondary) combined with the common "green line" for the new FPL. This increases the situational awareness and the verification is easier.

Scenario 2:

- Jepp View hat über das GPS im iPad die aktuelle Flugzeugposition, Mobile FD -> die fehlt, aber nicht weiter schlimm
  Jepp view has the current airplane position using the GPS of the iPad, mobile FD -> still missing, though this is not severe

- Eingabe eines neuen Wegpunkts über FMS anhand PBD oder PBPB oder Koord. umständlich, gleiches gilt für die Überprüfung der neuen Route.
  Insertion of a new waypoint via FMS using PBD, PBPB or coordinates is cumbersome, the same applies to the review of the new route

Participant 3

Scenario 1:

-

Scenario 2:

- FMS should show waypoints in my opinion, to minimize errors.

Participant 4

Scenario 1:

- Feedback nach Senden des FP an das FMS wäre hilfreich
  Feedback after transmission of the FP to the FMS would be helpful

- Koordinaten und/oder Name an Wegpunkten hilft bei der Übersicht
  Coordinates and/or names at the waypoints would help with the overview

Scenario 2:

-

Participant 5

Scenario 1:

-

Scenario 2:

-

Participant 6

Scenario 1:

1. Vorschlag:

    Display und Kartenausschnitt sollten vergleichbar sein, ohne den Maßstab zu ändern

    Suggestion 1: Display and map section should be easy to compare, without changing the scale

2. Vorschlag:

    Die geänderten WPT sollten Dist. + Kurse zeigen, um den Windeffekt beurteilen zu können

    Suggestion 2: Changed WPT is to show distance and course, in order to assess the effect of the wind

3. Vorschlag:

    Spritkalkulation muß Vergleich ermöglichen

    Suggestion 3: calculation of fuel has to enable comparision

4. Vorschlag:

    WPT nicht nur ziehen, sondern auch eingeben LAT/LON

    Suggestion 4: pilot should not only be able to drag the WPT, but also be able to enter WPTs directly via LAT/LON

5. Vorschlag:

    SIGMET automatisch darstellbar

    Suggestion 5: SIGMET should be automatically representable

Scenario 2:

-

Participant 7

Scenario 1:

Scenario was pretty close to real life however SIGMETs can be displaced in NAV chart for a better overview. (hint to use waypoints to show SIGMET area was good but I am pretty sure that pilots would use waypoints/route function to substitute this function)

Keeping the route as filed and cleared has a very high priority (even when the EFB has no influence to aircraft guidance)

Scenario 2:

Information about coordinates for given waypoints essential. I found that creating a waypoint by using my finger on a map (scale?) is too unprecise. It should/must be possible to define a new waypoint by using PBD/coordinates in relation to given waypoints.

Switch from map mode (flight) to flight plan to check revision is not helpful as revision is not underlined/colored/highlighted -> Risk of confusion/wrong revision.

Possible solution:

put the revised flight plan (text) besides the map so revision can be checked via map and text at the same time before it's sent to FMS.

Participant 8

Scenario 1:

- The SIGMET should be graphically visible on the chart
- To verify, the ID should be visible on EFB & FMS
- The modified route needs to be visible after leaving the editing mode
- The insertion status of the route should be graphically visible

Scenario 2:

- I was faster, because I already knew the task
- Realworld scenarios will take longer, than in this experiment, because the SIGMETs are often more complex

Participant 9

Scenario 1:

When using the map, it wasn’t quite easy to find the latitude/longitude right way, only when zooming in.

Otherwise the map strongly supported the mental/situational awareness.

Scenario 2:

The most time was spent localizing the SIGMET, once found, the rerouting was done and executed in an acceptable manner

Participant 10

Scenario 1:

- Connectivity between device and FMS very interesting.
- Input much easier with drag&drop
- Identifying bad weather airspace needed some imagination. Would it be possible to have affected airspace identified and be displaced in the device?

Scenario 2:

- FMS screen with too much information, more training needed. No clear way to solution. "Connectivity" between device and FMS only by brain

C Supplemental Information on Trajectory Optimization Algorithm

C.1 Weather Blending Method

This section describes the method used to blend weather information if the flight time is longer than six hours. The process consists of three general steps and is the same for forecast and observation files:

1. Identify general direction of travel
2. Identify which time cycles need to be blended
3. Identify position of blending
4. Blending

C.1.1 Identify Direction of Travel

Blending is conducted along longitudes or latitudes depending on the general direction of travel between departure and destination airport. Direction of travel is determined following figure C.1, where the direction is defined by the loxodrome connecting departure and destination airport.

If the direction was identified to be north or south, weather files are blended along longitudes where when the direction of travel was identified to be east or west, the weather files are blended along latitudes[1].

[1] Therefore, when traveling in a northern or southern direction, the border of the blended regions is a fixed latitude, where it is a fixed longitude when traveling in an eastern or western direction respectively.

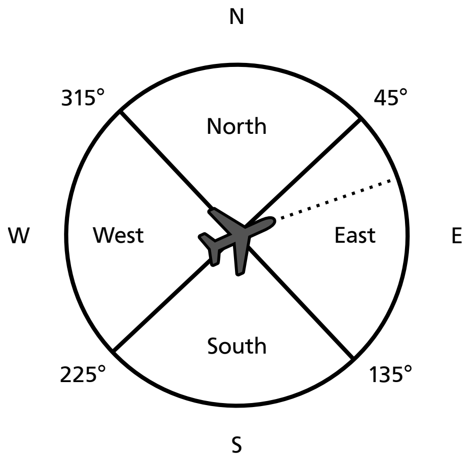


Figure C.1.: Rules to identify direction of travel [illustration by author]

C.1.2 Identify Time Cycles

Depending on the time of departure and the expected time of travel, the weather files needed for blending are identified. Forecasts are published for 00:00 Universal Time Coordinated (UTC), 06:00 UTC, 12:00 UTC and 18:00 UTC each with a validity period of six hours. Therefore, flights with a duration of less than six hours need no blended weather at all, flights with a duration of more than six and less than twelve hours need at least two weather files, flights with a duration of more than twelve hours at least three[2].

C.1.3 Identify Position of Blending

The exact position of the border between the regions that are blended needs to be identified. This border will not be located on top of a waypoint of the route, hence its location needs to be computed from known values. To do so, distances, estimated times and leg headings of the computed flight plan are used, the blending location does not change with simulated dates. Figure C.2 depicts an example situation for a blending at 18:00UTC on the leg between the waypoints WP_{i-1} and WP_i. t_{i-1}, d_{i-1}, t_i and d_i depict the time needed to travel from WP_{i-1} to the point

[2] Flights with a duration of more than eighteen hours are not simulated in the scope of this study.

of blending and the traveled distance, as well as the time and distance from the point of blending to WP_i.

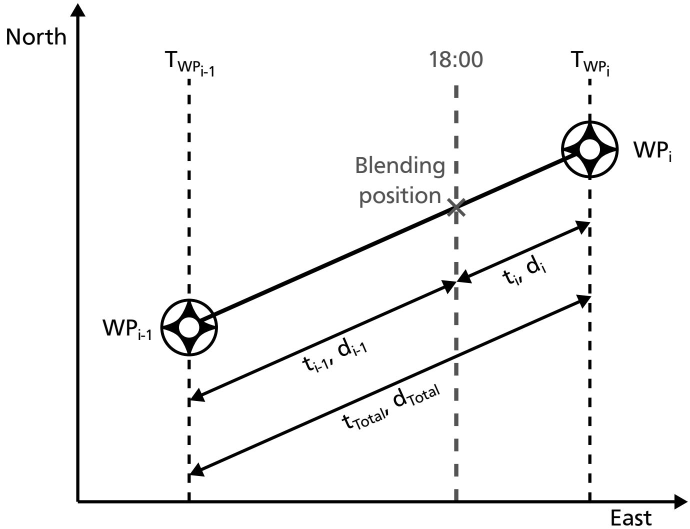


Figure C.2.: Example for the computation of the position of blending [illustration by author]

WP_{i-1} and WP_i were identified by their estimated flyover times from the computed flight time, t_{i-1} is computed by equation C.1

$$t_{i-1} = 18{:}00 - T_{WP_{i-1}} \tag{C.1}$$

in which $T_{WP_{i-1}}$ is the estimated UTC at WP_{i-1}. Equation C.1 leads, under the assumption of a constant speed, to determine d_{i-1} via the linear interpolation of equation C.2.

$$d_{i-1} = \frac{t_{i-1}}{t_{total}} \cdot d_{total} \tag{C.2}$$

Knowing latitude and longitude of $T_{WP_{i-1}}$ and the heading of the leg, the blending position is computed by traveling the distance d_{i-1} along a loxodrome beginning at $T_{WP_{i-1}}$. Since the resolution of the data in Gridded Binary (GRIB) format is 0.5 degrees, the result is rounded to the next latitude or longitude contained in the grid.

C.1.4 Blending

By performing the previous steps all relevant data was obtained to blend the weather files. To obtain a smooth transition and avoid steps in the weather description, the data is blended along a full degree with the schema depicted in figure C.3. On the border, the weather is mixed as the average of the earlier and later data, whereas one grid point next to the border the data is computed by a 25%/75% mixture of the corresponding earlier and later data.

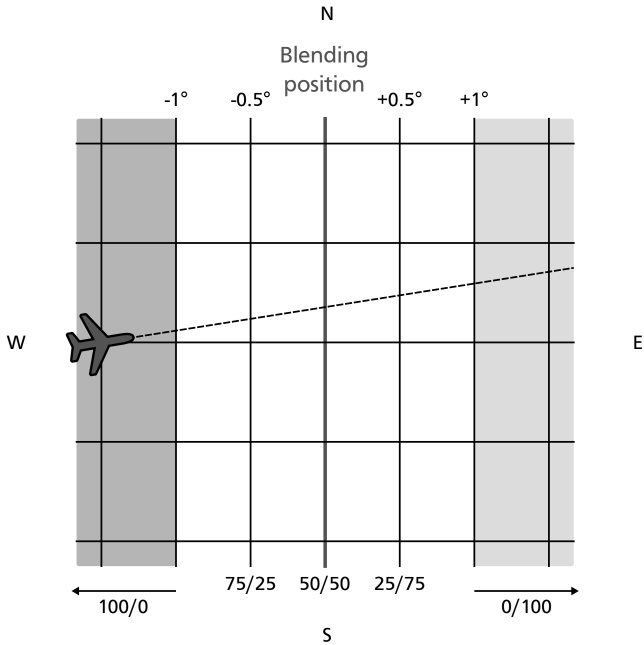


Figure C.3.: Blending along three grid points [illustration by author]

Blending is done for all pressure levels provided by the National Oceanic and Atmospheric Administration (NOAA). If needed, the process is repeated until a set of weather files is obtained suitable to depict the full duration of the flight.

C.2 RTA Computation

Required Time of Arrivals (RTAs) are computed on the basis of aircraft performance taken from the Base of Aircraft Data (BADA) library, the blended weather files as well as the computed flight plan. The waypoints for which RTAs are computed were defined by the user. For the RTA computation, cruise and climb phase of the flight are treated separately. Time constraints are given in seconds, where zero depicts the beginning of the flight.

C.2.1 Cruise

The computation for a time constraint is based on the distance that is covered on the corresponding portion of the route and an estimated Groundspeed (GS). While the distance is given in the computed flight plan, the GS depends on the flown True Airspeed (TAS) and the experienced wind conditions. First, the V_{TAS} at all waypoints contained in the portion of the route is computed. Figure C.4 depicts this situation, where WP_{i-1} and WP_i are two waypoints along the portion of the route, $V_{GS_{i-1}}$ is the estimated GS at the waypoint beginning the portion and d_{total} the distance between the two points.

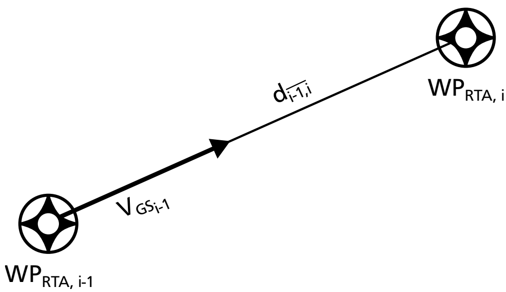


Figure C.4.: Computation of GS at the beginning waypoint of a time constrained portion [illustration by author]

$V_{GS_{i-1}}$ is estimated by computing an average of the winds experienced on a band of altitudes layers at $WP_{RTA,i-1}$[3] and the average TAS from the BADA using equation C.3

$$V_{GS_{i-1}} = V_{TAS} + V_{Wind}, \tag{C.3}$$

[3] The band of altitudes reaches from 10,000m to $h_{MO} - 1000m$, where h_{MO} depict the maximum operating altitude defined by BADA.

in which V_{Wind} is positive for headwind and negative for tailwind[4]. To increase the quality of the estimation of the experienced wind conditions, it is taken into account that the algorithm is more likely to choose altitudes with tailwinds. Therefore, tailwinds are weighted with a factor of 1.3 and tailwinds with 0.8 for the computation of the average experienced wind. It is assumed that the aircraft travels along $d_{\overline{i-1,i}}$ at a GS of GS_{i-1}.

Once all needed GSs are computed, the RTA at the last point can be estimated. As stated above, RTAs are given in seconds since start of the flight, so assuming a previous RTA $t_{RTA,i-1}$ exists the following RTA $t_{RTA,i}$ is computed by equation C.4

$$t_{RTA,i} = t_{RTA,i-1} + \sum_{n=0}^{j} \frac{d_{total}}{V_{GS_{n-1}}} \tag{C.4}$$

in which j depicts the number of legs between $WP_{RTA,i-1}$ and $WP_{RTA,i}$.

C.2.2 Climb

During the climb, only the horizontal component of V_{TAS} is accounted for computing RTAs. Climbing is simulated by taking into account average Rate of Climbs (ROCs) from the BADA library. Using the ROC, the horizontal component of V_{TAS} is computed by equation C.5

$$V_{TAS,horizontal} = \sqrt{V_{TAS}^2 + ROC^2} \tag{C.5}$$

and $V_{TAS,horizontal}$ is used in the same manner to compute the RTA as in the cruise. In addition, no average wind component is assumed, but the actual wind components of the current altitude are used to compute the current GS. The climb phase is considered to end at 10,000m, from which the computation switches to the cruise method.

C.3 Additional Informationon Evaluation Results of Time and Cost Priority Comparison

Figures C.5 to C.7 present the comparison of RTA deviations of cost and time priority trajectories for the respective routes FRA - DUS, HHN - BGY and HHN - LIS.

[4] The magnitude and sign of v_{Wind} is computed from the weather data and the heading of the leg.

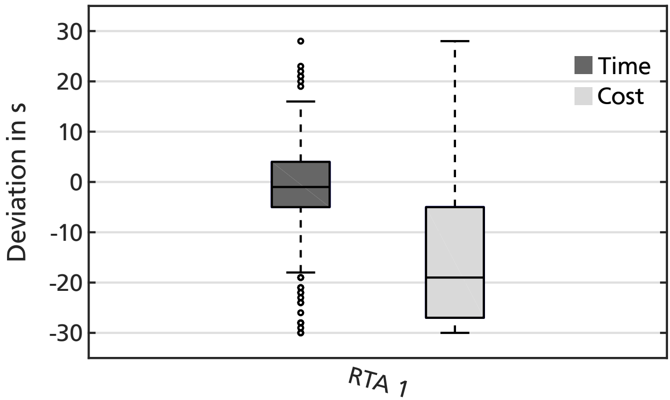


Figure C.5.: Deviation from RTAs compared for cost and time priority one the route FRA - DUS

C.3.0.1 Cost Differences

Table C.1 gives detailed information on the cost savings for all simulated flights and figure C.8 depicts the cost savings for the routes HHN - BGY and HHN - LIS as boxplots.

Table C.1.: Comparison of total cost

Flight	μ_{CP}	σ_{CP}	μ_{TP}	σ_{CP}	Savings
FRA - DUS	7,220	602	7,315	617	1.3%
HHN - BGY	18,063	922	18,292	946	1.25%
HHN - LIS	67,235	3,402	67,519	3,452	0.42%
FRA - NRT	350,915	5,149	351,365	5,167	0.13%

Table C.2 presents the comparison of consumed fuel for all four routes, where a negative saving indicates that the optimizations carried out under time priority consumed less fuel than the ones carried out under cost priority. Figure C.9 depicts the savings in fuel consumption for the flights HHN - BGY and HHN - LIS as boxplots.

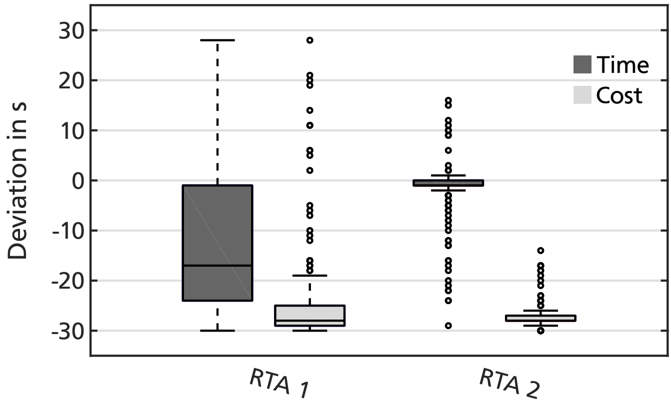


Figure C.6.: Deviation from RTAs compared for cost and time priority one the route HHN - BGY

Table C.2.: Comparison of fuel consumption

Flight	μ_{CP} in kg	σ_{CP} in kg	μ_{TP} in kg	σ_{CP} in kg	Savings
FRA - DUS	1,403	84	1,373	86	-2.16%
HHN - BGY	2,477	141	2,469	143	-0.30%
HHN - LIS	6,094	459	6,066	440	-0.46%
FRA - NRT	77,149	2,193	77,425	2,090	0.36%

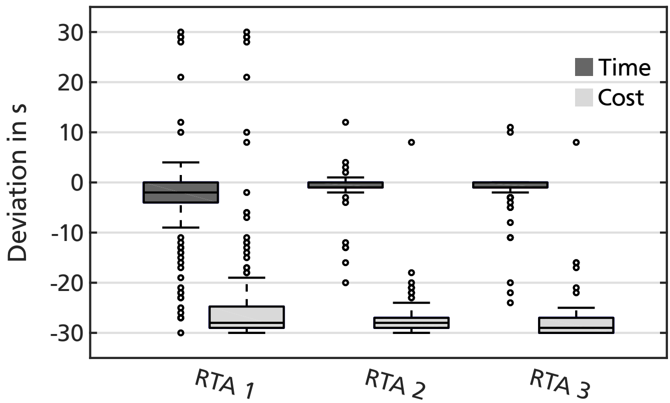
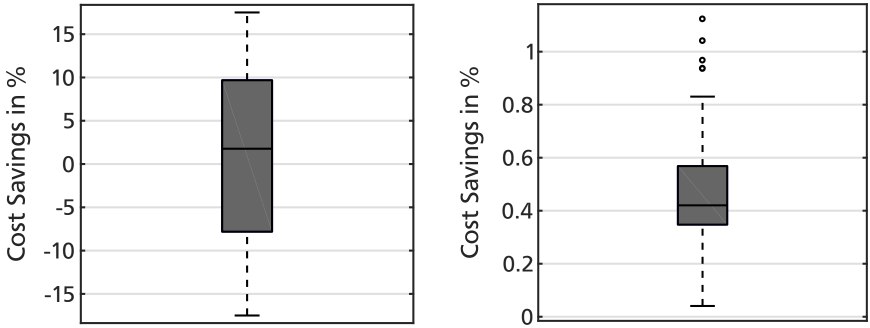


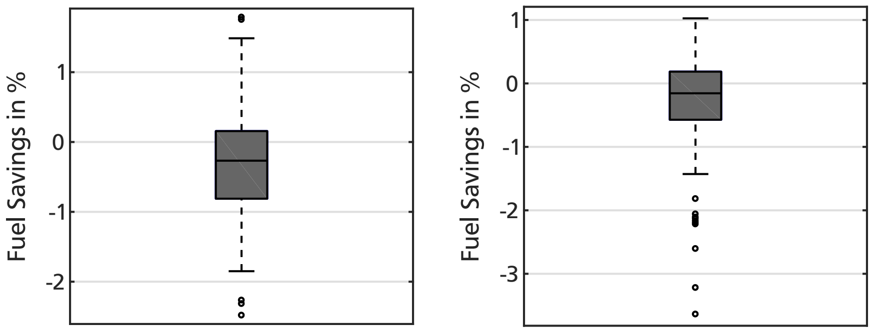
Figure C.7.: Deviation from RTAs compared for cost and time priority one the route HHN - LIS



(a) Flight HHN - BGY

(b) Flight HHN - LIS

Figure C.8.: Cost comparison of cost priority and time priority



(a) Flight HHN - BGY

(b) Flight HHN - LIS

Figure C.9.: Consumed fuel comparison of cost priority and time priority