Tanker allocation optimization during civil air-to-air refuelling operations

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by

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Preface

W.F.J.P. Brugmans
Delft, April 2017

I would like to thank my supervisor Dr. ir. H.G. Visser for the support given to me during this Master thesis. Along the entire duration of the research monitoring me where needed, sometimes gently steering the project and being critical, but always in a supportive and positive way which gave me motivation and confidence.

Furthermore, I would like to thank all the room mates from room 3.15 of the Aerospace faculty building for making this such a memorable time. The many good laughs, nice conversations on various serious or light-hearted topics and the support during this thesis work are things I will not soon forget.

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Abstract

Motivation and problem statement
At present, in-flight refuelling of aircraft is performed in a military operational context. Application of the refuelling concept for commercial aircraft requires detailed study of the concept's benefits and safety. Previous research in this field showed that profits can be obtained in terms of fuel usage and operating cost comparing current direct operations with staged operations of air-to-air refuelling. With the use of new technology conceptual aircraft for both tanker and passenger aircraft roles, concept gains are further increased. However, a detailed study of the concept in a real-life traffic environment is missing. This thesis investigates concept feasibility in terms of fuel and cost for direct implementation in today's traffic with the focus on tanker routing optimization. Geographical focus of this study is traffic over the North Atlantic, where an organized system of cruise tracks is active. From an academic point of view, the complexity of the problem is defined by solving the tanker routing problem for a representative number of commercial aircraft for daily varying flight schedules and conditions.

Research objective and methodology
The research objective it to analyse the potential benefit of a civil in-flight refuelling operational concept implemented in a real-life commercial air-traffic environment, by developing a tanker routing and allocation optimization model that aims to compare results in the form of overall system fuel consumption and tanker costs in reasonable computational time. The proposed methodology aims to identify the concept feasibility of the concept by splitting up the model in three parts. First, flight schedules and scenario conditions have to generated. With various input parameters as number of commercial aircraft, aircraft types and cruise speeds, aircraft inter-arrival times, stage lengths, number and location of tracks, traffic direction and the wind direction and velocity, scenarios can be generated that simulate multiple days of air traffic. Second, the generated scenario is used as input for tanker routing optimization, where optimized tanker cycles are determined to refuel all aircraft in the flight schedule. The goal of this optimization is to provide all cruisers with a refuel while aggregated tanker operating time is minimized. With the application of a refuelling time window and making use of a set-partitioning problem formulation, the vehicle routing problem is solved with an exact solution method. Third, a second optimization phase is designed to minimize the number of tankers needed to operate the set of optimal tanker cycles from the tanker routing optimization. For this second optimization the problem formulation is similar as used previously. The tanker cycles are distributed among tankers, where each tanker can be assigned to one or more cycles. With both optimization phases completed, results for fuel consumption and other operating cost can be computed.

Results
Ultimately, the methodology generates concept cost consisting of two components: fuel cost, which can be split up into tanker and cruiser fuel usage, and tanker depreciation cost resulting from the number of needed tankers. The first result of the model is the generated cruiser flight schedule, including cruiser type, track number, cruise speed, destination and arrival time at the time window boundary. Cruiser fuel consumption and fuel volume needed during refuelling are both derived from this schedule. The second result is a large tanker cycle overview as a result of routing optimization. This overview shows the set of tanker cycles that are generated including cruiser numbers and flight tracks. For tanker scheduling, a similar overview is generated for the allocation of tankers to these cycles. A case study is presented and serves as proof of concept. Results for representative case study are generated in less than ten minutes. Moreover, it is made explicit how the computation time is affected by the number of generated tanker cycles which have to be tested for feasibility by the implementation of constraints.

Conclusions and limitations
The main conclusion of this research is that the in-flight refuelling concept in the existing traffic infrastructure of the North Atlantic with the use of realistic aircraft does not seem to be viable. For most

scenarios no fuel gain can be detected when tanker and cruiser fuel usage is combined and compared to fuel consumption of direct operations. The use of conceptual tankers can lead to concept fuel savings which are annihilated when tanker depreciation cost are accounted for. For the concept to become closer to break-even compared to direct operations, a larger new technology tanker needs to be designed. When the concept loss is reduced, it can become interesting to investigate indirect benefits of the concept as airline fleet flexibility due to the fact that short haul aircraft can be operated on long-haul flight. Furthermore, this concepts works as an enabler for point-to-point networks, which can open up new markets. Furthermore, several limitations are identified. First, the use of a single tanker base leads to cruiser detours to get served by a tanker. Implementation of multiple tanker bases could reduce the detour length compared to direct operations. Second, no uncertainty is incorporated in the model. However, this will only worsen concept results. Third, the exact method that is used can cause computer memory limitations for large problem sizes. Applying other methods as column generation can improve computational performance.

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Symbols and abbreviations

Symbols

μ	ratio between tanker and cruiser ground speeds
ρ	air density $[kg/m^3]$
a	cruiser distance to rendezvous point [NM]
$A_{N+2,C}$	column matrix which includes the set of feasible tanker cycles for set of cruiser and tanker nodes
AR	aspect ratio
b	tanker distance to rendezvous point [NM]
$B_{R,S}$	column matrix including set of feasible tanker schedules for set of optimal tanker cycles
c_t	specific fuel consumption [Lb/(Lbs · h)]
C	set of tanker cycles
C_D	drag coefficient
$C_{D_{0L}}$	parasitic drag coefficient
C_L	lift coefficient
$C_{L_{md}}$	lift coefficient for minimal drag
d	distance between tanker position after refuelling and next cruiser in the tanker cycle [NM]
$d_{separation}$	track separation distance [NM]
d_{tracks}	distance between tanker current track and refuelling track [NM]
D_i	fuel demand of a cruiser i [kg]
D	drag [N]
e	Oswald efficiency factor
E	endurance [min]
$F_{N+2,C}$	column matrix with tanker arrival time at nodes for set of feasible tanker cycles
FL	flight level
I	number of cruisers in a tanker cycle
L	lift [N]
N	set of cruiser nodes
NM	nautical mile (≈1.852 kilometre)
Q_T	tanker fuel capacity
R	set of optimal tanker cycles $\subset C$
R	effective range [NM]
S	set of tanker schedules including one or more optimal tanker cycles
S	surface area $[m^2]$
t_c	tanker operating time of tanker cycle [min]
$t_{intersect}$	time it takes before tanker and cruiser intersect [min]
$t_{tw-entry}$	time it takes for tanker to travel to time window entry boundary [min]

$t_{tw-exit}$	time it takes for tanker to travel to time window exit boundary [min]
$track$	track number
$T_{i,c_{actual}}$	actual starting time of refuelling cruiser i in tanker cycle c [min]
$T_{i,c_{entry}}$	arrival time at time window entry boundary of cruiser i in tanker cycle c [min]
$T_{i,c_{exit}}$	arrival time at time window exit boundary of cruiser i in tanker cycle c [min]
$T_{r_{start}}$	starting time of tanker cycle r [min]
$T_{r_{end}}$	finishing time of tanker cycle r [min]
T_{rf}	refuelling time duration [min]
T_w	time window duration [min]
TAT	tanker turnaround time [min]
$U_{i,c}$	tanker fuel usage during refuelling of cruiser i on cycle c [kg]
$U_{(i-1,i),c}$	tanker fuel usage in between cruiser refuelling on tanker cycle c [kg]
V_{cr_i}	cruiser velocity [m/s]
V_t	tanker velocity [m/s]
V_w	wind speed along track direction [m/s]
W	aircraft weight [N]
Z	set of cruisers

Abbreviations

AAR	air-to-air refuelling
ACARE	Advisory Council for Aeronautics in Europe
ASM	available seat miles
ATC	Air Traffic Control
BADA	Base of Aircraft Data
BPP	Bin Packing Problem
CAT	Clear Air Turbulence
CVRP	Capacitated Vehicle Routing Problem
DOC	direct operating costs
ECMWF	European Centre for Medium-Range Weather Forecasts
FL	flight level
FLOPS	Flight Optimization Program
FRC	fuel ratio criterion
GFS	Global Forecast System
HS	hub-and-spoke
IATA	International Air Transport Association
ISO	intermediate stop operations
LP	linear programming
MDVRP	Multi-Depot Vehicle Routing Problem
MTOW	maximum take-off weight
NAT	North Atlantic Tracks
NAT-OTS	North Atlantic Organised Track System
NPV	net present value
OACC	Oceanic Area Control Center
OAG	Official Airline Guide
OD	origin-destination

OEW	operational empty weight
OTS	Organized Track System
PP	point-to-point
PRE	payload-range efficiency
RECREATE	Research on a Cruiser Enabled Air Transport Environment
Rlat	Reduced Lateral Separation
RMP	Restricted Master Problem
SFC	specific fuel consumption
SP	set-partitioning
SVRP	Stochastic Vehicle Routing Problem
TSP	Travelling Salesman Problem
UTC	Coordinated Universal Time (Temps Universel Coordonné)
US	United States
VF	vehicle flow
VRP	Vehicle Routing Problem
VRPHETW	Vehicle Routing Problem with Heterogeneous Fleet & Time Windows
VRPTW	Vehicle Routing Problem with Time Windows

Contents

1 Introduction

This document is the final report of the Aerospace Engineering Master of Science graduation thesis at Delft University of Technology. The research topic of this thesis is the optimization of tanker allocation for passenger aircraft mid-air refuelling considering both tanker routing and assignment. The goal of this study is to get a better insight in the attainability of the civil in-flight refuelling concept while focussing on tanker routing efficiency. This introductory chapter covers a brief background that forms the context in which this thesis is performed, a short introduction to the research problem is presented as well as an overview of the report structure.

1.1. Background

The global airline industry continues to grow rapidly, as the number of people travelling by plane keeps increasing. A 4.0% annual average growth in the number of passenger trips is predicted over the next 20 years [IATA, 2014]. This means a doubling in the number of passenger journeys world wide by the year 2034, which has direct impact on the number of aircraft movements. Forecasts by Eurocontrol [2015] show that the number of movements per year in Europe will grow at a steady rate of 2.6%, while Boeing predicts an annual growth of 3.6% in the total aircraft fleet for the next 20 years [Boeing, 2014]. Even while new aircraft are built with lighter structures and increasing fuel efficiency, all this growth in movements will have significant impact on the environment in the form of fossil fuel usage and CO2 emissions. Muller et al. [2010] states that the air transportation industry is responsible for approximately 2% of the global CO2 emissions. Besides the emissions of CO2, NOx and noise production are two other detrimental effects.

In response to these findings and due to increasing environmental harm caused by the air transportation industry, it was decided by the European Union to fund the REsearch on a CRuiser Enabled Air Transport Environment (RECREATE) project as it was in line with European objectives to reduce the impact of air travel Zajac [2015]. This RECREATE project contemplates a new way of air travel by introducing a cruiser-feeder concept for civil aircraft operations. The project addressed inefficiencies of current long-haul flights where all the required trip fuel has to be carried at take-off. This leads to the unwanted situation that a large portion of fuel, especially in the first part of flight, is burnt to carry fuel. This increase in fuel weight also impacts the structural weight of the aircraft.

For a period of 36 months two concepts have been under investigation: aerial refuelling of civil aircraft and a large nuclear propelled aircraft in combination with small feeder aircraft. At the end, focus tend more towards the first concept since this proves to be the more realistic concept of the two based on safety aspects and fuel consumption reduction [Zajac, 2015]. The RECREATE project conducted a full mid-air tanking concept analysis. Not only potential fuel gain, but among others, aspects as boom design, concept safety and aircraft design are addressed as well. The concept shows promising fuel savings (10-15%) for investigated flight schedules over the North-Atlantic in combination with a number of possible tanker base locations. Most research relies on more efficient conceptual aircraft designs to increase concept's efficiency. However, the concept is not tested in a real-life traffic environment with a detailed tanker routing optimization.

1.2. Refuelling concept and tanker routing

To investigate this in-flight refuelling concept, tanker aircraft (i.e. feeders) have to be routed along commercial aircraft (i.e. cruisers) to transfer fuel. The goal of this thesis is to get a better understanding of the efficiency of this refuelling concept for direct implementation and the variables that influence concept's efficiency. By simulating this concept in a more lifelike traffic environment it is hoped that factors of influence can be better grasped. Since civil air-to-air refuelling (AAR) is a conceptual form of operations in the airline industry, concept tanker routing problems have not been extensively studied. This research tries to combine these two aspects. From a operational perspective, potential fuel gains must exceed additional cost, for the concept to be viable. This is a fundamental difference compared to existing aerial refuelling for military application. This has as purpose to keep aircraft airborne for patrolling or other tasks and not necessarily because the method is cost-effective.

Not all operational aspects of AAR are taken into account in this research. Concept safety, design of the tanker refuelling boom and detailed description of the refuelling procedure including interception method between cruiser and feeder are outside the scope of this study. From a optimization perspective, routing and scheduling of tankers has to be optimized within a reasonable computational time. Routing and scheduling problems are common in the world of transportation and logistics for a variety of applications. Crew scheduling and fleet planning problems are typical examples within the airline industry. Tanker routing in the airline industry is relatively new since costs are not the main operational driver for aerial refuelling in a military context.

1.3. Report structure

Several studies have already focused their research investigating the impact of aerial refuelling of commercial aircraft. The main focus of Chapter 2 is to get a clear overview of the work done so far in the areas of civil aerial refuelling operations and solution methods for routing optimization. The concept of civil in-flight refuelling is introduced and compared to intermediate stop operations (ISO) which is another form of staged operations. Various aspects of the refuelling concept are highlighted, including potential fuel and cost savings and the design of specific cruisers and tankers to enhance concept benefits. For tanker routing and scheduling optimization, a closer look is taken at various solution methods used to formulate similar problems. In Chapter 3 the North-Atlantic airspace is addressed to get a better insight in the operational limitations that can influence the implementation of the refuelling concept. Traffic demand, separation standards and flight operations are gone over. Chapter 4 formulates the problem statement and objective of this research. The research framework is demarcated including model requirements and research scope. This framework has to be translated into a practical approach which is discussed in detail in Chapter 5. The research methodology is extensively explained in this chapter consisting of a lifelike cruiser schedule and a routing and scheduling solution method for tanker operation. Verification and validation of the model is performed and described in Chapter 6. A case study of the model and results are discussed in Chapter 7. Finally, this research is evaluated in Chapter 8 where research conclusions are presented and recommendations for further research are made.

2

Literature review

This chapter presents the state-of-the-art in the academic literature on civil in-flight refuelling operations and routing optimization techniques. Advantages and disadvantages of used methods, relevant gaps in the body of knowledge and similarities among studies are identified. The purpose of this review is to formulate an apposite research question and a research objective that is embedded in the research framework.

Research fields of both civil aerial refuelling operations and routing optimization methods are investigated. Since in-flight tanking of passenger aircraft is in a conceptual phase at present, the goal of this review is to give a clear overview of the current state-of-art and indicate potential benefits of civil AAR operations. To quantify and grasp this concept's potential, tanking operations have to be optimized. This optimization consists of a routing and allocation model where a set of tanker routes is determined which tanker aircraft can be assigned to. First, various aspects of in-flight tanking that affect possible fuel and cost savings are investigated.

In Sections 2.1 and 2.2 an (historical) overview is presented of the state-of-the-art on civil in-flight refuelling operations and routing optimization techniques respectively. The first section elaborates on the potential fuel and cost savings that can be gained by staging operations. Several aspects are addressed that influence these potential savings, like cruiser and tanker performance or refuelling location. In Section 2.2 route optimization and allocation techniques are discussed. Different solution methods that are developed including their optimization algorithms are contained in this section. Since the amount of optimization research performed in the field of tanker allocation in the airline industry is scarce, other cases like crew scheduling are looked at. Moreover, best practices of other research fields with regard to optimization research are studied as well. To finalize this chapter, the main conclusions are presented in Section 2.3.

2.1. Civil air-to-air refuelling operations

This section hoards studies on aerial refuelling and in a wider perspective on staging operations. In-flight refuelling can be used to carry additional payload over the same distance or to increase the operating range of aircraft. In addition, when payload and range are kept constant, AAR can lead to decreased cruiser fuel and emissions and therefore lower operating costs. The state-of-the-art of commercial aerial refuelling is discussed, including fuel and cost savings, tanker and cruiser design and side-effects of the concept. Next to mid-air tanking, ISO are another method of splitting up flights into multiple legs by physically land the plane. A comparison between both operational concepts is made at the end of this section. The most relevant studies are listed in chronological order in Figure 2.1.

2.1.1. Additional payload or extended range

Even though first experiments with aerial refuelling started in the 1920s, one of the earliest contributions describing the potential cost benefits for commercial aerial refuelling is done 80 years later by Visser [2001]. Mid-air refuelling of aircraft can have two main benefits: payload increase or range extension. Visser [2001] describes both scenarios where due to an in-flight refuel the payload at take-off can be

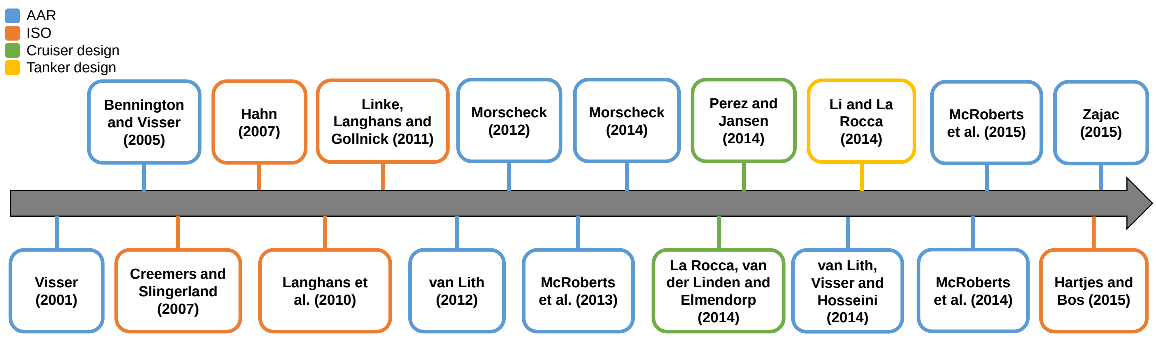


Figure 2.1: Time-line of most relevant literature on staged commercial flight operations

enlarged or the flight range for constant payload is extended. The increment in range is determined by assuming a linear relationship based on cruise speed and average fuel burn during cruise. A more precise method could be made use of that adopts the Breguet equations for the extended mission profile.

For the commercial AAR concept to get off the ground, a financial advantage over traditional operations has to be present. Visser [2001] evaluates profit and payback time for a system where two tankers are active. Considering both extended range and payload, it is concluded that both are incentives for profit generation with payload being the more lucrative option. However, this study fails to make a profit comparison with conventional flights. Furthermore, this study makes use of very simplistic formula's for cost and revenue generation and actual flight schedules for mission aircraft are missing. On the other hand, some general conclusions regarding civil in-flight refuelling can be drawn. The refuel connect-time, which is the time where tanker and cruiser are physically connected, is not a limiting factor during refuelling as large fuel volumes can be transferred in a small amount of time. This means that smaller refuel loads would enable the service of more aircraft from a given tanker, however much more fuel can be moved with larger refuel loads. Furthermore, it can be concluded from Visser [2001] that intangible benefits in terms of airline and aircraft manufacturer cost savings are large and need to be accounted for in addition to obvious economic value.

Following through on this work, Bennington and Visser [2005] focus strictly on optimizing payload increase deriving out of mid-air refuelling. Mission fuel is determined based on preliminary design techniques by Roskam [1986] and Breguet fuel fraction calculations [Ruijgrok, 2009]. For three different aircraft the optimum refuel point resulting in largest payload increment is calculated. An important point to be made for each of these scenarios is that the amount of extra payload carried is not equal to the amount of fuel required to be added during flight. The simplified analysis in the study of Visser [2001] set the refuel load required by the cruiser equal to the increased payload at take-off. With the additional payload however, the portion of take-off weight that does not decrease over time is larger, effecting the fuel consumption during flight. This forms the basis for a refuel load increment that is greater than the payload increment at take-off. For this reason, to maximize economic inducement, the optimal refuelling point is not necessarily at the point that maximizes payload.

For revenue and cost calculations, identical formulas are used as the study by Visser [2001]. For all three mission aircraft a uniform conclusion can be drawn; the optimum profit point does not coincide with the point of maximum payload. As both points are expressed as the moment refuelling needs to take place as a percentage of mission distance flown, the economical optimal point lies "in front" of the point at which the largest payload can be achieved. As the mission aircraft size diminishes, these points almost coincide. The maximum payload increase for the different aircraft types varies between 88-111%. When this additional payload weight is carried in the form of cargo containers, current planes are capable to fit this supplementary volume. Adding this auxiliary weight in the form of low density passenger payload seems not realistic.

Results, show that given a certain tanker fuel capacity, refuelling larger mission aircraft is more economical advantageous. Using existing aircraft for both tanker and passenger roles, all three aircraft types show profitably. Since larger aircraft require more fuel, a larger fuel volume can be transferred in a shorter time period by the same tanker. The reduced flight time of a tanker results in reduced tanker fuel cost. Another aspect of the shorter tanker mission time is the option to fly more missions with the same tanker.

Taking into account that a payload increment at take-off results in increased fuel consumption during flight and accordingly, an enlarged amount of fuel that is transferred, a decreased number of mission aircraft can be served per tanker. Bennington and Visser [2005] assume homogeneous transfer loads for all cruisers and, depending on this offload volume and cruiser type, a constant number of refuels per tanker mission. The inter-arrival times between consecutive cruisers and the availability of a certain type of mission aircraft for refuelling, which are of influence on the tanker operating cost, are not taken into account in this study. Although not examined in this study, a more complex model that incorporates an extended range capability could be interesting.

2.1.2. In-flight refuelling fuel and cost savings potential

The cost and fuel savings that can be achieved when the aircraft mission range is enhanced due to AAR are investigated by McRoberts et al. [2013]. This study is part of a larger research project that investigates different aspects of civil in-flight refuelling. The so-called RECREATE project is set-up by the European Union to show that air-to-air refuelling of commercial flight can lead to both fuel and emission reduction, keeping in mind the airworthiness of the operational concept. An overview of the work performed in this research project is given by Zajac [2015].

McRoberts et al. [2013] use, in contrast to previous studies, a real flight schedule to evaluate the effect of range extension due to in-flight refuelling. Because use is made of fictional aircraft for both cruiser and feeder operations, a numerical analysis is performed to model these aircraft using a software tool named Flight Optimisation System (FLOPS). Both cruiser and tanker designs will be further discussed later in this section. Two redesigned tanker aircraft are used, with a fixed capability of one and three offloads respectively. A day from Star Alliance fleet operations is chosen for evaluation where all direct flights with a range between 3,000-6,000 NM are compared with a cruiser-feeder combination on the same route. To model and compare operational cost, costing methods developed by Roskam [1986], with some alterations for in-flight refuelling related costs, are used. A tanker schedule is assumed with a fixed 20 minute refuel period and ten minutes loiter time in-between refuels. Tanker ranges of 250 NM and 500 NM are evaluated to get insight in the impact of feeder missions on the total efficiency of refuelling operations. For each of these ranges a minimum of tankers for each airport is found. This method does not entail an optimized scheduling of feeder aircraft which will most likely result in increased overall benefits.

Since payload capacity of the redesigned cruiser does not equal the capacity of original aircraft in the schedule, two scenarios are created. One maintaining the number of flights and the other keeping the available seat miles (ASM) constant. To make sure all cruiser aircraft are served, several airport around the world are selected as tanker base location and cruiser flight are redirected where needed.

Appraisal of the results shows that the implementation of in-flight refuelling gives for all cruiser-feeder combinations a reduction in fuel burn and operating costs compared to the baseline system configuration. The use of a 250 NM range feeder gives slightly higher cruiser fuel burn than the 500 NM operating range, due to extended cruiser detours. Furthermore, the single refuel tanker is always more fuel efficient than the one with three offloads. Taking the operational costs in mind, there can be concluded that the feeder aircraft with a 250 NM range outperforms the longer range tanker. This gives a first indication of a major cost driver in achieving maximisation of efficiency within a cruiser-feeder operational concept, which is based on optimisation of tanker operations, rather than those of the cruiser. The lower operating costs can be explained due to replacement of large passenger aircraft by the smaller redesigned cruiser. A single offload tanker with a range of 250 NM produces largest gains with 9% reduction in total fuel burn in the system and a 14% reduction in total operating costs.

In a later paper, McRoberts et al. [2015] add a single-stage cruiser, not suitable for in-flight refuelling, with the same technology level as the mission aircraft used for AAR operations, to evaluate the viability of the refuelling concept in a more precise way. Hence the impact of technology is taken into account. Replacing flights in the original schedule with this new technology aircraft for direct operations reduces the fuel burn with 17.6% alone. While this is not as significant as what can be achieved with the feeder-cruiser cases (30.1% and 29.6% reduction for 250 and 500 NM range, respectively), it displays the impact of technology.

In general these two papers highlight an important issue: the cruiser operating schedule drives the optimal design of the feeder to gain maximum performance of the complete system. In an ideal situation, commercial flight schedules should be matched to an optimized tanker schedule, not the other way around. The question arises about the feasibility of such a system considering the sensitivity of operations to scheduling, and the impact of changes and delays in the schedule on concept efficiency.

While the studies by McRoberts et al. [2014, 2015] investigate the implementation of AAR operations on a global scale, Morscheck [2012] tries to indicate the advantages on a more regional level. Data by Eurocontrol on air traffic crossing the North-Atlantic is used as baseline for the scenario. Just like McRoberts et al. [2014], this study makes use of the same new technology cruisers, with and without refuelling capability. Different in this scenario is the fact that all original flights are being replaced with new cruisers. Therefore the same cruiser can receive multiple refuels to fulfil the mission range. Fuel consumption between traditional and refuelling operations for both types of cruisers are compared. The used method can be split up into two parts: first a cruiser optimization is applied, followed by a feeder allocation.

The cruiser optimization routine is based on fuel burn, therefore fuel calculations form the basis of this optimization. Equivalent to McRoberts et al. [2014], cruiser trajectories are based on Great Circle Routes between origin and destination, including detours made for refuelling. Morscheck [2012] makes use of fuel flow calculations based on the aircraft's X-factor, which is also used in the Breguet equations.

Two cruiser design ranges are chosen of respectively 2,500 and 3,000 NM as replacement for current flights over the North Atlantic. Since the average optimal point for the entire flight schedule is located on the North Atlantic, four tanker bases are selected around this location. In an ideal operating scheme, cruiser aircraft replacing original flights have a design range of half the initial mission length. In this way fuel savings are maximized, since refuelling takes place at the halfway point. However, in realistic operations, the new cruiser will rarely operate at an exact multiple of its design range, resulting in reduced fuel savings across the scenario. Other factors of influence for fuel burn savings, are possible detours and the unavailability of a midway cruiser flight refuel due to schedule interferences.

Morscheck [2014a] uses three cases to test the fuel reductions that can be gained. For the first case, the cruiser takes a direct route towards the destination and a feeder flies as close as possible to the optimal refuelling point. In the second case, the refuelling location is in range of one of the eight feeder bases. For the last case, both cruiser and feeder have matched routes. The feeder service range is varied for all scenarios between 100-1,400 NM, with a refuel capability between 1 to 6 offloads. Among these scenarios, the first scenario gains the largest fuel savings of 23% compared to the reference fuel usage. The usage of realistic feeder bases reduces the benefits with 4%. When comparing fuel savings between the 2,500 and 3,000 NM cruiser range, it can be noticed that the 2,500 NM cruisers slightly outperforms the larger range aircraft.

Examining both cruiser and feeder efficiency, as both are important for fuel savings, larger reductions can be gained by increased feeder efficiency. Even with less efficient cruisers, the system could still result in fuel savings of up to 10%. Studying feeder operating range, there can be concluded that very little difference in fuel savings exists between a 100, 500 and 1,000 NM tanker operating range [Morscheck, 2014a]. On the other hand, the number of refuels per feeder has significant impact on the savings, where the optimum number of refuels depend on the cruiser design range and optimization of feeder routes. Looking into the feeder system as a whole for both scenario one and two, largest fuel savings can be gained with a tanker providing two offloads. However, analysis on the various tanker bases independently shows that this optimal tanker offload capacity can vary. Both general workload on a feeder base and the height of traffic peaks have large influence on tanker efficiency. Therefore, in a multi feeder base system, optimization of tanker capacity and scheduling should be looked at per base individually.

The studies by McRoberts et al. and Morscheck show that both cruiser and tanker operations should be mutually coordinated to gain maximum fuel benefits. Since feeder operations have a larger impact on overall fuel efficiency, ideally cruiser schedules should be fine-tuned on feeder operations. However, as already mentioned by McRoberts et al. [2015] this seems not realistic. Therefore, the study by Lith [2012] investigates the implementation of in-flight refuelling operations for flights over the North Atlantic Track (NAT) system, where cruiser movements are very restricted. By making use of a vehicle routing problem formulation, which will further elaborated upon in Section 2.2, it is tried to optimize the required tanker fleet size with its composition in terms of tanker offload capacity, and the assignment of tankers to cruiser aircraft. Just like other studies, a real-life cruiser schedule is used (2010 Official Airline Guide (OAG)) to determine air traffic between Europe and the United States (US). All flights longer than 4,500 NM are replaced by the a new technology cruiser suitable for AAR operations. This corresponds with 36% of all flights in the schedule. In this way, the number of movements is kept constant while the produced ASM is reduced, which is also done by McRoberts et al. and Morscheck. A westbound wave over the tracks is assumed to last for about five hours with a traffic density of 52 aircraft per hour. With 36% of all flights being replaced, this lead to a total amount of approximately 95 aircraft that need to be refuelled during this period. A single, similar tanker base is chosen as done by Morscheck: Gander International Airport (Newfoundland, Canada).

In comparison to previous studies, Lith [2012] is more detailed in the description of feeder operations. A refuelling rendezvous procedure is selected, based on existing military refuelling procedures. By means of a trade-off, the so-called RV Golf procedure is selected among others. An important advantage of this procedure is that mission aircraft can maintain their predetermined flight path and the feeder is responsible for manoeuvring. This means a minimal increase of workload for the cruiser's pilots. Another benefit of this procedure is that the tanker does not have to be in a holding pattern since the rendezvous point is a predetermined location where both aircraft have to arrive at a given time. This saves fuel and lowers the direct operating costs (DOC). Different to other studies, this study makes use of a time-window in which the passing cruiser must be refuelled. This time window starts above the tanker base and has a duration of ten minutes. Lith [2012] shows that for the scenario with cruiser flying along a track, a larger time-window decreases the tanker flight time.

Furthermore, this study investigates the optimal refuelling point for aircraft flying over the tracks passing a tanker base that lies 270 NM off track. Making use of Breguet equations to calculate fuel usage, it can be concluded that for up to three offloads per tanker, this optimal point is practically above the tanker base. For more offloads per tanker the optimum location shifts more and more towards the original flight track of the cruiser.

Two different tanker aircraft are compared with a capacity to refuel respectively three and six cruisers. For both feeders, refuelling takes place at their own and each others optimal refuelling point. This means in practice that for the smaller tanker an offset of 270 NM is used, which moves the refuelling location over the tanker base. For the larger tanker a reduced offset of 167 NM is applied. The comparison is made based on operating cost, where fuel burn is the main driver. Both tankers are most economical at their own refuelling point, with the smaller tanker operating above the base is most cost efficient overall. In addition, a fixed cost is added to the overall cost function for each tanker that is used. The fixed cost parameter consist of the depreciation value per day for an assumed lifetime of 20 years. For a scenario that consists of 95 cruisers that need to be refuelled, 43 or 30 tanker cycles with the use of respectively a small or large tanker are needed. Comparing total cost of both tankers shows that using a smaller tanker is more cost efficient. A remark that has to be made is that this study determines the amount of tanker cycles and not the amount of tankers that is needed. Since multiple tanker cycles can be performed by the same tanker, it can influence the outcome in terms of cost efficiency.

Interference

As an extension to other work, Morscheck [2014b] adds interferences to their previously used cruiser-feeder scenarios. Since this system with feeder aircraft depending on cruisers is vulnerable for interferences, different types of impedance like delays, missing cruisers and shutting down of tanker bases is evaluated. Assumed that delays are the most frequent occurring form of interference, Morscheck [2014b] addresses a solution to mitigate this type of impedance. For a delayed cruiser known in advance, take-off time of the tanker can be delayed. When a feeder is already airborne, reserve fuel can be used. A delayed cruiser can also have impact on other cruisers, when tankers have to serve multiple cruisers in a single sequence. The other way around, a delayed feeder will always cause a cruiser delay. The cruiser needs to make use of its reserve fuel while waiting to be refuelled. Very high delays on cruiser or on feeder side could result in a situation where the planned feeder can't serve the cruiser. This can be treated similar to a situation with a feeder failure. In this case, another feeder has to take over. As a solution, any feeder base should have a spare feeder that can assist in these situations. It is not addressed in this study how many additional tankers are necessary for a particular disruption. Comparable to delays, the difficulty of this problem lies in the fact how long in advance of cruiser arrival the interference is known. It can also occur that a feeder base is unavailable for one reason or another. The solution that is addressed is the re-routing of all cruisers that are rejected by the unavailability of this base. As in the previous cases, the effects depend on the time left for re-routing. When the unavailability is planned in advance, all flights are re-routed to an alternative base. This will have a small effect on fuel savings, but a large effect on the number of feeders needed at alternative base(s). Especially when one the of the bases with the highest traffic is closed, it can double the amount of required feeders on other bases. When the closing of a base occurs suddenly, which is the least preferred scenario, the cruisers that are not able to reroute over another base, will have to land at an alternative airport. Morscheck [2014b] shows that feeders with large capacity are more affected by interference than smaller capacity feeders. In general, interference with some lead-time can be accommodated with re-routing of flights, while sudden impedance leads to alternative landing for the cruiser. The downside of re-routing is an increased workload on alternative bases. This implies a larger amount of spare feeders per base, which can be costly. To accommodate this situation it could be reasonable to choose a feeder base with lower traffic during the optimization phase, even if the results in fuel saving is slightly worse. The re-routing of cruisers will only work in a multi tanker base system. For a system that includes a single tanker base, in case of interference with limited time to cruiser arrival, cruisers will be obligated to land at the tanker base or alternative airport.

Cruiser design

The various researches mentioned above all use next to conventional cruisers, a non-existing new technology cruiser for comparison with existing aircraft. To increase concept efficiency, this design entails a long-range commercial aircraft for shorter ranges and operate them using staged operations.

Morscheck [2014a] tests cruisers with a design range varying between 1,500 NM and 4,000 NM to fly over the North Atlantic. Cruiser with a design range of 2,500 NM give the highest fuel saving results at their optimal distance and one refuelling operation. Since this study uses tanker bases that are located around this design range, this outcome is not unexpected.

Rocca et al. [2014] focus more on the conceptual design of such a new technology passenger aircraft. An identical design is used as for a conventional aircraft, with cylindrical fuselage and cantilever wing, but with peculiar payload and range requirements. A typical twin aisle medium range aircraft like the A330 is combined with the range of a single aisle short range aircraft like the B737. This results in a relatively large fuselage compared to its wing size. An overview of the top-level design parameters of this cruiser is displayed in Table 7.8.

Table 2.1: Conceptual cruiser design parameters according to Rocca et al. [2014]

Conceptual cruiser design parameters	
Range [NM]	2,500
Capacity [pax]	250
MTOW [kg]	100,865
OEW [kg]	52,589
Wing area [m²]	164
Span [m]	42.4
L/D cruise	16.2

Comparing cruiser performance with an identical conceptual cruiser having an intermediate stop in stead of an in-flight refuel, results show that 7% less mission fuel is required for the AAR cruiser. In contrast to a new-technology cruiser in direct operations, having twice the design range of the AAR cruiser, mission fuel is decreased with 20%. Finally, a comparison in mission fuel is made between the conceptual cruiser and two existing aircraft, one with comparable payload capacity the other with similar range. Table 2.2 shows an overview of the comparison of the conceptual AAR cruiser with these four different cruisers. Two of those are comparable new technology cruisers designed by Rocca et al. [2014], only used in other forms of operations. The other two are existing aircraft that form the basis of the design of the conceptual AAR cruiser. Mission fuel is based on a total flight distance of 5,000 NM and refuelling takes place at the cruiser's optimal refuelling point (i.e. at 2,500 NM). In practice mission fuel gains will be lower, since the ideal situation where the total distance is twice the cruiser design range is in practice a rarity.

Table 2.2: Required mission fuel with respect to conceptual AAR cruiser by Rocca et al. [2014] with a single refuel midway of the total flight distance of 5,000 NM

Aircraft type	Form of operations	Stage length [NM]	Total distance [NM]	Δ fuel compared to AAR cruiser
Conceptual ISO cruiser by Rocca et al. [2014]	ISO	2,500	5,000	7%
Conceptual cruiser for direct operations by Rocca et al. [2014]	Direct	5,000	5,000	20%
B737-800	Direct	5,000	5,000	-14.3%
B767-300	Direct	5,000	5,000	55.3%

The fuel benefit found with respect to the B767-300 is higher than results found by McRoberts et al. [2015] since tanker fuel is not included in this comparison. Due to the smaller aircraft size and weight, the B737-800 needs less fuel to complete the total travel distance. However, payload capacity is reduced with 50% compared to the AAR cruiser.

Tanker design

Next to the use of a high-efficiency cruiser, the design of an appropriate tanker aircraft that is both efficient and has sufficient fuel capacity can contribute to enlarge fuel savings of the in-flight refuelling concept. Rocca et al. [2014] choose to design two families of tankers that have a refuelling capacity of one up to five refuels and differ in operating range. For both families, two conceptual designs are generated consisting of a conventional and a joined-wing design. Tanker performance is compared to existing military tankers and the in-flight refuelling concept is contrasted against ISO and direct operations. Figure 2.2 shows that the joined-wing tanker design is overall slightly more efficient than the conventional design with two refuels per sequence being optimal. Furthermore, the tanker family with a operational range of 250 NM shows better performance compared to the larger operational range. Morscheck [2014a] concludes similar findings, looking at the feeder range limit.

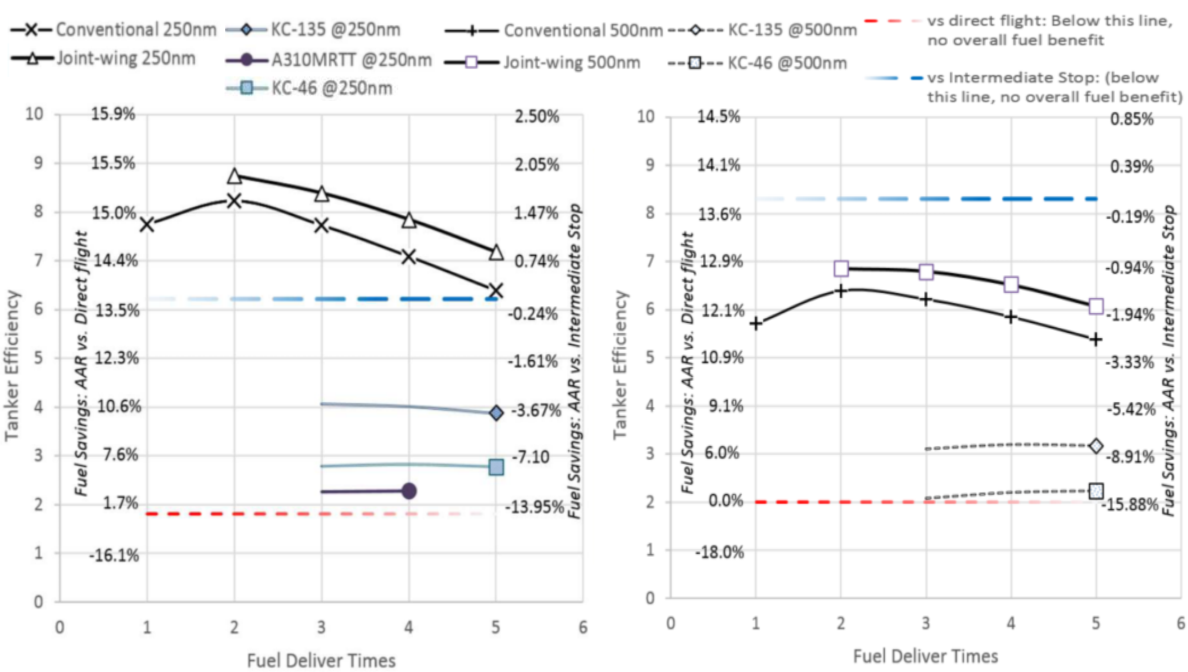


Figure 2.2: Fuel saving comparison of both tanker families with respect to existing military tankers for AAR operations contrasting ISO and direct operation Rocca et al. [2014]

Tanker operating range has only limited effect on both fuel savings of the complete system as well as the number of refuelling operations. However, the number of refuels per feeder has significant impact on the savings, where the optimum number of refuels depend on the cruiser design range and optimization of feeder routes. Looking at the mass of the entire system incorporating both cruisers and feeders, the lowest mass is found to be at a cruiser design range of 2,000 NM with a single offload feeder.

Network layout

As already mentioned by Bennington and Visser [2005], one of the additional benefits of civil AAR operations can be that it acts as an enabler to shift from a current hub-and-spoke (HS) to a point-to-point (PP) network. The use of smaller aircraft results in more flexibility in the operating network. McRoberts et al. [2014] investigates the impact of in-flight refuelling for current network structures and how a PP network affects economic and environmental cost. The viability of a PP network is researched applying two case studies, including an idealised and real-life scenario respectively. For the first case, increased ASM was found for the PP network together with a higher empty seat ratio, resulting in a larger fuel burn compared to a HS structure. In combination with in-flight refuelling the penalty of flying empty seats is somewhat reduced. In the second scenario, based on real airport configurations, again PP network shows a fuel burn increase. However, implementation of AAR operations to both network structures shows comparable operating cost despite the increased fuel usage and empty seats in the PP network. With an increase in ASM of approximately 20% and reduced fuel and cost increment, PP network shows revenue potential on particular routes. It must be noticed that comparing both network types is rather complicated since complex relationships regarding operating cost, passenger demand and revenue potential are experienced depending on the type of network utilised.

2.1.3. In-flight refuelling versus intermediate stop

All studies that investigate the potential fuel savings that can be achieved adopting AAR operations, come to the conclusion that this concept has fuel saving potential. Several other studies have investigated the effects of implementing ISO as a form of staged operations. This section gives an overview of these studies and compares results with in-flight refuelling operations.

Creemers and Slingerland [2007] investigate the effects of intermediate stops on fuel usage, emissions and direct operating costs. This study incorporates a more extensive model, based on Breguet equations, to predict the total block fuel usage, incorporating both taxi and climb fuel. A B747-400 aircraft, designed for long-haul flights, is used as baseline aircraft. The payload-range efficiency (PRE), which relates the fuel weight needed to conduct the mission for a particular payload weight and mission range, is determined. For the Boeing's design range of 7,180 NM, the PRE value is 1,780 NM. The optimal PRE value for this aircraft is found to be 2,105 NM at a range of 2,270 NM. Splitting up long-haul missions with this aircraft into smaller medium-range flights can save up to 15% in fuel when the same aircraft is used. These results are compared with a fictitious redesigned medium-range version of the B747-400, the so-called B747-400MR. Using this modified aircraft for multi-stage operations results in a fuel efficiency improvement of 27% compared to a direct flight with the original aircraft. Due to the fact that less fuel is burned, impact of emissions will also be reduced. Calculations show that emissions are decreased with 13%. Looking at the DOC, also here an improvement of 9% can be achieved.

The study by Hahn [2007] comes up with a different approach where the minimum benefit of staged operations is determined. Hahn chooses a B777-200HG aircraft with a design range of 8,100 NM as starting point for his comparison. Just as Creemers and Slingerland [2007], not only an existing aircraft is selected for this analysis, a redesigned version of this existing aircraft is used to investigate the potential extra fuel saving that can be achieved. For the redesigned aircraft Hahn makes use of the calibrated computer model FLOPS. Likewise, the PRE metric forms the basis for comparison of fuel efficiency. According to Hahn's study, splitting up the 8,100 NM into three stages would give a 17% fuel benefit. A further 12% improvement can be gained using the redesigned aircraft for the 2,700 NM stage length, which results in a total improvement of 29%. Not incorporated is the extra fuel needed for take-off and taxiing during each mission stage. Another missing facet that is left out that causes additional fuel burn, is the aircraft's diversion to make their intermediate stop.

Different to previous studies, where only a single type of aircraft over its design range is investigated, is Langhans et al. [2010] that consider all routes that are flown by A330 and B777 aircraft over the year 2007, making use of the OAG database. Staged operations are matched against direct operation, making use of redesigned aircraft with a design range between 2,000 NM and 6,400 NM. To determine the best suitable intermediate airport, Langhans et al. [2010] introduce two new criteria. One of those is the detour factor, which indicates the extra miles that have to be flown via the refuelling point compared to the direct route. An additional factor is introduced called the offset factor, to indicate the offset of the refuelling point to the total mission's midpoint. To perform the analysis, the fuel ratio criterion (FRC) is chosen as comparison parameter, which is the total fuel consumption during staged operations compared to the fuel consumption of direct flight. It follows that the design range of 3,000 NM for the hypothetical aircraft gives the maximum fuel saving potential over the total route structure. A 10.4% overall fuel reduction can be achieved by having one intermediate stop with this aircraft, resulting in approximately 10 million tons of CO2 deduction. Routes that cannot be served by ISO due to the limited aircraft range or lack of suitable intermediate airports, are operated directly. Looking at the airports that are used for an intermediate stop, a significant amount of the total flights are served by only a few airports. This can have tremendous impact on the capacity of these airports.

In more detail there is elaborated on routes between the East Coast of the US and Europe. For these routes it is critical for range optimized aircraft to have a design range of at least 3,500 NM to serve these routes. When this design range is implemented on the total route structure, fuel savings drop to 9%. This implies that for maximum savings, not a single type of cruisers can be implemented on all routes.

The economical analysis that is performed in this work, uses DOC in combination with Net Present Value (NPV) as metric. It can be concluded that the cost savings of block fuel due to enhanced fuel performance of ISO not always directly lead to economical benefit. Detours can result in longer travel times and lower utilization, which have negative effect on revenues. To obtain a complete view of staged operations potential, both fuel and economical analyses are important.

The study performed by Hartjes and Bos [2015] tries to capture this total potential of the staged concept by taking into account additional costs and benefits. Each long-haul origin-destination (OD) pair in the evaluation is analysed individually to determine the most efficient operation per route. Besides the total fuel costs, a more extensive appraisal is performed on crew costs, fees and maintenance cost. This is all implemented in a software tool that applies a Dijkstra's algorithm to find the most suitable airport to make use of for an intermediate stop. In this way, the focus of this study is more towards the economical effects of stops implementation.

Three types of aircraft are used to investigate the feasibility of stops on current routes. Each of these aircraft differ in range, passenger capacity and technology level. Staged operations are compared to direct flights with the same aircraft. Results show that using a large, older aircraft can lead to a total cost reduction between 5-10% on most routes. The use of a smaller, new technology aircraft gives only a 2-6% reduction in total cost with a single stop operation. The cost per seat, that this study uses as comparison parameter, are the lowest using the smallest and newest aircraft, which is apparent. In general, cost reductions are relatively small and are heavily dependant on intermediate airport location and local fuel prices. Furthermore, some limitations in this study need to be addressed. Effects on demand due to intermediate stops are not incorporated in the model, while this concept will have influence on passenger demand due to the increased travel times. Furthermore, aircraft utilization, which is taken into account by Creemers and Slingerland [2007], is not included in this study.

Linke et al. [2011] proceed with their work and evaluate routes flown by all A333 and B777 variant aircraft over the year 2010. The same routine for analysis is used as its previous work [Langhans et al., 2010]. Results show that with the use of original A333 and B777 aircraft in combination with intermediate stops, only flights longer than 3,600 NM and an offset around 0.5 are beneficial in fuel usage. With these aircraft, a total of 1.26% in fleet-wide fuel savings could by gained. The largest potential shows on longer routes between 6,800 NM and 7,000 NM where an advantage of 7% in fuel savings can be gained. It is assumed that intermediate airports are located at ideal locations. The use of a fictitious redesigned aircraft with reduced range generates much larger savings. For a design range of 3,000 NM, which is found to be optimal, the total fleet-wide fuel reduction is calculated to be 11.3%. This result is very comparable to the result found in their previous study [Langhans et al., 2010]. This reduction can be further split up; where around 60% of the savings can be attributed to stop operations with the redesigned aircraft, approximately 37% is generated due to direct flights with the redesigned aircraft and a small 3% can be saved by flying in stages using the original aircraft. For flights over the North Atlantic, Gander International Airport (Canada) is found to be the airport with the largest fuel savings (1.3% at a design range of 2,800 NM). This study is, just like Langhans et al. [2010], limited by the fact that the influence of stops on the available airport's capacity and infrastructure is not researched.

From these studies on ISO it can be concluded, that just like AAR, results on actual fuel savings are diversified. This is due to the fact that a lot of variables come into play in the effectiveness of operations. Some studies use existing aircraft, others develop new ones tailored for staged operations. The routes and route lengths that are analysed differ per study. Different number of refuels and tanker capacities are being used in case of AAR. These are just examples of choices that have to be made while investigating cost and fuel saving potential of staged operations. However, there are several general disadvantages to intermediate stop operations compared to aerial refuelling. The main downside of ISO is that splitting a journey into legs is always slower than direct flights. Creemers and Slingerland [2007] calculated that one intermediate stop for a direct flight with a block time of 16 hours, the block time would increase to 17.2 hours. This increase of 1.2 hours or 7.5%, is still excluding turnaround time. In an ideal world this could remain constant with the implementation of mid-air refuelling. However, from literature it is made clear that for optimal fuel savings, passenger aircraft have to make a detour in the direction of a tanker base. Therefore, it is very likely that also for in-flight refuelling flight times increase.

Another serious disadvantage of intermediate stops is the increased number of flight legs, which has adverse effect on airport capacity. This also induces a increased probability of schedule disruptions due to weather, congestion or technical issues. On the contrary, AAR operations introduce complexities for the scheduling of tanker and passenger aircraft rendezvous. Besides, tanker bases need to have sufficient capacity to be able to cope with all tanker movements. An advantage of mid-air tanking is that the number of flights to be scheduled by airlines is not increased. However, for both forms of staged operations applies that the use of a new technology mission aircraft with reduced capacity exerts increased pressure on airline scheduling.

Looking at the costs associated with the use of airport facilities, like landing fees, an increase can be presumed for intermediate stops. On the other hand, no tanker aircraft have to be bought and operated as is the case with in-flight refuelling.

Another aspect that is taken into account is the influence on maintenance. Hahn [2007] notes that aircraft operated with intermediate stops would be subject to more load cycles, resulting in a less durable aircraft. This is not the case for aircraft operated with one or more refuels during cruise. However, due to a relative short cycle time, many flight cycles are produced by tanker aircraft, causing additional maintenance as well.

In short, in-flight refuelling operations posses the opportunity to mitigate key disadvantages of intermediate stops; longer total flight times, increased probability of delays, greater complexity and reduced aircraft durability. Additional benefits exist with the use of new technology aircraft of both cruisers and tankers. Another important aspect is the optimization of cruiser and tanker schedules. Solution methods for tanker routing and scheduling will be discussed in more detail in the upcoming section.

2.2. Vehicle routing models and assignment problems

The operational part of the AAR concept, where cruisers have to be refuelled by tanker aircraft, can be viewed as a routing optimization problem, where tankers have to fly over a given route to refuel cruisers at minimum cost. When the most optimal set of tanker sequences is known, an assignment problem arises where tankers have to be allocated to the generated sequences in an optimal way. For both routing optimization and tanker allocation, various problem formulations and solving techniques are compared in this section. Case studies from within the airline industry and other research fields are explored. An overview with the most relevant literature is displayed in Figure 2.3.

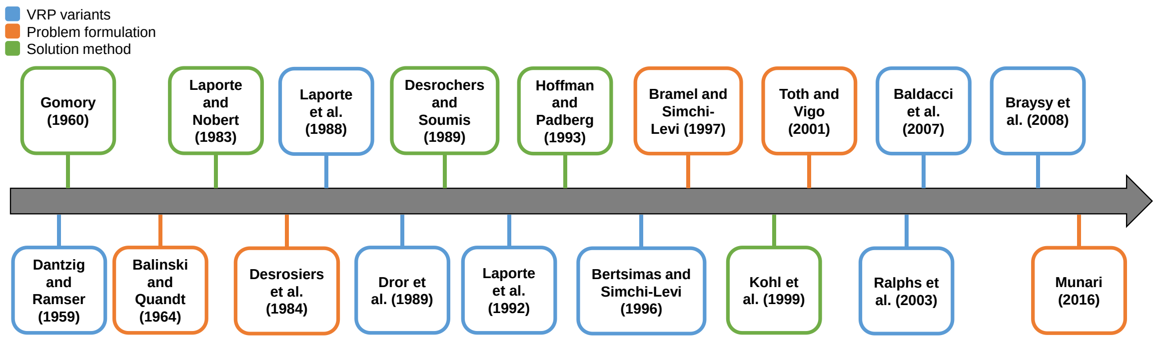


Figure 2.3: Time-line of most relevant literature on vehicle routing problems and optimization solution methods

2.2.1. Classical vehicle routing problem and variations

Routing problems appear in various forms and applications. Examples of these types of problems can often be found in transportation or communication. The classical Vehicle Routing Problem (VRP) was first introduced by Dantzig and Ramser [1959] and is a well known problem in fields of distribution, transportation and logistics. The general VRP formulation optimizes the routing of identical vehicles from a depot to a certain amount of customers. It is considered a combinatorial problem that contains elements from both the Bin Packing Problem (BPP), a packing problem [Eisemann, 1957], and the Traveling Salesman Problem (TSP), a routing problem [Flood, 1956]. The objective for this problem formulation is commonly to minimize the total travel cost of delivery vehicles. Figure 2.4 shows a representation of the general VRP. Later, variations of this classical formulation and combinations of these variants are used. One of the most common forms is the Capacitated Vehicle Routing Problem (CVRP) [Ralphs et al., 2003], where uniform vehicles serve customers with varying demand for a single commodity. This is the case when the AAR problem has to be solved for different cruiser types with varying OD-pairs.

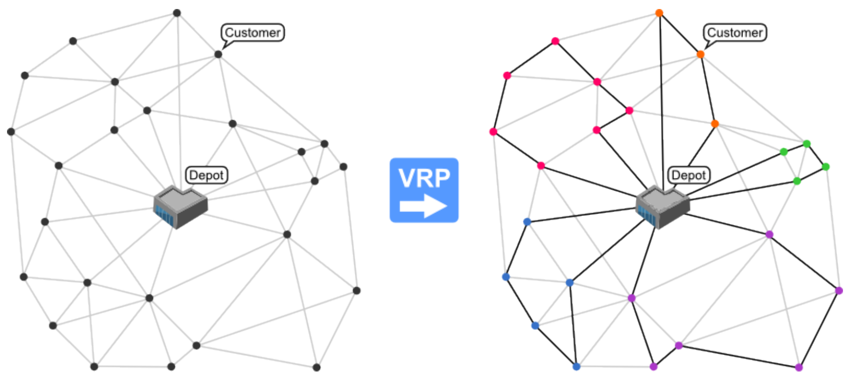


Figure 2.4: Illustrative example of a vehicle routing problem in which the objective is to minimize the sum of the costs associated to each cycle [NEO, 2016]

When tankers can provide cruisers from multiple tanker bases, a Multi-Depot Vehicle Routing Problem (MDVRP) is created, which introduces multiple depots from where customers have to be served. Each base has its own fleet of vehicles that serve a sequence of customers [Laporte et al., 1988]. The study by Morscheck [2012], discussed in the previous section, uses multiple bases for refuelling flights over the North Atlantic.

The study by Braysy et al. [2008] combines two different variants of the classical VRP, using a heterogeneous fleet in combination with time windows (VRPHETW). Lith [2012] uses this particular variant to model the tanker routing problem of the AAR concept. In Section 2.2.2 the solution method of this study is discussed in more detail.

More variations and combinations of classical VRP variants exist, but are not seen as relevant for the tanker routing problem of the AAR concept. All VRPs and variants can be further differentiated into static or dynamic problems and deterministic or stochastic problems [Pillac et al., 2011]. For static deterministic problems all input variables are known in advance and chosen vehicle routes will not change during their execution [Baldacci et al., 2007]. For the AAR concept this is the case for most studies discussed in previous section which make use of a fixed cruiser flight schedule and very basic tanker routing.

Other VRPs have a static and stochastic nature [Bertsimas and Simchi-Levi, 1996]. Stochastic VRPs (SVRP) are VRPs where one or multiple input parameters of the problem are random. Three different kinds of SVRPs can be distinguished:

- Stochastic customers: each customer is present with a given probability [Bertsimas, 1988].
- Stochastic demands: the demand of each customer is determined according to a certain probability [Dror et al., 1989].
- Stochastic times: when service or travel times are modelled by random variables [Laporte et al., 1992].

This will result in a more realistic model of aerial refuelling since the number and type of customers, demand and service times will not be fixed and change on a daily basis. For dynamic and deterministic VRPs, some or all input parameters are unknown. During the design or execution of the routes these values will be revealed in dynamical fashion. Constant communication is required between customer and supplier to provide status updates. Lastly, dynamic and stochastic problems behave similar to dynamic and deterministic problems but in contrast to these problems stochastic knowledge is available in the dynamically revealed information. Looking at the refuelling concept, dynamic problems are most lifelike. However, computational times increase due to the fact that solution route choices have to be reassessed over time. Another point to highlight is the question to what extend it is needed to use a dynamic problem formulation to get accurate insight on the AAR concept's viability.

2.2.2. Exact solution methods

Now that the routing problem and its variants are familiar, solution methods are addressed to solve a VRP. These solution methods can be split up in exact methods and so-called heuristics. Heuristic solution methods do not necessarily generate the optimal problem solution, but try to find solutions close to the optimal one in a reasonable amount of time. Since problem sizes grow very rapidly, this can be a good trade-off to prevent having a too large computational time. First exact solution methods will be discussed followed by heuristics.

Vehicle flow formulation

VRPs can be modelled using different types of problem formulations. The most intuitive of these methods is the vehicle flow (VF) representation. This formulation makes use of network nodes and arcs for problem representation. Nodes represent the depot and customers, where both the first and final node are used to represent the depot in a CVRP. Nodes are connected with the use of arcs which all have a cost assigned [Munari, 2016]. With the use of valid inequalities and constraints the solution space is constricted. Even with the use of very elaborate inequalities, VF formulations may be still very challenging for current optimization solvers due to the weak linear relaxation of this formulation.

The study by Lith et al. [2014] uses a VF formulation to solve the VRPHETW problem. This research focusses on solving the tanker routing problem for commercial in-flight refuelling using a mixed fleet of tankers departing from a single tanker base. Furthermore, a time window is associated with each customer (i.e. cruiser) , defining a time interval wherein the cruiser has to be supplied. Another time limit is applied to tanker endurance, which is set to a fixed value. The objective in the research by Lith et al. [2014] is to minimize the vehicle fleet costs and the sum of tanker travel time to supply all cruisers in their associated time interval. Lith et al. [2014] tries to solve a problem set of 95 cruiser passing over the tanker base with homogeneous speed on a single track and altitude with a VRP formulation method. Unfortunately, the increasing number of passing cruisers significantly increased the problem complexity and computational time. This resulted in the unsatisfying outcome of not solving the problem for the targeted number of cruisers. To resolve the problem for larger cruiser numbers and increasing scenario complexity, an alternative approach has to be found. The focus lies on studies trying to solve a VRPTW since the tanker routing problem of the AAR concept exists of customers with limited service time.

Set partitioning formulation
The set partitioning (SP) formulation is somewhat different compared to the VF formulation. The SP formulation generates sets of feasible routes which include one or more customers. The objective is to find the collections of sequence with minimum cost while satisfying all constraints. Bramel and Simchi-Levi [1997] show that the SP formulation for the VRPTW has a tighter linear programming (LP) relaxation than the VF formulation. By LP relaxation, the constraint that each variable must be binary is replaced by a weaker constraint that allows variables to be continuous on the interval between zero and one. A tighter relaxation means that the relative gap between the fractional linear programming solution and the global integer solution is closer. On the other hand, Toth and Vigo [2001] indicate that a drawback of the SP model can be the number of variables for loosely constrained problems. However, when constraints are tight and the option of feasible routes is limited due to time windows or complicated route restrictions, it can be a successful formulation. Therefore it could be that defining the AAR tanker routing problem with a SP formulation will obtain better results than the results of Lith et al. [2014].

Since this SP formulation can be a suitable alternative for the VF formulation, this formulation will be discussed in more detail by taking closer look at its mathematical formulation. Let R be the set of feasible routes that comply with all problem requirements based on the type of VRP. The decision variable λ_r is binary which entail that it is equal to 1 if and only if a route $r \in R$ is selected and zero otherwise. Munari [2016] shows that the SP formulation looks as follows:

$$\min \sum_{r \in R} c_r \lambda_r \tag{2.1}$$

$$\text{s.t.} \sum_{r \in R} a_{ri} \lambda_r = 1, \qquad i \in C, \tag{2.2}$$

$$\sum_{r \in R} \lambda_r \leq K, \tag{2.3}$$

$$\lambda_r \in \{0, 1\}, \qquad r \in R \tag{2.4}$$

The objective function of Equation 2.1 minimizes the total cost of the selected feasible routes. Equation 2.2 restraints the problem for having exactly one visit to each customer. The fleet of K delivery vehicles restricts the number of sequences that can be selected as is presented in Equation 2.3. When multiple sequences can be assigned to a similar delivery vehicle, or the fleet of delivery vehicles is sufficiently large, this constraint can be neglected. As already mentioned, the decision variable λ_r is binary which is displayed in Equation 2.4. The cost of the feasible route $r \in R$, expressed by c_r, is computed given that a route r sequentially visits nodes $i_0, i_1, \ldots, i_p$ with $p > 0$ and results in Equation 2.5

$$c_r = \sum_{j=0}^{p-1} c_{i_j i_{j+1}} \tag{2.5}$$

Balinski and Quandt [1964] use the SP formulation as one of the first for a basic truck delivery problem testing a cutting plane algorithm to find the integer solution to its linear programming problem. Novoa et al. [2006] use a SP formulation for a SVRP with stochastic demands, but can also be used for other stochastic variables. For this stochastic problem a recourse strategy is included to serve missed customers.

Desrosiers et al. [1984] use an exact algorithm for a routing problem with time-window constraints and without capacity constraints with a SP problem formulation. Agarwal et al. [1989] compare their exact method with the method of Desrosiers et al. [1984] making use of a SP formulation for the CVRP. This study tend towards heuristics to solve VRP problems due to rapid increase of the feasible column matrix even for problems with limited number of customers. This is the reason that studies using exact methods are scarce. Popular heuristic solution methods in combination with a SP formulation are discussed in the next section.

2.2.3. Heuristics

Whereas formulating the routing problem as a SP problem seems a promising method for problem solving, an exact solution method will not always be effective. To be able to come up with a solution to large problem sizes, heuristic solution methods in combination with a SP formulation have been developed over-time. These two-phased methods are now discussed.

A well-proven method for both exact as heuristic solution approach is Column Generation which is based on the fact that many linear programs are too large to consider all variables explicitly. By linear relaxation of the extensive formulation, a subset of variables is taken into account in the Restricted Master Problem (RMP). First this RMP is solved. From the obtained solution, dual prices for each of the constraints are identified. This information is utilized in the objective function of the sub-problem. Then the sub-problem is solved. If the objective value of the sub-problem is beneficial for the main objective function, the responsible variable is added to the RMP and the RMP is re-solved. This process continuous until the solution of the sub-problem does not further reduce cost.

Desrochers and Soumis [1989] use column generation for solving a urban transit crew scheduling problem. The column generation approach decomposes the problem into two parts consisting of a master problem with a SP formulation and a sub-problem that consists of a shortest path problem. With the applied column generation, Desrochers and Soumis [1989] were able to solve some problems including 100 customers optimally.

Foster and Ryan [1976] use a zero-one integer program heuristic algorithm to solve the problem with SP formulation. An integer problem formulation of the VRP is discussed in combination with standard LP relaxation techniques as branch and bound [Laporte and Nobert, 1983] and cutting planes Gomory [1960].

Hoffman and Padberg [1993] use a branch-and-cut algorithm to solve an airline crew scheduling problem. This problem makes use of both branch-and-bound and cutting planes to solve a problem consisting of 145 customers (i.e. flight legs). This extensive branch-and-cut approach is faster compared to a branch-and-bound algorithm.

Kohl et al. [1999] developed a more efficient optimization algorithm by introducing a new valid inequality within a branch-and-cut algorithm, called k-path cuts, which solves 70 of the 87 Solomon benchmark problems to optimality. However, due to the exponential size of the solution space, it is unlikely that these optimization procedures can be used for larger-scale problems.

Another solution method for the VRP is by applying a generic tabu search heuristic [Kelly and Xu, 1999]. Just like column generation, this method consists of two phases: a generation and an integration phase. For the second phase a SP formulation is used. The generation of the column matrix is generated using a mixture of two neighbourhood moves: the ejection chain move and swap move which provide local search. The problem relaxation is provided with the use of a penalty term which is determined by a dynamic search algorithm. This solution methods shows a good performance (i.e. within 5% of optimum) with limited computational time.

2.3. Conclusion

In Section 2.1, studies in the field of civil aerial refuelling have been discussed extensively. The overall performance of the concept has been looked at and factors of influence are addressed. Many variables play a role in the performance of the AAR concept. Largest fuel savings can be gained by replacing current available tankers and cruisers by more efficient designs. However, the question arises to what extent it is realistic to use conceptual aircraft designs to test this concept in a real-life traffic environment. Compared to ISO, in-flight refuelling has many advantages and has proved to be more fuel efficient. Most studies assume an uniform set of tankers with limited operating range and a fixed number of refuels to compare system performance. What is missing in literature, is a detailed research on the performance of this concept in a lifelike traffic environment with the focus on tanker scheduling optimization. Just a single study addresses this tanker optimization, but fails to implement realistic traffic characteristics. No research has been done on the effects of variable tanker offloads for heterogeneous cruisers. Moreover, the track system that is applied over the North Atlantic is not captured to its full extent in previous research investigating trans-Atlantic flight. A further elaboration on the track system over the North Atlantic is discussed in the next chapter.

Since the aerial refuelling problem is restricted by time windows, it is found in literature that a SP formulation of the routing problem can provide better results than found with a VF representation [Lith, 2012]. Furthermore, exact solution methods as well as heuristics were discussed. Based on this discussion, the consideration has to be made for a static or dynamic and deterministic or stochastic model. Dynamic and stochastic models can better represent real-life operations. However, with static and deterministic models the upper limit of concept performance can be investigated. When with the use of such a model, the concept proves to be feasible more realistic model variants can be tried in a later stage. Furthermore, an exact solution method for problem solving is chosen since the number of cruisers that can be included in a tanker cycle is limited by the tanker size. Besides, application of time windows and the use of an efficient algorithm can help to mitigate the number of columns of the solution matrix.

3 North Atlantic airspace

As this and most other research on civil aerial refuelling operations focus on flights crossing the North Atlantic, more insight in this oceanic airspace is essential. In this chapter a more detailed description of the North Atlantic airspace and its track system is presented. Overall structure, communication limitations and separation rules are discussed.

3.1. Overall structure

The oceanic airspace above the North Atlantic has the highest traffic density in the world and is mainly used by flights between North America and Europe [Ruis, 2011]. On a daily basis, around 1400 flights traverse in both directions making use of this oceanic airspace [Flightradar24, 2016]. Half of this total amount uses the so called Organised Track System (OTS). Since radio communication between pilot and Air Traffic Control (ATC) is limited and radar surveillance is not applicable in this airspace, this organized track system is established to have conflict-free air traffic. It consists of an arranged system of flight tracks that run parallel in similar direction on various flight levels. Each day, the OTS is created for both westbound and eastbound directed traffic. This tidal air-traffic flow behaves according a daily repeating pattern that follows the difference in local time on both sides of the ocean. The OTS in westbound direction is predominantly active during daylight hours and valid between 11.30 a.m. and 7.00 p.m. Coordinated Universal Time (UTC). Eastbound flow takes place overnight and tracks are active between 1.00 a.m. and 8.00 a.m. UTC. The reason for existence of these traffic flows is a combination of the difference in local times on opposite sides of the ocean together with the transit times of flight at current speeds. Aircraft airspeed on the OTS vary between 0.80-0.87 Mach depending on aircraft type and assigned flight level and cruise speed.

The OTS consists of four to eight parallel tracks to accommodate all flights. There are ten flight levels available between FL310 up to FL400 with alternating traffic direction [ICAO, 2015a]. Even flight levels (between FL320-FL400) are designated to traffic in westbound direction, odd levels (between FL310-FL390) are used by traffic in the opposite way. Lower and higher flight levels can be used throughout the whole day, maintaining alternating traffic between consecutive levels.

The track layout for the upcoming day is determined on a daily basis. The Oceanic Area Control Center (OACC) is responsible for setting up these tracks. When designing the track layout for the following day, the OACC takes into account airline's track preference, expected opposite traffic, weather forecasts (jet stream) and airspace restrictions. For tracks in westbound direction, the track entry points are located 0-15°W and 45-60°N. Track exit point lie between 50-60°W and 45-60°N. Tracks in westbound direction are typically located further north than the eastbound tracks, which are situated such that maximum advantage can be taken of the more southerly located jet stream. This jet stream consists of prevailing winds from west to east that can reach wind speeds of 100 to 400 km/h. It is located between 30° and 60° latitude at altitudes from 7 to 12 km (FL230-FL400). Figure 3.1 gives an overview of the typical location of the jet stream.

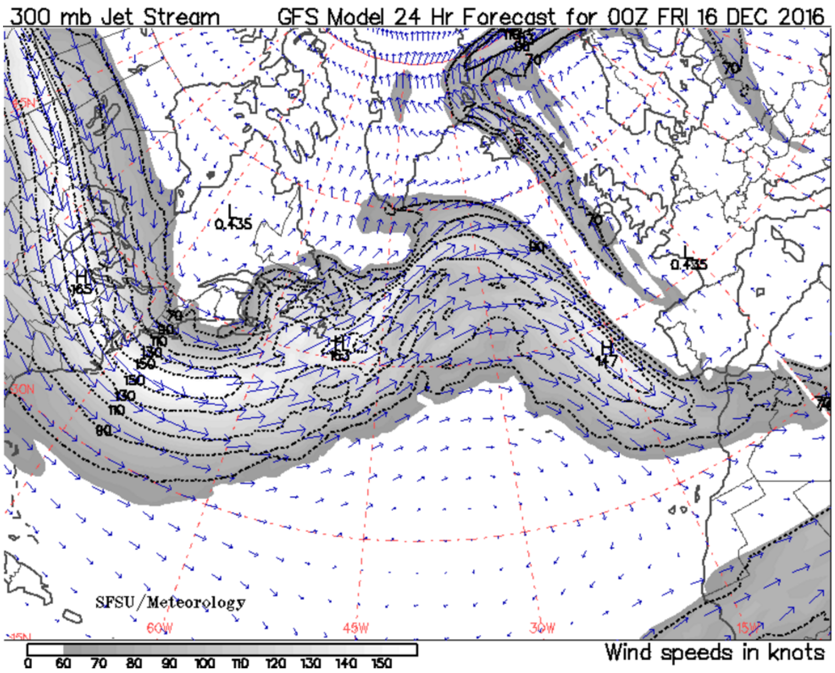


Figure 3.1: Example of jet stream over the North Atlantic on December 16th 2016 [Turbulence-forecast, 2016]

In between track entry and exit point, aircraft fly over way-points where pilots make a position report. These way-points are located at the crossings of each ten degrees longitude with specified whole degrees latitude. A typical OTS track consists of five segments in between reporting points, which have a length around 350 NM (650 km) depending on track latitude. As can be seen in Figure 3.2, track layout in both directions is depicted including intermediate way-points. Most previous studies use Gander International as tanker base for their aerial refuelling assessments. The figure shows tanker operating ranges with 250 NM and 500 NM radius from Gander. It can be concluded that for a larger radius more tracks can be covered.

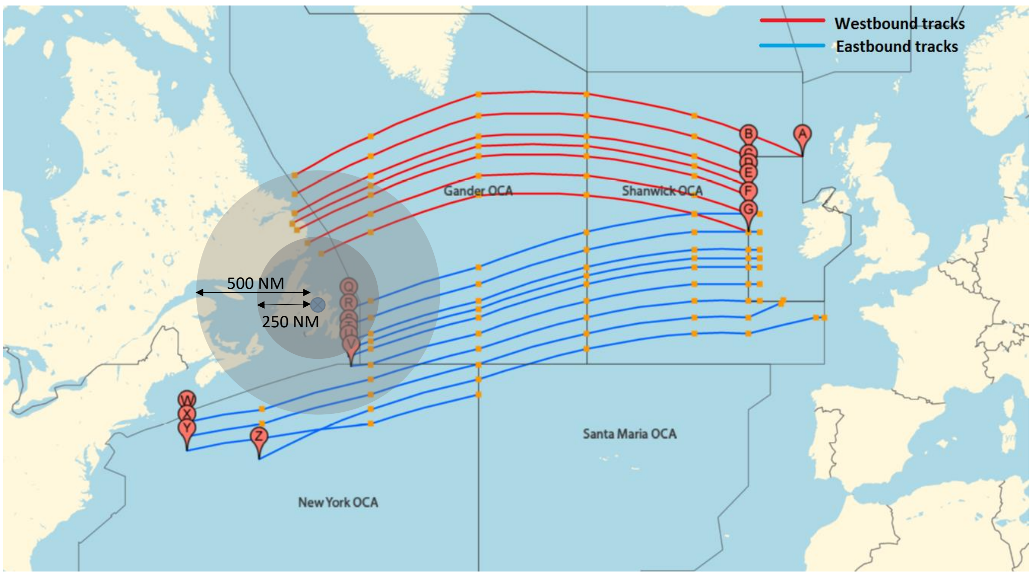


Figure 3.2: An overview of the active tracks in both directions including way-points on December 13th 2016 [Norwegian, 2016]

3.2. Traffic density

Looking at traffic density, on May 6th 2016 a total of 2,464 aircraft crossed the Atlantic, from which 1,414 flights were long or medium haul passenger aircraft [Flightradar24, 2016]. Approximately half of the all traffic crossing the Atlantic makes use of the OTS [Ruis, 2011]. This means that on a daily basis around 700 aircraft travel in either direction over the tracks. Not all traffic is evenly distributed over the available tracks. Before entering the OTS, airlines report track preference including flight level and cruise speed depending on destination and aircraft performance. If there is no conflict with other aircraft, an aircraft can be cleared according to its initial request. Otherwise, the aircraft's requested flight level, Mach number, OTS track, arrival time at the oceanic boundary or a combination of the previous mentioned elements is changed by the air traffic controller such that the aircraft can be cleared. Depending on the time of day, aircraft arrive at the OTS boundary, likeliness of conflicting request changes. Taking westbound traffic as an example, requests for clearance around noon are more popular than arriving late in the afternoon. A similar trend can be distinguished for track preference, where the tracks situated most North are less popular than other tracks. In practice, around 90% of all requests receive clearance for the preferred track. Chances to get approval for the desired Mach number or flight level are lower, around 66%. Deviation from the original flight plan is in general not more than 0.01 Mach or 10 FL's [Ruis, 2011]. Figure 3.3 gives an overview of track usage for traffic in westbound direction. The number of aircraft per tracks differs considerably, with the two central tracks being most popular.

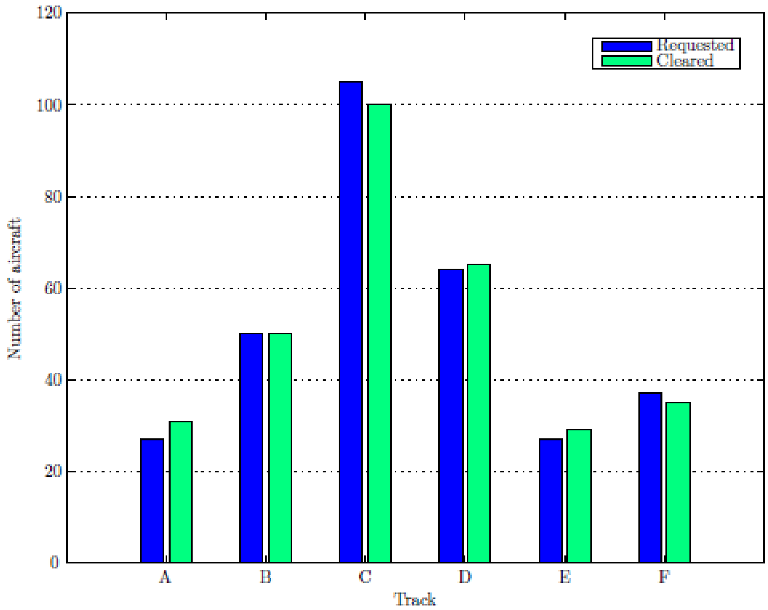


Figure 3.3: An overview of track usage in westbound direction on June 4th 2010 [Ruis, 2011]

3.3. Separation standards

The high traffic density on the OTS requires that separation between aircraft is always ensured. Communication is limited over this vast oceanic airspace and therefore separation standards are larger than for air spaces with better surveillance. Aircraft travelling on the track system must always comply with lateral, longitudinal and vertical separation requirements between aircraft. Minimum lateral separation is ensured with a 60 NM distance between neighbouring tracks. Aircraft on the same track are separated vertically by 1,000 ft and longitudinally by using the so-called Mach Number Technique [ICAO, 2015b]. In contrasts to the two previous separations standards, this separation is based on a minimum time interval between aircraft by maintaining the cleared true Mach number entering the OTS tracks. Differences in airspeed are taken into account at track entry to ensure longitudinal separation over the complete duration of the track. Time in between two consecutive aircraft should be minimal five minutes on every instance of the track. In practice, this means that consecutive aircraft with similar Mach number have a constant ten minute separation. To compensate for difference in airspeed by preceding and following aircraft, a chart is created to determine the required separation time at track entry. With a slower trailing aircraft, separation time can be the minimum five minutes as for a faster trailing aircraft separation at track entry can get up to 31 minutes. Longitudinal separation in eastbound direction is somewhat different due to a higher ground speed as result of the jet stream. This means that for sequential aircraft with dissimilar Mach number the additional separation time can be slightly lower.

3.3.1. Step climbs on tracks

During cruise, aircraft burn fuel which impacts the aircraft's weight over a longer period of time. This influences the optimal cruise altitude for an aircraft, which increases for decreasing weight. An optimal cruise with minimal fuel burn would mean a continuous climb during cruise. This significantly increases the workload for ATC above the North Atlantic, due to increased risk for aircraft interference. To prevent this, aircraft must maintain a fixed altitude and speed over the tracks. By implementing a series of step climbs, aircraft can approximate the optimal cruise climb. Since it takes a while before aircraft weight has decreased such that the optimal altitude has increased to the next available flight level, on short stage lengths often no step climb is made. When a pilot requests a higher flight level on the OTS, clearance is only given when safe separation on a higher flight level can be guaranteed. During peak hours, it is not uncommon that a flight is denied to make a step climb between two flight levels. In practice, most flights have the possibility to make a single step climb on the OTS [ICAO, 2015a]. Some airlines plan their flights over the North Atlantic with this in mind. At the track entry point a optimal flight level for current weight is requested and a step climb is planned later on the track. Other airlines make the assumption that the step climb is not possible and use a compromise level for their flight plan, which is in between optimal altitudes.

3.3.2. Refuelling operations on tracks

In the adopted scenario by Lith [2012], AAR operations are assumed to be executed on a separate track with 15 NM offset to the right of the original track. This distance guarantees adequate lateral separation and is also used during emergency procedures [ICAO, 2015b]. The cruiser descends on this separate track to a lower altitude where refuelling takes place. The refuelling altitude can be the same as used by Lith [2012], which is around 8,000 m. Because of the lower altitude, the cruise Mach number for both tanker and cruiser drops to around 0.77 Mach. At this Mach number the cruiser can maintain its position relative to other cruisers on the tracks. Once the AAR procedure is finished, the cruiser returns to its original NAT OTS track. In this way, tanker aircraft can maintain their altitude and refuel all cruisers on a lower refuelling altitude. Only descending towards refuelling altitude and climbing back to the track needs to be done by the cruiser in such a way that the ground speed stays constant compared to cruise speed over a track. A hazard for refuelling cruiser over the North Atlantic is the occurrence of Clear Air Turbulence (CAT). Lee [2013] investigated the amount positive turbulence observations over the North Atlantic. Since it is found that this amount is rather low (0,014%) in combination with current CAT prediction skills and flight planning, it is concluded that CAT can be effectively avoided in the North Atlantic region.

After discussing relevant literature in Chapter 2 and pointing out most important aspect of the NAT system regarding flight operations, a foundation is created for research expansion in the field of commercial in-flight refuelling operations. Taking geographical restrictions and flight rules into account, a lifelike scenario can be generated for testing the AAR operational concept. Next chapter will go further into detail on demarcation of the research framework and associated model requirements.

4

Research framework

This chapter delineates the problem statement, main research objective and the scope in which this study is performed. Important to accentuate is that this research builds on previous work which aimed to solve the tanker allocation problem for civil in-flight refuelling procedures. Since this allocation mechanism can be researched in more depth and scenarios can be modelled with increased lifelikeness, this preceding work functions as a starting point of this study. As it was unclear at the beginning of the research project what advancement could be made in solving the problem by using a distinct formulation, the research framework is not established on a single brainstorming session at the beginning of the project. The presented research framework in this chapter is the result of an iterative process where project goals are redefined and model complexity gradually is expanded.

4.1. Problem statement

In Chapter 2, the impact civil aerial refuelling can have on the fuel consumption by commercial air transport is discussed. It is proven that the AAR concept can be profitable under certain conditions. However for real-life commercial traffic it is unknown if fuel and cost savings can be obtained. Largest efficiency can be achieved when cruiser and tanker schedules are perfectly matched and state-of-the-art aircraft are implemented. Since large modifications in current flight schedules, routes and aircraft are not realistic, the implementation of the aerial refuelling concept for present flight schedules is investigated. The statement of the research problem can be looked at from different viewpoints. A distinction is made between opportunities that can be spotted from within the airline industry and difficulties that have to be coped with when looking from a scientific and operational standpoint.

Industry viewpoint: The main driver from an industry viewpoint is the attainable financial benefit of the in-flight refuelling concept:

- Airlines have in general low operating profit margins. Fuel cost take up a majority share of the DOC of an airline [IATA, 2016]. From a financial point of view, in-flight refuelling could be an interesting option for fuel consumption reduction if the gains outweigh costs.

- Airlines have limited fleet flexibility on long-haul routes. This increases the number of aircraft types in a fleet, more inefficient flights and longer travel times due to a HS network structure. Aerial refuelling can function as an enabler for short range aircraft on long-haul flights. Fleet homogeneity can reduce maintenance and crew costs. New markets can be reached due to tendency towards a PP network.

- If less fuel has to be taken on-board, aircraft become lighter and more fuel efficient. This reduces pollution and noise production around airports.

Scientific viewpoint: Aerial refuelling is currently used only for military purposes. Implementation of the concept for commercial flight is challenging in terms of safety and boom design. Besides, tanker routing can be challenging because:

- In-flight refuelling is a known concept in the aerospace Defence industry, but tanker operations optimization is new. Currently no extensive tanker assignment schedules are used for military air-to-air tanking. To design a suitable solution method, study is needed in the field of operations research.
- Earlier study on this topic did not succeed to come up with satisfying result. An alternative solution method to the traditional VRPTW has to be applied to tackle this problem.

Operational viewpoint: Civil airspace is crowded which provides limited space for schedule and route modification. This implies that air-to-air refuelling has to be fitted into existing networks. This shifts the focus towards optimization of tanker allotment and scheduling.

- Due to a limited operational range of the tankers, passing cruisers have to be refuelled in a certain time window. This entails that tanker aircraft must be in time at the cruiser interception point. This time window implies that a missed cruiser can not be caught up with by the tanker since cruise speeds of both cruiser and tanker are more or less similar.
- Since cruisers have to maintain ground speed at lower refuelling altitude and feeders have to match speeds during the refuelling procedure, both tanker and cruiser have to be capable to fly these required velocities at reduced altitude.
- Cruiser arrival times over a tanker base are not known way in advance. This means that tanker allocation planning is short-term and subject to uncertainty. For flights over the North Atlantic and Pacific which fly along tracks, arrival times are known longer in advance. In general, aircraft maintain their flight level and Mach numbers for the duration of the tracks. This gives opportunities for optimized allocation schedules with less uncertainty. Furthermore, the systematized track structure can help reduce model complexity.

4.2. Research objective and model requirements

The goal of this research is to get better insight in the feasibility of a civil in-flight refuelling operational concept by developing a routing and scheduling algorithm for tanker aircraft refuelling commercial flights crossing the North Atlantic. The focus lies on implementation of the concept in a current real-life traffic environment. The performance of the concept is compared to a baseline scenario which includes the same flights over direct routes. In more detail, the research objective is formulated the following way:

To analyse the potential benefit of a civil in-flight refuelling operational concept implemented in a real-life commercial air-traffic environment, by developing a tanker routing and allocation optimization model that aims to compare results in the form of overall system fuel consumption and tanker costs in reasonable computational time.

It is important to clarify concepts of reasonable computational time, tanker costs and real-life traffic environment in order to set-up a suitable methodology to achieve the formulated objective of this thesis.

Computational time: the goal of this research is to find out if civil in-flight refuelling is a valuable concept. Therefore the optimization model has to be capable performing a tanker allocation optimization for a given set of passing cruisers in various configurations and conditions. The purpose of this model is not to use it as tanker scheduling tool for daily operational flight schedules. However, the model could take-up this functionality for commercial aircraft travelling in westbound direction along the oceanic tracks. Since flights maintain Mach number and altitude along the tracks, cruiser arrival time above the tanker base can be predicted a couple of hours in advance. Traffic in eastbound direction just enters the OTS above the tanker base and therefore accurate planning of arrival times is more difficult. Since this model is not used for short-term decision making, it is considered acceptable if solutions can be generated within two hours for a complete wave of incoming aircraft. In the end, model complexity and computational effort have direct effect on each other and are interchangeable. An increased model complexity comes at the cost of additional computational time and vice versa.

Tanker cost: to measure the effectiveness of this refuelling concept, both total fuel consumption and initial tanker cost have to be evaluated. This concept can only succeed if the fuel consumption of the overall system is reduced relative to the current scenario. Furthermore, tanker aircraft have to be acquired to complete the allocation schedule. This highlights the two components from the research objective that are investigated and in the end decide whether or not this concept can be profitable.

Real-life traffic environment: ideally, a real-life air traffic scenario is simulated using actual traffic data of aircraft flying over the North Atlantic in both directions along the track system. Unfortunately this data is not openly accessible. However, quantitative traffic data is available, and together with the strict operational guidelines for NAT use, real-life traffic can be simulated. Important is the simulation of multiple traffic scenarios with variance in wind speed & direction, track usage and travel direction, to examine the effect on tanker's allocation schedule and volume.

4.2.1. Model requirements

The main model requirements give a general overview of the model's capabilities and restrictions and are listed below. A detailed description of the model, its constraints and objective function is elaborated on in Chapter 5.

- The algorithm must solve, given a set of aircraft with predetermined altitude, speed, arrival times and fuel offload needed, the minimization of the objective function. In this case, the aim is to refuel all aircraft in a minimum required tanker flight time.
- The number of tankers needed to refuel the full set of cruisers is determined with a second optimization that minimizes the required amount of tankers to complete all refuel cycles.
- Robustness of the model is important to easily change the model's scale and test various traffic scenarios.
- A single, fixed tanker base is selected for the evaluation of both eastbound and westbound flights. Gander International Airport (Newfoundland, Canada) is picked as tanker base for the model.
- The model must be able to take wind speed and direction into account during the refuelling procedure. Wind also affects the amount of fuel that is required by the cruisers.
- The tanker has an operating range of 500 NM from the tanker base.
- Due to the tanker's limited operational range around the tanker base, the use of time windows for cruiser refuelling is needed.
- Separation requirements used for oceanic flights are valid during the entire flight track system.
- Only aircraft flying over the organized tracks are considered in this model.
- Multiple aircraft types with various OD-pairs are considered in the model, which requires dissimilar fuel offloads.
- Refuelling takes place on a side track of the original track. Aircraft deviate in lateral direction from the original track to descent to refuelling altitude.
- The algorithm must be able to handle a realistic throughput of aircraft in reasonable computational time.

4.2.2. Software

A computer model is built to simulate real-life traffic scenarios and carry out experiments. The programming language that is used for model creation is MATLAB (version R2014B). The methodology, that is described in the next chapter, is translated to this programming language. The decision to choose this program is based on accessibility of a large variety of advanced toolboxes, good documentation, availability of customer support and existence of a large open source file exchange. A drawback of this software is the necessity of a license, which is provided by Delft University of Technology. In addition to MATLAB, an optimization software package is used as a solver for the optimization problem. CPLEX Optimization Studio (version 12.6) is selected since it can be easily integrated in the MATLAB environment. Similar to MATLAB, this software tool requires license provided by the university. The model is run on a computer with a 2.40 GHz processor consisting of 4 cores and 8 GB physical memory.

4.3. Scope

Due to the fact that during this thesis limited resources are available in the form of time, the scope of research it restricted. Study and model limitations that are employed to achieve the research objective are discussed in this section.

Geographical focus: this research is focused on commercial air-traffic crossing the North Atlantic over the OTS. Multiple reasons for this geographical limitation can be addressed. First of all, this fulfils the research objective to investigate and explore the incorporation of aerial refuelling into real-world air management systems and airline schedules. Second, previous studies already investigated the implementation of this refuelling concept for scheduled trans-Atlantic flights between Europe and North America. In this way it is possible to compare results. Finally, the airspace above the North Atlantic is well structured which increases chances for a successful implementation of the mid-air tanking concept.

Model's restricting factors and robustness: The model is designed to make an analysis of the performance for refuelling commercial flights in an existing traffic environment. The model provides insight in the concept's effectiveness by comparing different traffic scenarios through scenario creation, simulation and optimization. The model is limited for the number of aircraft in a scenario due to increasing computational time. When considering the amount of cruisers that can be visited per tanker round-trip, the tanker's fuel capacity is the restricting factor. Model robustness is reassured by having easy modifiable model inputs to simulate a large variety of scenarios. The influence of input factors on the tanker time and amount of tankers needed can be investigated independently.

Safety: a safety assessment of the concept lies outside the scope of this research. Even when aerial refuelling for commercial flights proves to be advantageous, the concept's safety should be evaluated before a final verdict on attainability can be given.

Refuelling procedure: no detailed investigation will be done on the refuelling procedure itself. The process described by Lith [2012], where the tanker intercepts and approaches the cruiser from behind and below, is incorporated in this research. A fixed duration for the procedure, including uncertainty margin, is assumed. Furthermore, the tanker's refuelling boom design will not be elaborated on in this study. A forward swept tanker boom is used as designed during the RECREATE project [Zajac, 2015].

Tanker routing and allocation schedule: the following aspects that influence the tanker routing and allocation schedule are not in the scope of this research: disturbances or uncertainties for both cruiser and tanker schedules, interference between cruisers on refuelling side-tracks and no future cruiser demand is taking into consideration. Therefore the VRPTW is static with deterministic input variables.

Computer science: thorough examination of factors that affect the computational time is considered out of scope for this study. As long as the computing time stays within previous mentioned limits, the field of computer science remains untouched. Influencing components regarding calculation time are: the used optimization method, the software programs used and their interaction, programming efficiency, parallel computing and computer related specifications as memory and processor.

4.4. Impact and contribution

The purpose of this study is to fill a gap in the body of knowledge. Therefore, the present state-of-the-art and the added value of this research must be clear. The impact and contribution of this study are displayed in Figure 4.1, both seen from an industry and scientific viewpoint. Figure 4.1 summarizes the current state of the body of knowledge and the contribution this research can have, seen from both perspectives.

	Scientific	Industry

Status quo	Civil in-flight refuelling operations are based on:
	▪ VRPTW with a VF formulation [Lith et al., 2014]
	▪ Simplistic tanker routing without scheduling
	▪ Many operational assumptions:
	  ▪ Fixed time between refuels [McRoberts, 2014]
	  ▪ Uniform tanker offload volume [Lith, 2012]
	  ▪ Traffic flow in westbound direction [Morscheck, 2012]
	  ▪ Single track, homogenous cruiser speed [Lith, 2012]
		Civil in-flight refuelling profitability is based on:
		▪ Implementation of conceptual aircraft (both cruiser and tanker)
		▪ Single, one directional scenario
		▪ Profitablity calculations based on fuel cost

Contribution of proposed research	Civil in-flight refuelling operations are based on:
	▪ VRPTW with a SP formulation
	▪ Extensive tanker routing and scheduling optimization
	▪ More lifelike operations:
	  ▪ Variable time in between consecutive refuels
	  ▪ Variable fuel offload volume
	  ▪ Multiple cruiser types with varying speed and OD-pairs in both traffic directions
	  ▪ Multiple cruiser tracks and flight levels
	  ▪ Varying number of tracks and track location
		Civil in-flight refuelling profitability is based on:
		▪ Lifelike traffic environment with the use of existing aircraft
		▪ Varying multiple day scenarios
		▪ Tanker depreciation cost included in cost calculations

Figure 4.1: Current state of knowledge and contribution of the proposed methodology for both science and industry

5
Methodology

This chapter provides a detailed description of the modelling framework where the building blocks that are used to create the model are presented. First, a general overarching representation of the methodology and model is provided to get insight in the interaction between model segments and to translate the objective and requirements from the research framework into a model representation. Next, the way scenarios are generated in the model is discussed. Finally, two primary optimization segments, a tanker routing and assignment, can be defined which make use of a set partitioning formulation are addressed in more detail individually.

5.1. General model overview

Starting from a top level model description, the overall goal of the methodology is to accomplish the research objective. To ensure the model fulfils both the research objective and model requirements stated in the previous chapter, a translation has to be made from the research framework to an appropriate and applicable modelling framework. Three main objectives and requirements are highlighted and function as a starting point of the modelling framework; a real-life traffic scenario, model scenario variation and proof of concept. Figure 5.1 presents an overview of this transition from objectives to a methodology and optimization models.

To test the concept of civil aerial refuelling for a real-life traffic scenario, several factors have to be taken into account: an actual flight schedule, general factors of influence (i.e. wind) and an existing infrastructure. As mentioned before and discussed in detail in Chapter 3, the NAT OTS is chosen as infrastructure for concept testing. Due to presence of the jet stream on aircraft cruise altitude over the North Atlantic, it can be regarded as a factor of influence for aircraft crossing this oceanic airspace and will probably affect tanker routing. A more elaborate description on the applied wind model is provided in Section 5.2. Unfortunately, no actual up-to-date flight schedules for traffic crossing the North Atlantic making use of the tracks are available during this research. Therefore a flight schedule has to be created which resembles actual schedules. Section 5.2 describes in more detail how this flight schedule is computed.

Another important aspect to include in the model is scenario variation. To fully understand the potential of civil in-flight refuelling, tanker routing not only has to be subjected to multiple flight schedules but to various changeable input parameters as well. Predefined variables as number of cruisers, cruiser type and cruise speed, direction of flight and the number of active tracks and their location can all have influence on the outcome of experiments.

To make a statement on the potentiality of the civil mid-air tanking method, a proof of concept is needed to make a comparison with current operations. For this concept to be successful, a benefit in financial terms has to be realized. Since profits, which can be broken down in revenue and costs, are an airline's main driver for their operations, air-to-air tanking can be promising if costs can be reduced. Taking both operating costs and fixed cost into account in terms of overall system's fuel cost and tanker acquisition cost, this concept is tested and results are compared. A detailed explanation on fuel calculations is presented in Section 5.2. Fuel cost and tanker cost are direct derivatives of tanker routing

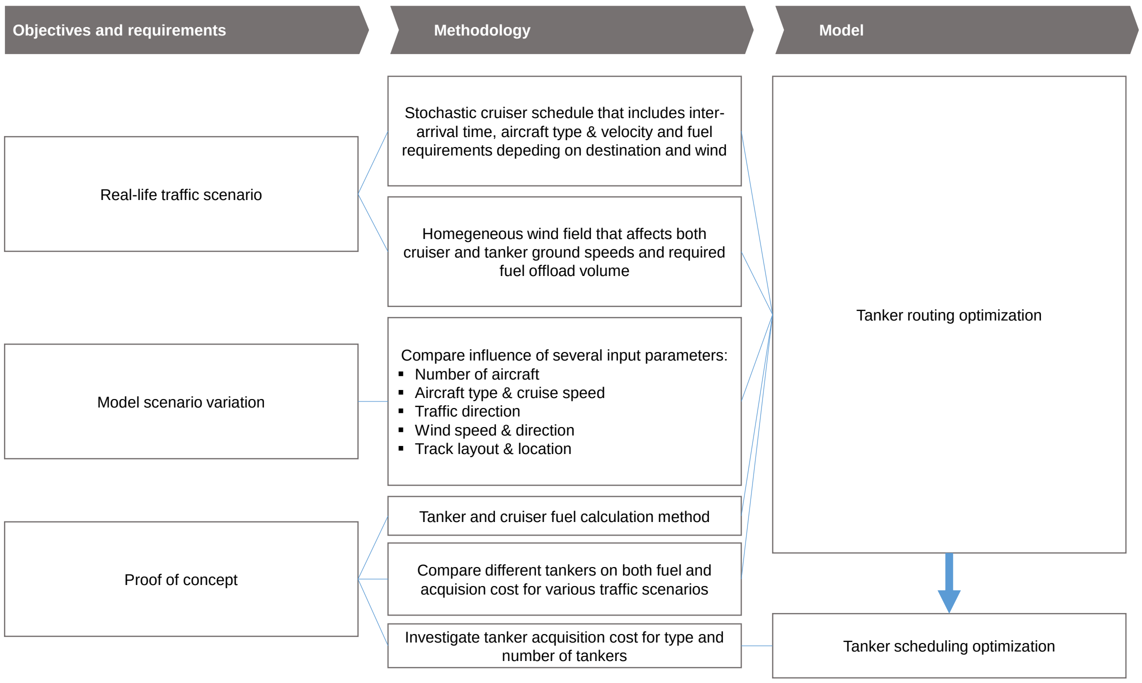


Figure 5.1: Translation of research framework objectives to a methodology and model formulation

and allocation optimizations and can be found in Sections 5.6 & 5.7.

From Figure 5.1 it can be seen that the objectives and model requirements are translated into a methodology that forms the basis of the model. In the end, the modelling framework combines the various aspects of the methodology to simulate the civil in-flight refuelling concept for both tanker and cruiser operations. Figure 5.2 shows that the modelling framework consists of three parts, including two optimization segments. Furthermore, the interaction between different model segments is depicted that complete the modelling framework. The first segment builds the cruiser schedule consisting of cruisers that need a refuel over the tanker base. This schedule is used as input scenario for tanker routing and scheduling optimization and consists among others of the number and types of cruisers, OD-pairs and travel direction and the number and location of NAT OTS tracks. This first segment is further extensively elaborated on in Section 5.2. The second segment, including the tanker routing optimization, is the most extensive of two optimization segments. The goal of this optimization is to minimize the total tanker travel time while serving all cruisers in the cruiser flight schedule. The tanker routing model builds all feasible tanker sequences for a given cruiser schedule and input conditions by means of operational constraints. An optimization cycle, where the problem is defined as a set partitioning problem, provides the combination of tanker sequences for which every cruiser is refuelled exactly ones by a tanker at minimal total operating time. This combination of selected tanker sequences functions as input for the tanker assignment model. The tanker routing optimization is discussed in more detail in Section 5.6.

For the tanker assignment model, a known set of tanker sequences with tanker base departure and return times from the preceding optimization is required. To reduce tanker acquisition cost and increase concept efficiency, a single tanker can be assigned to multiple sequences. The assignment model has minor complexity compared the routing model, since tanker assignment is only limited by the start and end time of a tanker sequence while for tanker routing multiple constraints apply. The outputs of both tanker routing and assignment segments are used for concept feasibility examination. Total system fuel usage and tanker depreciation cost can be deduced from the routing and assignment model respectively. Subsequently, a comparison can be made between concept's cost indication and a baseline scenario including direct cruiser flights. On the hand of Figure 5.2, all three major model segments are discussed in upcoming sections.

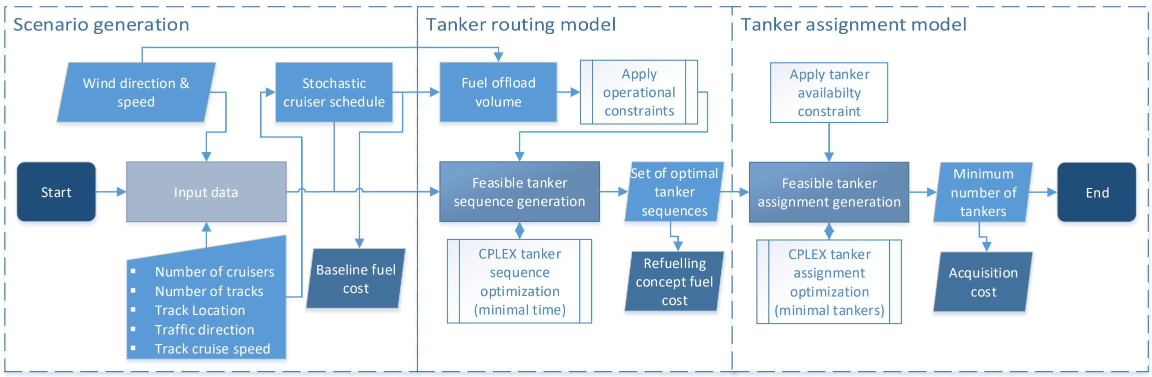


Figure 5.2: Flowchart representation of modelling framework with model segment interaction

5.2. Scenario generation

This section thoroughly discusses the input data used for real-life traffic scenario generation. Manual input data is first explained, followed by the homogeneous wind model and stochastic cruiser schedule segment. Before the created scenario is subjected to tanker refuelling operations optimization, fuel costing methods for cruiser and tanker are addressed upon.

Number of cruisers

For simulating a lifelike traffic environment, it is inevitable to determine a realistic number of cruisers that have to be refuelled. Depending on the time of year and the travel day, on a daily basis between 200 and 350 aircraft travel in each direction making use of the track system [Flightradar24, 2016]. During traffic peak hours, around 60 aircraft can be cleared per hour over the active tracks [Ruis, 2011]. To mitigate the dramatic increase in computational time, it is decided that the amount of simulated aircraft is capped and therefore only traffic between the US and Western Europe is considered. Doing so, the average number of daily total flights that remain in each direction is 320 [OAG, 2010]. Assuming that half of those flights make use of the NAT OTS, 160 flight have to be modelled. For a full concept understanding, this does not have to be a limiting factor since peak and off-peak traffic can be simulated by adjusting cruiser inter-arrival times. Another legitimate reason for using a limited number of simulated aircraft is that not all flights over the tracks require by definition a fuel offload. Airlines can still prefer a direct flight without refuelling, for example when cruiser's destination is at a relative short distance from the tanker base or when the cruiser has to make a significant detour to get refuelled. Since track location changes every day, the number of cruisers that can be refuelled from this single tanker base can fluctuate. With a limited tanker operational range of 500 NM, the number of tracks that lies within tanker's range therefore differs. It can occur that only two or three tracks are within tanker operating range, this influences the amount of cruisers that need to be refuelled. Now that the number of aircraft that can be modelled is determined, the number of tracks in the simulation will be discussed.

Number of tracks

One of the reasons to test the idea of civil aerial refuelling over the North Atlantic is the presence of a highly structured airspace due to the track system. As mentioned previously, these tracks are running parallel and are separated 60 NM in lateral direction. For the cruiser to make a safe descent towards refuelling altitude, a side track is used 15 NM from the original track as depicted in Figure 5.3. In this way, direct flights are separated from flights that need refuelling and interference with traffic on lower flight levels is prevented. Each main track has two side tracks, one on each side of the main track, to prevent conflict among two aircraft that descent from distinct cruise altitudes towards refuelling altitude. With the creation of side tracks, lateral separation standards are reduced to 30 NM. This is not in violation with separation standards since some tracks already make use of so called Reduced Lateral Separation (Rlat) where separation among tracks is 25 NM [ICAO, 2015a]. Each day there are five to eight active tracks in westbound direction and eight to ten active tracks in the opposite way, depending on the amount of traffic, track location and weather conditions. For the model, the number of active primary tracks can be varied between one and four, which gives up to eight side tracks that can be used for in-flight refuelling. Since the model makes use of a reduced number of cruisers and only tracks in range of the tanker base are modelled, the number of tracks in the model is capped as well. Next, the effect of track location on the number of active tracks within tanker base range is examined.

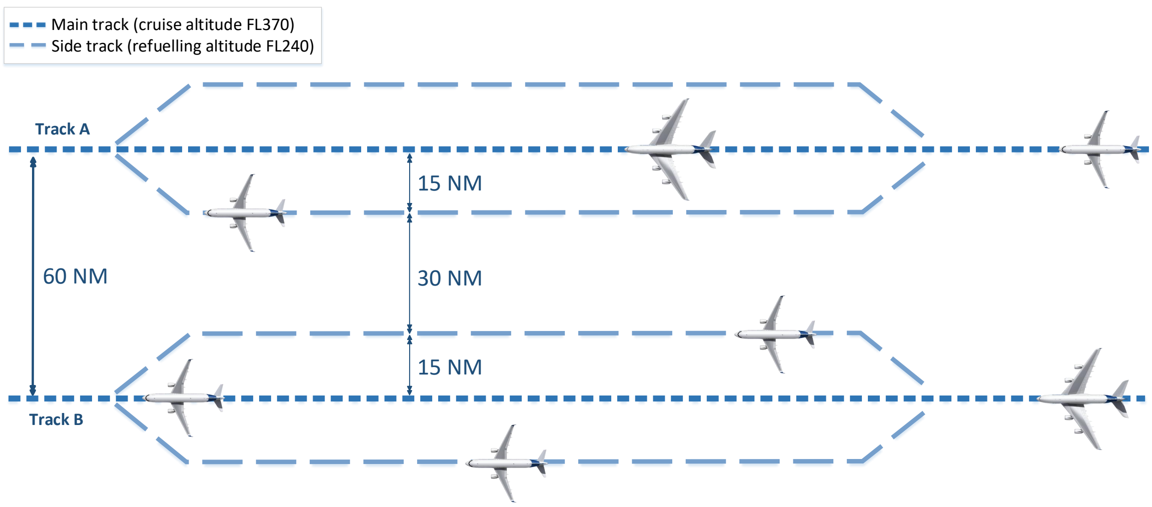


Figure 5.3: Top view of two primary tracks with each having two side tracks where cruisers descent to refuelling altitude to be refuelled

Track location
Since track layout in both directions is reassessed daily, track location varies with respect to the tanker base location. Because it is decided to use Gander International as single tanker base and tanker operating radius is limited, insight is needed in the variation of track layout. Track placement is investigated for both travel directions for a period of three months is investigated. Track entry/exit way-points on the western perimeter of the North Atlantic are registered for all active tracks in the period between August 1st and November 1st 2016. The way-point coordinates are compared with the tanker base location to determine their position relative to the base. A table overview with track way-point count over the recorded period can be found in Appendix A. What can be concluded is that track location has effect on the number of tracks in range of the tanker base. Especially tracks in westbound direction are often not all in range since they have the tendency to be located more north or south to avoid the jet stream. Tracks to guide traffic in eastern direction are located directly over the tanker base in the heart of the jet stream. Therefore the model provides the possibility not only to change the number of tracks but also the track location. Three track locations are investigated for this model and can be selected for a scenario: tracks situated straight over the tanker base and tracks located 500 NM north or south of the base. Figure 5.4 gives an overview of three track layouts for westbound traffic. The location and force of the jet stream influences track location, as can be seen in the figure. The jet stream not only affects track layout but also has direct impact on tanker refuelling operations. How this is accounted for in the model is explained in Section 5.2.1.

Traffic direction
For a tanker base located exactly in the middle of an OD-pair, traffic direction has no influence on the fuel offload volume dispatched by the tanker when wind impact is neglected. Morscheck [2014a] already determined that the ideal refuelling location lies in the ocean and that Gander International is the most suitable alternative. Since the model is capable of simulating traffic in both directions, this dis-proportionality in flight legs has effect on the fuel volume that is discharged. Over the year 2010 all scheduled flights from Europe to the US and vice versa are examined on flight distance from origin to the tanker base [OAG, 2010]. Figure 5.5 shows the percentage of total amount of flights that falls into

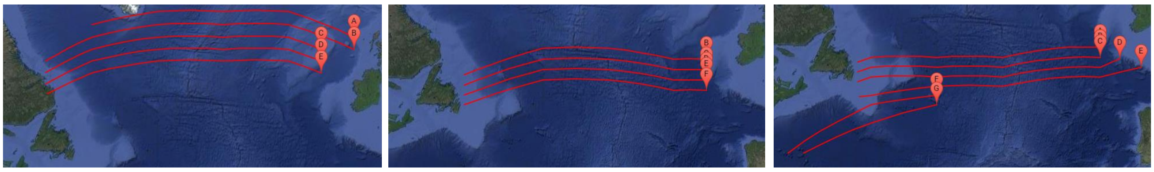


Figure 5.4: Example of three different track locations where tracks are situated with respect to the tanker base. a) north of Gander, b) over Gander and c) south of Gander

a specific range from Gander. For simplicity, all calculations are done based on Great Circle distances since tracks are subjected to alteration. Results show a clear differentiation between both traffic directions. A vast majority of westbound traffic departs from airports located between 2,000 and 2,500 NM from Gander. Eastbound traffic is less clear-cut, nonetheless in general airports are based closer to the tanker base. This results in the need for larger fuel offloads for eastbound traffic compared to opposite traffic. How this is computed is explained in detail in Section 5.2.3. First another factor of influence for the fuel offload volume is discussed in the next section.

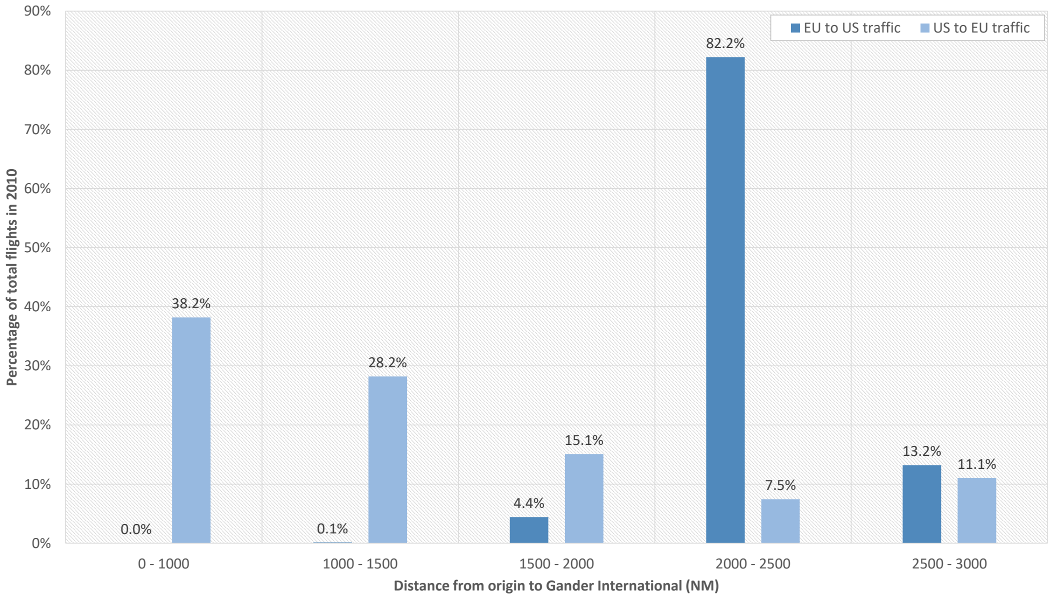


Figure 5.5: Distance to Gander International from origin airport [OAG, 2010]

5.2.1. Wind model

The jet stream in a non negligible wind that influences both fuel offload volume and tanker routing operations. A homogeneous wind field is applied to model the effect of wind. The choice for a homogeneous wind field is substantiated by the model's purpose, which is not to optimize tanker flight trajectory but to get a general understanding of the civil aerial refuelling concept. Other arguments to use a homogeneous wind field over a more detailed grid structure with varying wind speed and direction are the limited area of tanker operation and the single refuelling flight level which both limit the variation in wind speed and direction. To model the effect of wind during refuelling operations, the wind field is established for the three track locations previously determined as shown in Figure 5.6. The effect of wind for the delivered cruiser fuel offload is determined based on the effective range of cruiser flight. In upcoming sections both methods are thoroughly described.

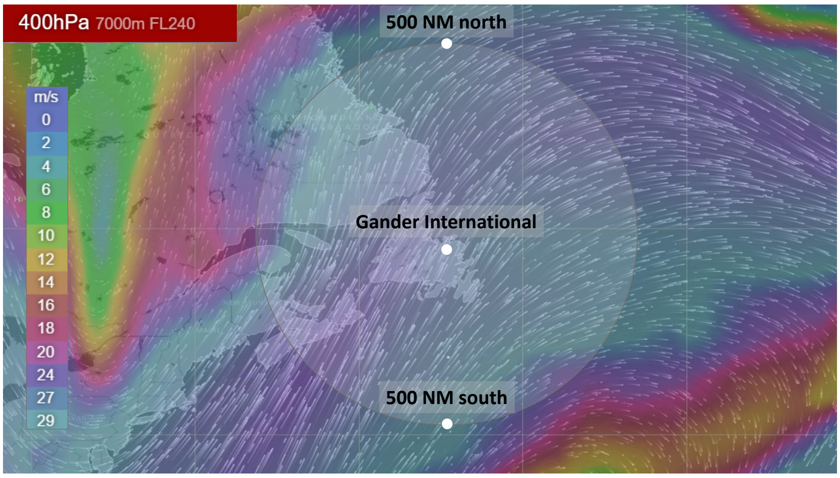


Figure 5.6: Wind speed and direction for all three track locations at refuelling altitude on October 3th, 2016

Wind model used for tanker refuelling operations

The modelling of wind is of influence for both tanker routing operations and cruiser fuel offload demand. The implementation of the wind model for tanker routing has direct influence on tanker refuelling operations. The tanker is subjected to constantly alternating head or tail wind while changing direction travelling from one cruiser to another. Therefore it can be interesting to investigate the impact wind speed and direction have on tanker routing optimization. The wind model consists of a homogeneous wind field based on historical data. Over a period of three months, from August to November 2016, the wind speed is recorded for the three track locations taken up in the model [Windytv, 2016]. The wind speed and direction are measured on an altitude of 7,000 m or FL240. Figure 5.6 shows the three locations where wind is measured and results are turned into wind roses. Figure 5.7 depicts the wind rose of the measurements taken directly over the tanker base. Wind roses of the two other measurement locations can be found in Appendix A. What stands out is the wind direction on all three measurement locations. Wind is primarily directed towards the east for all regions. However, the northernmost location shows more diversity in wind direction than the other two locations. This coincides with the location of westbound track placement investigated in the previous section, which occurs predominantly north of Gander due to these preferable wind conditions. The wind data from Figure 5.7 and the other two locations is inserted into the model, where a wind direction can be selected with according average wind speed.

Cruisers have varying incoming headings entering the tanker operating range depending on the track location. Therefore, tankers and cruiser fly not always directly into or along the wind direction. In the model, the appropriate wind speed vector parallel to both tanker and cruiser flight direction is determined based on aircraft headings. The effect of side wind is not taken into account. For the southernmost track location, a heading of 270° for westbound traffic is chosen (90° for eastbound traffic). Over Gander a heading of 250° (or 70°) is applied and traffic for the northernmost track location has a 230° or 50° heading depending on traffic direction. The wind model on local level, during cruiser refuelling, is not the only influence wind can have on refuelling operations. Zooming out to cruise altitude, cruisers crossing the North Atlantic experience head or tail wind which affects their fuel consumption. How this is accounted for in the model is discussed next.

Effect of Wind on cruiser range and endurance

The duration of an aircraft's air time is not affected by its location with respect to the ground, therefore wind has no effect on endurance. However, range can be considerably affected by wind. Headwind decreases the aircraft's ground speed while tailwind has the opposite effect. In the same amount of time, considering constant thrust settings, the distance travelled by the aircraft varies depending on wind speed and direction. With a linear approximation the effect of wind on the aircraft's range can be described. This is depicted in Equation 5.1, with the assumption that there is a homogeneous wind field applied with a constant wind vector blowing along the flight trajectory.

$$R = R_{no\,wind} \pm V_w E \tag{5.1}$$

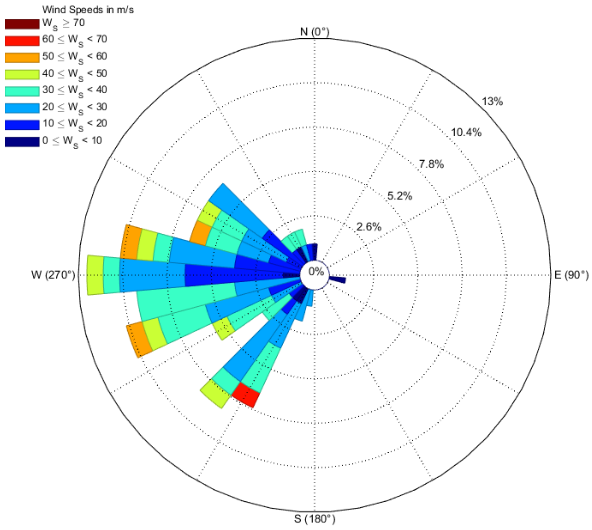


Figure 5.7: Wind rose for wind speed and direction measured over the tanker base at FL240

where R is the effective range flown, $R_{no\,wind}$ is the range given for flight without wind, E describes the flight endurance, V_w is the component of wind along the flight trajectory which is assumed constant and the $+$ or $-$ sign is used for indication of tailwind or headwind respectively.

In reality, as a consequence of the occurrence of wind, different airspeeds can be flown to maximize the range for a particular wind condition. For tail wind conditions, reduced airspeed means that for a longer period of time advantage of the wind can be taken which can save fuel. When head wind conditions apply, range is reduced and increasing airspeed will reduce the time flying into the wind. In this study, cruiser and tanker airspeeds are set constant for all wind conditions. The presence of wind will only affect the aircraft's ground speed. The endurance from Equation 5.1 is determined by dividing the Great Circle distance between OD-pairs by the aircraft's fixed cruise speed, which can be found in Appendix B and C.

For cruisers flying between origin and destination with a known range, the travel time and the amount of fuel taken on-board are influenced by the wind speed and direction. Therefore fuel offload volumes for aerial refuelling operations depend not only on the travel distance to their destination but also on wind conditions. Cruisers travelling with head wind need a greater amount of fuel for the remainder of flight than for a scenario without wind. The opposite applies to a situation in which the cruiser travels with tail wind.

Before the effect of wind can be translated into fuel consumption, average ground speed difference among opposite trans-Atlantic traffic is inspected. The average wind speed for multiple routes crossing the North Atlantic is determined by using the worldwide wind map provided by Windytv [2016] in combination with actual traffic data from [Flightradar24, 2016]. Variation in ground speed for opposite traffic is compared making use of 24 aircraft in each direction containing four different aircraft types. The ground speeds of these flights at track entry and exit are measured and remain almost constant during the entire oceanic crossing for both directions. Over the Atlantic, ground speeds for flights in westbound direction are on average 230 km/h higher than in the opposite direction. Over land this ground speed difference is somewhat reduced but remains greater than 185 km/h. Results of these measurements can be found in Appendix A. This data is compared with wind data from the wind map at an cruise altitude of 11.7 km or FL390. At multiple locations, both over land and ocean, wind speeds are measured and similar results are obtained. Wind speeds over the North Atlantic are generally higher (120-200 km/h) than over land (70-150 km/h) [Windytv, 2016]. There can be concluded that, for a particular day, it is not uncommon to have over the entire course an average effective wind speed along the flight trajectory of 130 km/h. The model is capable to generate scenarios with higher wind speeds, however wind speeds are capped at this 130 km/h wind speed to prevent creation of unrealistic scenarios. With known remaining effective flight distance from the refuelling location above Gander to their destination and particular aircraft flight performance characteristics as cruise speed and specific fuel consumption, the fuel offload volume can be estimated. How this is done is further explained in

Section 5.2.3.

5.2.2. Stochastic cruiser schedule

Previous determined input variables as number of aircraft, the number of tracks and track location, traffic direction and wind form the basis of scenario generation. In this section, the cruiser schedule creation is discussed in more detail. Besides the number of aircraft, other variables like cruiser arrival time, cruiser type, cruise speed and OD-pair come into play for schedule generation. Since every day a varying amount of aircraft consisting of different commercial aircraft types operating at a range of cruise speeds making use of the oceanic airspace, this should be accounted for in the model. Furthermore, longitudinal separation standards have to be taken into account determining the cruiser inter-arrival times. How these factors are accounted for in the model is described in this section.

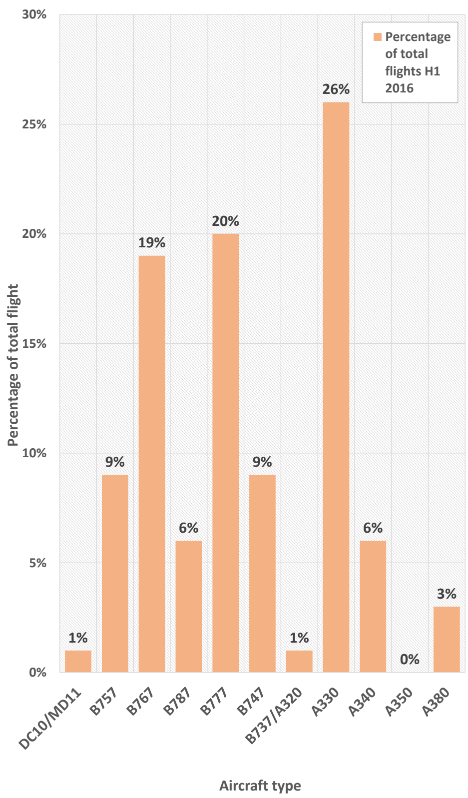
Aircraft types and cruise speed

For simulation of a real-life cruiser schedule, various aircraft types and associating cruise speeds have to be taken into account. Figure 5.8a shows the number of aircraft per type crossing the North Atlantic for the first half of 2016 [CAPA, 2016]. It is decided for simplicity that not all aircraft models displayed in this figure are taken up in the model. Six aircraft models with the largest contribution represent 90% of all flights and are selected to be included in the model. For each aircraft type a characteristic subtype is selected. An overview of included aircraft is displayed in Figure 5.8b. The new cruiser designed during the RECREATE project [Rocca et al., 2014], which has similar capacity as the Boeing 767-300ER and range as the Boeing 737-800, is not included in the model. Instead the most recent version of the B737-800 aircraft, which is used for short to medium haul flights, is added for comparison. This decision is based on the fact that including an existing aircraft model is more realistic than adding a conceptual design. In direct operations, the deployment of the B737 is limited for trans-Atlantic flights due to its restricted range as can be seen in Figure 5.8a. Therefore it can be interesting to investigate the performance of this aircraft type for the refuelling concept.

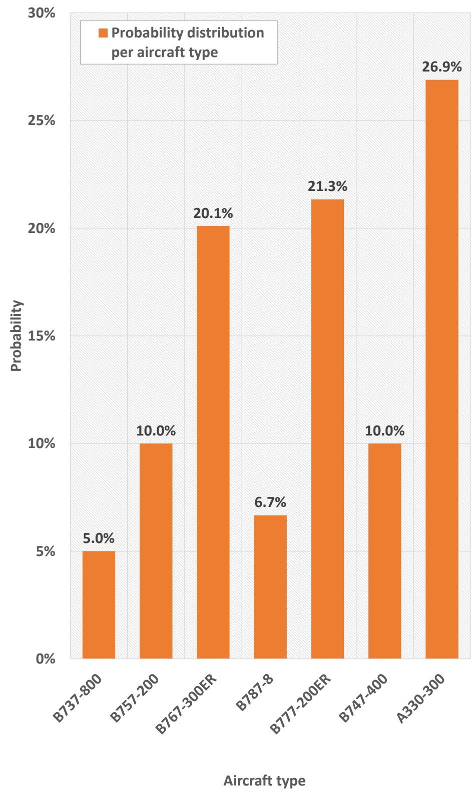
For cruiser schedule generation, the aircraft type occurrence of Figure 5.8a is modified, consisting solely of represented aircraft in the model. The new distribution is depicted in Figure 5.8b where flights operated by other aircraft types are distributed over the included models. Furthermore, the occurrence of the B737-800 aircraft is enlarged considering the fact that OD-pairs across the North Atlantic can be served by this aircraft operated while refuelled in mid-air. The probability distribution from Figure 5.8b is used to split up the total number of aircraft modelled by type.

In addition to the different aircraft types included in the model, cruise speeds of the various aircraft in the cruiser schedule have to be determined. One aircraft is faster than the other which has to be accounted for in the schedule. Appendix B gives an overview of the flight performance characteristics, including cruise speeds and maximum cruise altitudes of the different aircraft types in the model. It can be concluded that smaller aircraft are typically slower than larger aircraft.

In the model, cruisers can fly at multiple cruise altitudes on a single track. To maintain their position with respect to other aircraft on the same flight level, cruisers have to maintain cruise speed while descending from cruise altitude to refuelling altitude. Commercial aircraft passenger Mach numbers are converted for both cruise flight levels (FL390 and FL370 for eastbound and FL400 and FL380 for westbound traffic) to refuelling altitude (FL260). As depicted in Figure 5.9, traffic on different flight levels making use of the identical track has to be separated while descending to refuelling altitude. Since refuelling altitude is a single flight level, two refuelling side tracks are needed to separate traffic from the two different cruise altitudes. As mentioned earlier, in the model up to four main tracks can be active. This implies eight refuelling side tracks where cruisers can descent to receive a fuel offload. Aircraft flying on the higher cruise altitude typically manoeuvre to the side track on the left while aircraft on the lower level descent on the track right of the main track, as can be seen in the figure. Due to the fact that different aircraft are used in the model, cruise speeds differ. However, it is assumed in the model that a similar cruise speed applies for all cruisers flying on the same flight level of a particular main track. As an example, the aircraft from Figure 5.9 are taken which represents a westbound traffic flow. Eastbound traffic behaves identically for the odd flight levels. Aircraft flying on FL400 have a different cruise speed compared to flights on FL380. Since all aircraft from a single flight level will end up on an individual refuelling side track, consecutive aircraft on a side track will not gain or lose distance on each other. This implies that cruisers have to be arranged on cruise speed to determine



(a) Distribution of aircraft type on the trans-Atlantic for the first half of 2016 [CAPA, 2016]



(b) Distribution of aircraft types included in the model for both flight directions

Figure 5.8: Cruiser type distribution for historical data of flights crossing the Atlantic and cruiser types included in the model

which cruiser types can fly together on an identical track. Another concomitant is that slower aircraft will not be able to fly on refuelling side tracks that are used by faster cruisers and vice versa.

To check if all cruisers are able to maintain their cruise speed at lower flight level, the Base of Aircraft Data (BADA), an aircraft performance model developed and maintained by Eurocontrol, is consulted to investigate cruiser flight envelopes [BADA, 2016]. Another operational problem can occur when one or more cruiser types are flying faster at refuelling altitude then the tanker. Both conceptual tankers designed during the RECREATE project Li and Rocca [2014] are used in the model and have a cruise speed of 0.8 Mach at refuelling altitude. Since tanker fuel capacity is limited and possibly insufficient in combination with large passenger cruisers, three existing (military) tankers are added to the model. A table with flight performance characteristics of the included tankers can be found in Appendix C. No limitations for operations are found for tanker cruise speed as well as cruiser flight envelopes.

Inter-arrival times

Inter-arrival times for the cruiser schedule are generated for time window entrance and are stochastically determined using an uniform distribution. According to longitudinal separation standards a minimal separation of ten minutes needs to be adhered to for consecutive cruisers on the same track and flight level. The upper limit of the arrival time distribution is based on the number of cruisers that has to be refuelled and time the track layout is active. It is determined that with a scenario including 160 cruisers, four active main tracks (eight refuelling tracks) and a seven hour active track layout, the average inter-arrival time must be 22,5 minutes to handle the throughput of cruisers over the tracks in the given time span. This implies that arrival times need to be uniformly generated with a fixed lower boundary of 10 minutes and an upper bound of 35 minutes. The upper limit of this window is affected by the number of aircraft, tracks and duration of active tracks and is subjected to change for various input

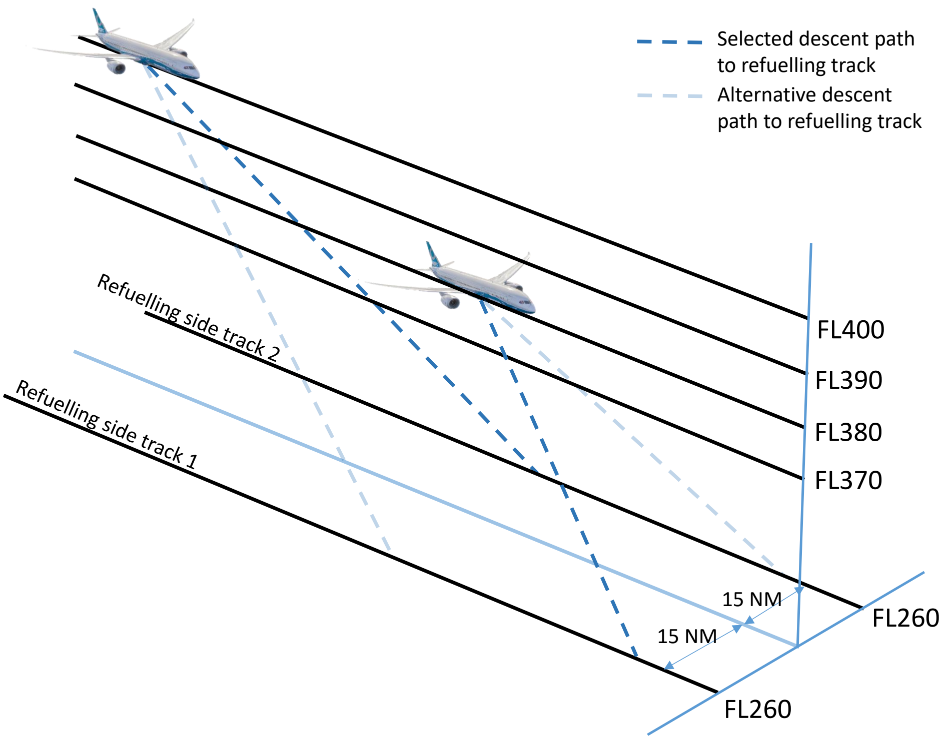


Figure 5.9: Schematic drawing of cruisers descending from a single main track with contrasting flight levels to different refuelling side tracks (westbound traffic depicted)

scenarios. The arrival time of the first cruiser of each refuelling track is determined the same way as the other cruisers with the exception that the lower bound of its time interval is determined based on the time it takes for a tanker to depart from the tanker base and arrive at the refuelling location. This travelling time is predominantly influenced by track location and track number. Since the departure time of a tanker from the tanker base can not be smaller than zero, the start of the first refuelling is always later than the time it takes for the tanker to travel from the tanker base to the first cruiser on a track.

OD-pairs

To finalize scenario generation, the OD-pairs that are incorporated in the cruiser flight schedule have to be determined. Figure 5.5 already depicted the share of total traffic within a particular range of the tanker base. It is chosen to include only the busiest routes between the US and Europe according to the OAG database while taking into account the representation of distance variation to Gander. Since the majority of flights is operated from an European airport at a distance between 2,000-2,500 NM from Gander, the three busiest airports in this range are selected. The four busiest US airports with scattered ranges from the tanker base are selected, leaving only the 2,000-2,500 NM unrepresented. An overview of the selected OD-pairs can be viewed in Table 5.1. Both Great Circle distances of direct and staged operations over the tanker base are stated [Flightplanner, 2016]. Most OD-pairs require a detour to receive a refuelling, this is taken into account in the fuel calculations.

Table 5.1: Flight distances for direct flight and staged operations of included model OD-pairs

	LHR		CDG		FRA	
	Direct (NM)	Staged (NM)	Direct (NM)	Staged (NM)	Direct (NM)	Staged (NM)
JFK	2,991	2,992	3,150	3,151	3,341	3,342
ORD	3,423	3,491	3,596	3,650	3,761	3,841
MIA	3,839	3,872	3,980	4,031	4,191	4,222
LAX	4,730	4,961	4,915	5,120	5,033	5,311

5.2.3. Fuel calculations

Cruiser fuel calculation

Fuel offload volumes for flights in the cruiser schedule have to be determined for both staged and direct operations. Cruiser trip fuel and reserve fuel are determined with the use of an online fuel planner [Fuelplanner, 2016]. First, fuel volumes per aircraft type for direct flights between various trans-Atlantic OD-pairs are computed. This is rather straightforward since the fuel planner provides trip fuel and reserve fuel per aircraft type for given OD-pairs. Computing the required fuel with a refuelling segment over Gander is more tedious. First, the trip is split into two stages, one from origin to Gander and a second from Gander to destination. Figure 5.10 shows the mission profile for both direct and staged operations.

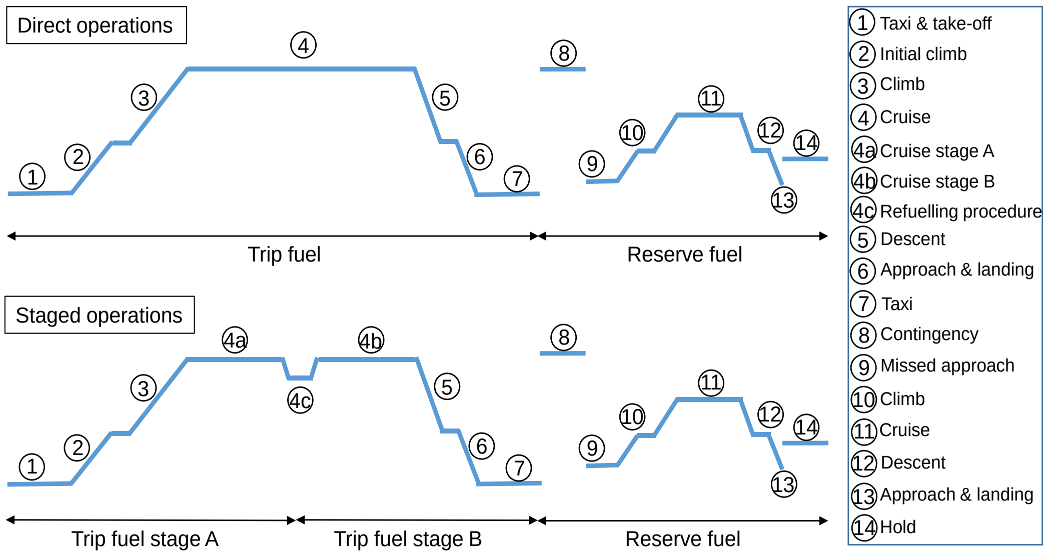


Figure 5.10: Mission profiles for both direct and staged cruiser operations

Looking at the mission profile for staged operations of Figure 5.10, the cruise phase is split up into three segments. The first cruise segment (4a) is the cruise phase from origin to the refuelling location, which is taken directly over the tanker base. This segment is computed by taking the required trip fuel for the direct flight from origin to Gander (stage A) with the use of Fuelplanner [2016] and subtract the descent, landing and taxi segments of the direct mission profile. Mission fuel fractions by Roskam [1986] are used to subtract these from the trip fuel. Furthermore, reserve fuel, provided by Fuelplanner [2016], is incorporated to calculate the total fuel for stage A. The required cruiser offload volume, which includes segments 4b up until 7, is determined similarly. Now taking the direct trip fuel from Gander to destination (stage B) and subtract the first three mission segments. Reserve fuel is a constant amount of fuel and is not affected by mission length but varies per aircraft type. Since reserve fuel is still present at the moment of refuelling, it does not have to be included in the fuel offload volume.

Another cruiser related fuel aspect is the additional fuel needed during the refuelling segment (4c). The refuelling segment consists of three phases: cruiser descent to refuelling altitude, cruise at lower altitude during refuelling procedure and a climb back to original track height. The descent phase is finished before a cruiser enters the refuelling time window. The fuel usage during this refuelling segment is investigated and compared to a cruise at original cruise altitude [BADA, 2016]. Results show that depending on aircraft type and second stage length, this extra fuel consumptions during this segment can be significant. Therefore, it is decided to add this extra fuel to the offload volumes. An example of this fuel calculation and results for different aircraft are further elaborated on in Chapter 6.

As mentioned previously, wind determined in the wind model affects the effective range flown by the cruisers. This effective range influences both direct and staged flights. Tables including fuel offload volumes needed by diverse cruisers are listed in Appendix B.

Tanker fuel calculation
In general, the range of an aircraft is considered to be the distance the aircraft can fly from a given speed and altitude until it runs out of fuel, while endurance is defined as the time it takes to run out of fuel. Both range and endurance can be computed for any given flight condition. Since range computation for tankers that take-off and land on the same base with limited operational range is not a concern, tanker endurance is emphasized. A limitation for the amount of cruisers that can be refuelled within a tanker sequence is the tanker's own fuel capacity. In contrast to Lith [2012], who assumes a fixed tanker endurance of four hours, the endurance in this study is based on the tanker's fuel consumption and variable cruiser fuel offload. Figure 5.11 shows the mission profile for tanker operations. Tanker fuel needed for the first and final three flight segments is determined by both mission fuel fractions [Roskam, 1986] and BADA data [BADA, 2016]. What can be noticed is the cruise segment which is split up in multiple phases. In this example, three cruiser refuelling phases are included in the tanker cycle. The number of cruisers taken up in a tanker cycle can fluctuate due to required fuel offload volume and tanker fuel capacity. Besides trip fuel, tankers have reserve fuel on-board which is determined according to Fuelplanner [2016].

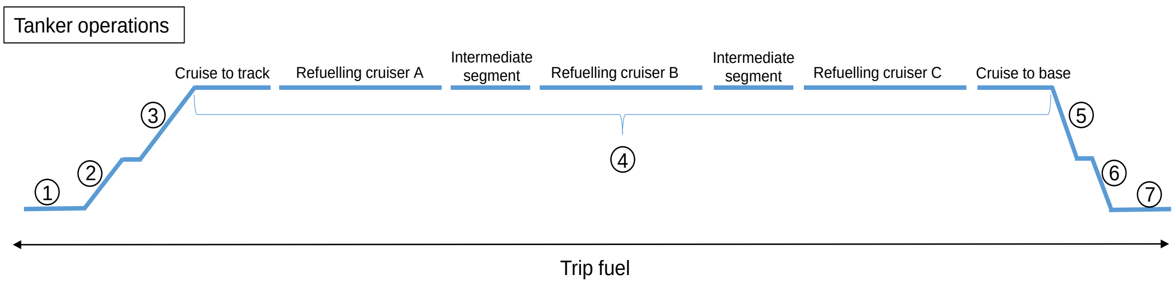


Figure 5.11: Example tanker mission profile including three cruisers in the tanker cycle

To capture both the effect of fuel offload volume as well as own fuel consumption, tanker fuel consumption is calculated making use of a variant of the general Breguet Range equation [Ruijgrok, 2009]. Since tanker altitude and velocity remain constant during refuelling, the endurance for thrust rated aircraft with constant altitude and velocity flight is used. Equation 5.2 describes the tanker endurance for cruise condition as defined by Ruijgrok [2009]. Since variations in cruiser airspeed and wind have influence on tanker airspeed and endurance, tanker velocity is not constant during the complete cruise phase. A solution is found by splitting up the tanker endurance calculation during cruise into multiple cruise segments where a distinction can be made between refuelling segments and intermediate segments as depicted in Figure 5.11. In this way tanker velocity remains constant during each segment. The assumption is made that velocity changes among consecutive segments occur instantaneous since variations are relatively small. During refuelling segments a fuel offload is provided by the tanker. These segments cover the complete refuelling procedure and have a fixed duration of 25 minutes. Intermediate segments cover the segments in-between refuelling where the tanker travels from one cruiser to another. How the duration of these segments is determined will be discussed in Section 5.5. With known durations, the change is aircraft weight (i.e. fuel consumption) can be calculated. In between tanker cruise segments, an instant velocity change is assumed.

$$E = \frac{2}{c_t}\left(\frac{L}{D}\right)_{cruise}\left[tan^{-1}\left(\frac{C_{L_1}}{C_{L_{md}}}\right) - tan^{-1}\left(\frac{C_{L_2}}{C_{L_{md}}}\right)\right] \tag{5.2}$$

where c_t is the specific fuel consumption of the tanker and $\frac{L}{D}$ the lift-over-drag ratio during cruise. C_{L_1} and C_{L_2} are both lift coefficients for the start and end of the cruise phase. In general form, the tanker's lift coefficient can be described as:

$$C_{L_n} = \frac{W_n}{\frac{1}{2}\rho V^2 S} \tag{5.3}$$

with ρ representing the atmospheric density, V is the tanker airspeed and S describing the wing surface area of the tanker, which are all constant during a cruise segment. The aircraft weight W_n at the start and end of each segment is determined by just the tanker fuel consumption for intermediate segments. During refuelling segments, besides fuel used by the tanker, a fuel offload to a cruiser is provided. The tanker weight variation between start and end of a refuelling segment can be determined by adding the cruiser fuel offload weight to the computed tanker fuel usage during the refuelling segment.

For the general case during cruise, the minimum drag flight condition must be determined by selecting both parasitic and induced drag coefficients from the aircraft's drag polar given by Equation 5.4. To determine the parasitic drag coefficient $C_{D_{0L}}$, Eurocontrol's flight database BADA is consulted [BADA, 2016]. The parameter K which is included in the induced drag coefficient can be extracted from Equation 5.5. With both the parasite drag and K, the lift coefficient during cruise for minimal drag conditions follows from Equation 5.6.

$$C_D = C_{D_{0L}} + K{C_L}^2 \tag{5.4}$$

$$K = \frac{1}{\pi ARe} \tag{5.5}$$

With AR representing the wing aspect ratio and e being the Oswald efficiency factor. The span efficiency factor is in the range of 0.7-0.95 for conventional wing aircraft. For the conceptual joined-wing tanker from Li and Rocca [2014], an Oswald factor higher than one can be achieved. According to Zohlandt [2016], the efficiency of high subsonic Prandtl aircraft can reach up to 1.45. An overview with detailed tanker performance characteristics of all tanker included in the model can be viewed in Appendix C.

$$C_{L_{md}} = \sqrt{\frac{C_{D_{0L}}}{K}} \tag{5.6}$$

Track location and track number of the first cruiser in the tanker cycle determine the tanker cruise-to-track segment duration. For track locations with an offset to the tanker base, a cruise segment is needed to arrive at the first cruiser. This cruise segment is negligible for tracks positioned over the tanker base. Depending on the refuelling location of the last cruiser in the tanker cycle, the duration of the cruise-to-base segment is determined. This final cruise segment can be neglected in cases where the tanker position after finishing the refuelling of the final cruiser in the tanker cycle is within the descent range to the tanker base.

Besides the fuel used during cruise, tanker fuel needed for climb, descent and landing are taken into account as well. Fuel used during the landing and taxi segments is determined according to mission fuel fractions. Fuel consumption for both climb and descent segments are computed making use of the BADA tool. For all five tanker types included in the model, fixed fuel usage for climb and descent segments are determined. Only the cruise fuel fraction depends on segment duration and initial aircraft weight. Knowing the aircraft's OEW, reserve fuel and crew, fuel fractions of the tanker's mission profile are computed backwards, starting with the known landing weight. The assumption is made that every tanker type has three crew-members on-board, weighing 100 kg each including luggage.

The reason for computing tanker fuel usage is not only to calculate the total concept fuel usage but also to test if a tanker cycle can be executed. The first segment of the mission profile is not included in the tanker fuel calculations. Since working back-to-front computing tanker weight produces tanker take-off weight ($W_{takeoff}$) as a result. This calculated $W_{takeoff}$ can be compared to the tanker's fuel capacity to check if the tanker cycle can be executed. A more detailed elaboration on how tanker fuel acts as a model constraint can be found in Section 5.6.

For the three existing military tankers, aircraft data of their commercial equivalent is used to compute all fuel fractions. This data is not available for both RECREATE tankers included in the model. A Boeing 737-600 aircraft, which is of comparable size as both tanker designs, is used to compute fuel consumption during these flight segments. Table 5.2 provides an overview of the flight segments involved for tanker fuel calculations with the used method for . All cruise phases are computed with the endurance formula, all other segments are predefined. A five minute margin of error is included among the first three flight segments to prevent a missed cruiser. The influence of wind is only included in the cruise segment (4) since only in this segment wind has direct impact on tanker routing.

Table 5.2: Overview of various tanker flight segments including fuel usage and calculation method for all tankers included in the model

	Flight segment	RECREATE tankers Fuel used [kg]	A310MRTT Fuel used [kg]	KC-46 Fuel used [kg]	A330MRTT Fuel used [kg]	Fuel calculation method
2,3	Climb	1,155	2,328	2,755	3,354	BADA
4	Cruise to track	Determined by track location and target track number				Equation 5.2
	Cruiser refuelling	Determined by cruiser speed, wind and travel direction				Equation 5.2
	Cruiser to cruiser	Determined by tanker position, target cruiser speed and position, wind				Equation 5.2
	Cruise to base	Determined by tanker position after final refuel				Equation 5.2
5,6	Descent	375	679	652	612	BADA
7	Landing + taxi	Fixed fuel fraction: 0.008 · (OEW+W_crew+W_reserve)				fuel fraction by Roskam
Reserve fuel		2,800	5,326	6,391	7,187	Fuelplanner

To recap the scenario generation, all input variables that are included in the model and influence cruiser schedule and tanker operations are reviewed. Cruiser fuel computation for both direct and staged flight are discussed and the impact of wind on cruiser fuel is examined. The operational concept will be explained in more detail in the next section before the optimization models used to compute tanker fuel usage and the number of tankers needed are elaborated upon.

5.3. Tanker routing in the refuelling concept

To get a better understanding of the tanker routing problem, the tanker cruise segment of the mission profile is discussed in more detail. This section will elaborate on tanker routing operations in the AAR concept by means of a simple example scenario. Basic operational restrictions are explained followed by a description of the method used for computing the rendezvous location between tanker and cruiser.

The general idea of tanker routing in the refuelling concept is a tanker that serves one or more passing cruisers and provide these commercial aircraft with fuel to extend their mission range. The goal is to provide every cruiser exactly once and while tanker operating time is minimized. Figure 5.12 depicts a basic scenario with five incoming cruisers on four different tracks. Tracks are located over the tanker base, with the tanker base placed in the middle of the time window. Time window duration is assumed to be 10 minutes at a cruise speed of 0.8 Mach, which corresponds to a time window distance of 80 NM. This time window distance is chosen in such a way that tankers will remain within a 500 NM range of the tanker base irrespective of the number of active tracks. Due to wind, an increase or reduction in cruiser ground speed alters this time window duration. Furthermore, varying cruiser type and cruise altitude make that time window duration differs per passing cruiser due to varying cruise speeds. For now, this is not of influence for the general explanation of the tanker routing problem.

Both tanker base and cruisers can be seen as nodes in the model that have to be served by a tanker. The number of cruiser nodes N is equal to the set of cruisers Z in the model. Since the tanker base is the start and end point of every tanker cycle, two additional nodes are assigned to the tanker base (node 0 and $N+1$). This makes that the complete number of nodes, including both tanker base and cruisers, is equal to $N+2$. A tanker cycle is defined as the combination of nodes and arcs included in a tanker tour starting from the moment the tanker leaves the tanker base till the moment of returning to the base. In Figure 5.12, the cruisers are numbered based on the order of entering the refuelling zone independent of their track. Since this specific example includes five cruisers, nodes one up to five are assigned to the cruisers.

Cruisers can only be refuelled in the refuelling zone, limited by a time window. It is therefore not unusual that multiple tankers are needed to unsure the refuelling of all cruisers in the flight schedule. Since the refuelling procedure duration is 25 minutes and assumed to be fixed, tankers always have to turn around after finishing the refuelling of a cruiser to head to another cruiser. This point of rendezvous between cruiser and tanker has to be somewhere inside the time window zone. How the rendezvous point between a tanker and cruiser taken up in the tanker cycle is determined, will be discussed in the

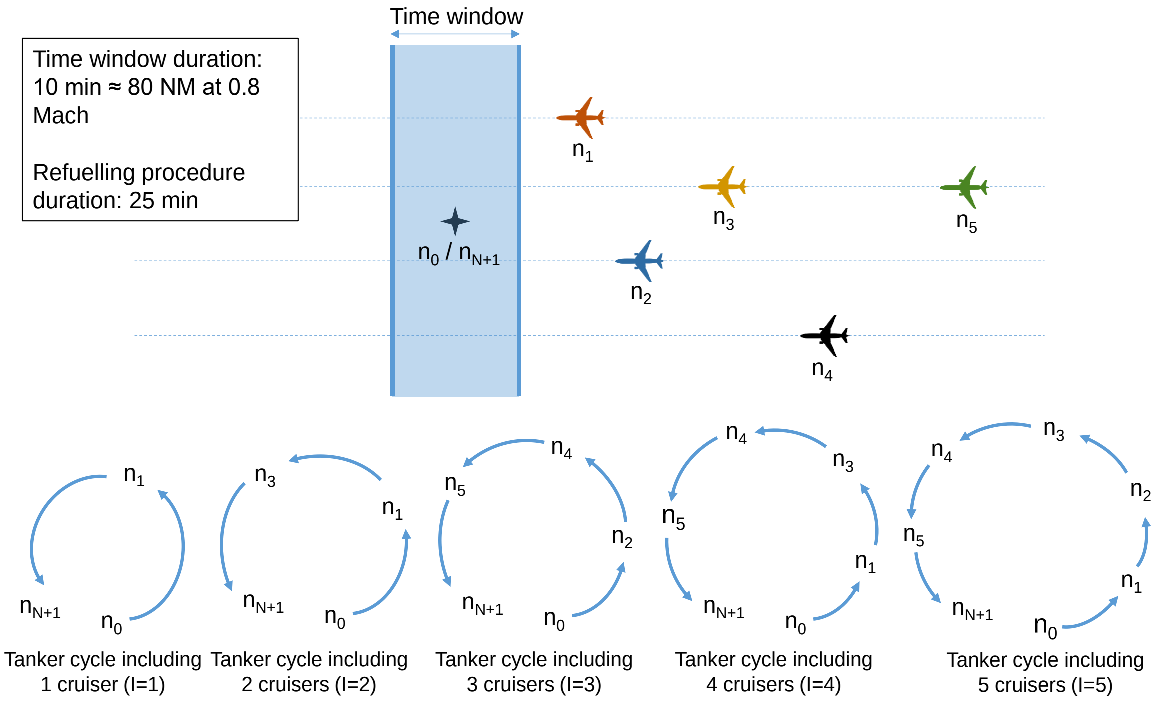


Figure 5.12: Top view of tracks oriented over the base with incoming cruisers on multiple tracks. Tanker base and cruisers can be defined as nodes which all have to be included in one or more tanker cycles

next section. The first cruiser in the tanker cycle is always intercepted at the time window boundary when entering the refuelling zone. Depending on traffic direction, this can be on either side of the time window. It is important for the tanker not to arrive late at this time window entry point since a missed cruiser can not be caught up with due to the limited time window distance. Therefore a five minute safety margin is incorporated in tanker departure time from base for tracks directly over the base. When tracks have an offset with respect to the tanker base this safety margin is increased with an additional five minutes due to a larger tanker travel time. Dependent on the arrival time of a cruiser and its assigned track in combination with track placement, a tanker departure time is computed according to Table 5.3. It is assumed that independent of tanker type, these durations are fixed. However, a difference can be noticed for the tanker cruise phase to the first cruiser for different track locations. Tracks placed over the tanker base are all in tanker climb range and no cruise phase is required. Depending on the used track by a cruiser, five minutes tanker cruise time has to be added per track for outer placed track. Using the scenario displayed in Figure 5.12 as an example, the additional tanker cruise time to tracks 1 and 4 is five minutes. This can increase to 15 minutes in a scenario with eight tracks. For tracks located with an offset north or south from the tanker base, the difference between the closest and the furthest track with respect to the tanker base is 35 minutes.

Table 5.3: Overview of various tanker flight segments including tanker flight duration and distance travelled

Flight segment		Track location	Duration [min]	Distance [NM]
2,3	Climb	all	15	70
4	Cruise to closest track	base	n/a	n/a
		North / South	30	300
	Cruise between tracks	all	5	30
	Cruiser refuelling procedure	all	25	Determined by cruiser ground speed
	In between refuelling	all	Determined by cruiser and tanker position and speed	
	Return cruise after final refuel	all	Determined by final tanker position w.r.t. tanker base	
5,6	Descent	all	22	85

The first cruiser that is taken up in a tanker cycle does not have to be the cruiser that arrives first at the time window boundary. In Figure 5.12 several examples are given of tanker cycles including one or multiple cruisers. It can be noticed that tankers, after leaving the tanker base, start refuelling a later cruiser. If a tanker includes n_1 (i.e. cruiser 1) in its cycle, it could be possible that after completion of the refuelling process it is not in time to intercept n_2 within the time window. This implies that cruiser 2 has to be refuelled by a different tanker than cruiser 1. To check if tanker cycles are feasible, constraints are applied. How these feasible tanker sequences are generated and which constraints apply are discussed in more detail in the upcoming sections.

It is not possible for a tanker to travel from a later cruiser to an earlier cruiser. For example, it is not possible for a tanker to first serve cruiser 3 and after completion set course to cruiser 2. Once a cruiser number is chosen, additional cruisers in the tanker sequence can only have larger numbers. Another point of attention is that every tanker cycle starts and terminates at the tanker base. Since this illustrative scenario only includes five cruisers, no more than five cruisers can be included in the tanker cycle. This implies that in theory for scenarios with an extended number of cruisers, cycle lengths could match the number of included cruisers. However, due to constraints as limited tanker fuel capacity and time windows this will not be the case in practice.

In the end, the goal is to optimize the operating time of the selected set of tanker cycles needed to refuel all passing cruisers. Consequently, feasible tanker cycles have to be generated from which an optimal set of tanker cycles can be selected. The algorithm that is used to generate these feasible tanker cycles is presented now.

5.4. Feasible tanker cycle generation

The optimization formulation that is used in this research, makes use of a predefined set of tanker cycles. By means of constraints, only feasible tanker cycles remain. These are taken into an optimization phase where a subset of cycles with a combined minimum tanker operating time is selected. Tanker cycle generation is discussed together with a method used to reduce the number of added columns to the cruiser column matrix.

Figure 5.13 shows a general overview of tanker cycle generation for the feasible column matrix $A_{N,C}$. All columns $[1, ..., C]$ represent tanker cycles. All rows represent the nodes $[0, ..., N+1]$ included in the model. Since nodes 0 and $N+1$, which represent the base, are per definition included in every cycle, these are not taken into account creating the cruiser column matrix. Cruisers taken up in a tanker cycle are indicated by a one and zero otherwise. Figure 5.13 displays how the feasible column matrix is generated. Starting with a single cruiser included in the tanker cycle, the number of columns added to $A_{N,C}$ is equal to the amount of cruisers in the flight schedule Z. A tanker has to be selected that is capable to serve at least all cruisers as a single customer in its tanker cycle. Next, an additional cruiser is added to the tanker cycle to generate possible combinations with two cruisers included per cycle. As can be seen in Figure 5.13, the number of columns added to the matrix increases. This can process can be repeated until a cycle including all cruisers in generated. In practice, considering the number of cruisers that can be active in the flight schedule, this is a time consuming process which is very demanding memory wise. The number of possible tanker cycles with I number or cruisers taken up in the tanker cycle is determined according to binomial combinations as displayed in Equation 5.7.

$$C(N,I) = \frac{N!}{I!\,(N-I)!} \tag{5.7}$$

Due to fuel capacity restrictions of the tanker, even for the largest tanker in the model no more than seven cruisers can be incorporated in a tanker cycle. Still, this will ask lot of memory. To give an example, the number of combinations for tanker cycles including five cruisers for a flight schedule of 150 cruiser is 591.6 million. To mitigate this problem, the used algorithm applies constraints with iterations in between matrix expansion to significantly reduce the number of columns added to the column matrix. How this is applied is showed in Figure 5.14 with an example considering the five cruisers in the scenario. The applied method is compared with an algorithm that does not implement the use of intermediate constraints.

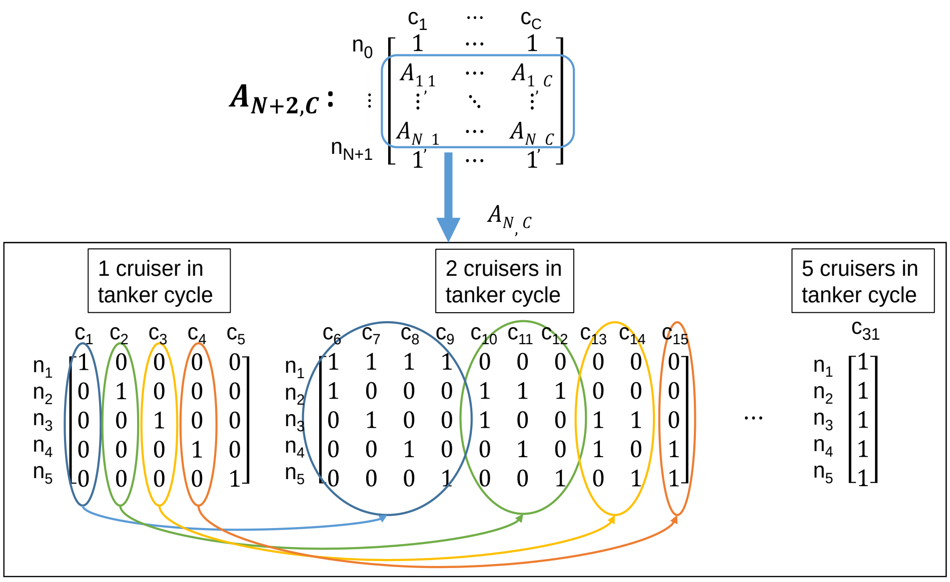


Figure 5.13: Explanation of the generation of the column matrix including all possible tanker cycles including one or more cruisers. No constraints are applied yet

Figure 5.14 shows the transition between a tanker cycle consisting of two cruisers to cycles including a third cruiser. For the method that first computes all columns before applying constraints, cycles that can be expanded with another cruiser are encircled. Other columns have already included the final cruiser and no other cruiser can be added to the cycle. Depending on the last cruiser that is taken up in the tanker cycles with two cruisers, cruiser position of the added cruiser is changed until all combinations up to the final cruiser are generated. In this example, it means that both matrices consisting of tanker cycles with two and three cruisers have ten columns. The used algorithm in the model has a different approach. Applicable constraints are applied after generating the tanker cycles including two cruisers. For the four cycles that remain feasible, another cruiser is added. As can be seen, the column matrix including three cruiser combinations is limited to three columns. Scenarios with a larger amount of cruiser can benefit greatly of applying this method. Moreover, more and stricter constraints will help to increase the number of deleted columns which reduces the remaining feasible tanker cycles.

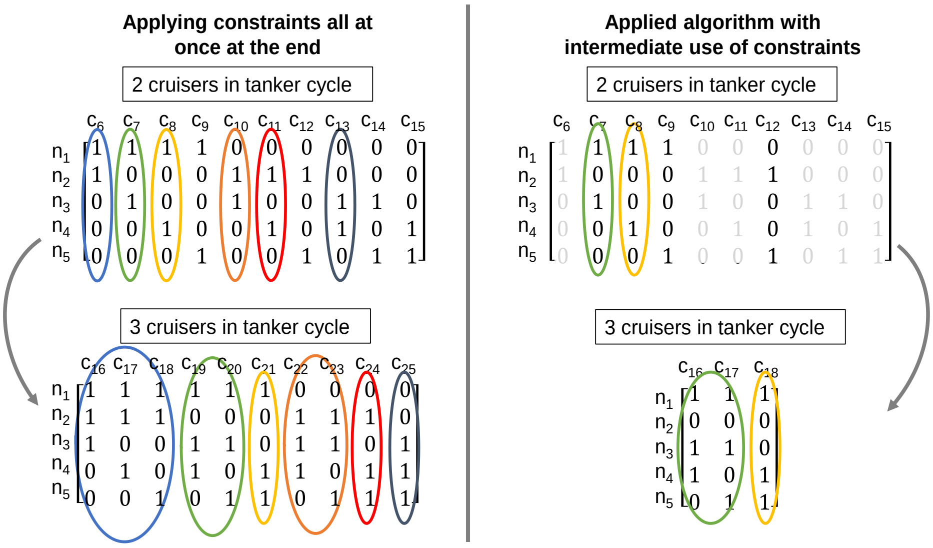


Figure 5.14: Comparison between two algorithms, where the first one generates all tanker cycle combinations and applies constraints all at once at the end versus the used algorithm that applies constraints intermediately

Besides the tanker fuel capacity, another limitation is applied to reduce the number feasible tanker cycles. Tanker fuel capacity limits the amount of cruiser offload fuel that can be taken on-board. Furthermore, fuel needed by the tanker itself also has to be taken into account. Both cruiser offload fuel and tanker fuel usage have already been discussed extensively in this chapter. The other limitation that applies is the time window, which forces the tanker to start the cruiser refuelling procedure in the refuelling zone. For tanker cycles with just a single cruiser included this is no constraint. However, with multiple cruisers incorporated in the tanker cycle, the point of interception between cruiser and tanker has to be determined to check if the generated cycle is feasible or not. A detailed description of the applied method for rendezvous calculation is presented in the upcoming section.

5.5. Point of interception calculation method

In this section a closer look is taken at the way the operational concept is modelled and the rendezvous point between tanker and cruiser is determined. Now that parameters affecting scenario generation are discussed and the primary operational restrictions are clarified, detailed tanker operations have to be investigated in a geographical context. The first cruiser in a tanker cycle is always refuelled at its time window entry point. However, for subsequent cruisers in the cycle, refuelling location is not fixed and has to be determined. After finishing the refuelling procedure of a cruiser, the tanker turns around to rendezvous with a following cruiser. The tanker can only serve this cruiser if the point of interception lies within or before the specified time window. This section covers in more detail the way this rendezvous point is determined. Figure 5.15 shows an example of the operational layout of the refuelling area around the tanker base. Depending on the track number of two consecutive cruisers in a cycle, two options for tanker manoeuvring exist: fly back along the same track for cruisers on identical tracks or head to another track when cruisers are on contrasting tracks. Both situations will now be further explained. The variable notations used in this section can be found in Table 5.4.

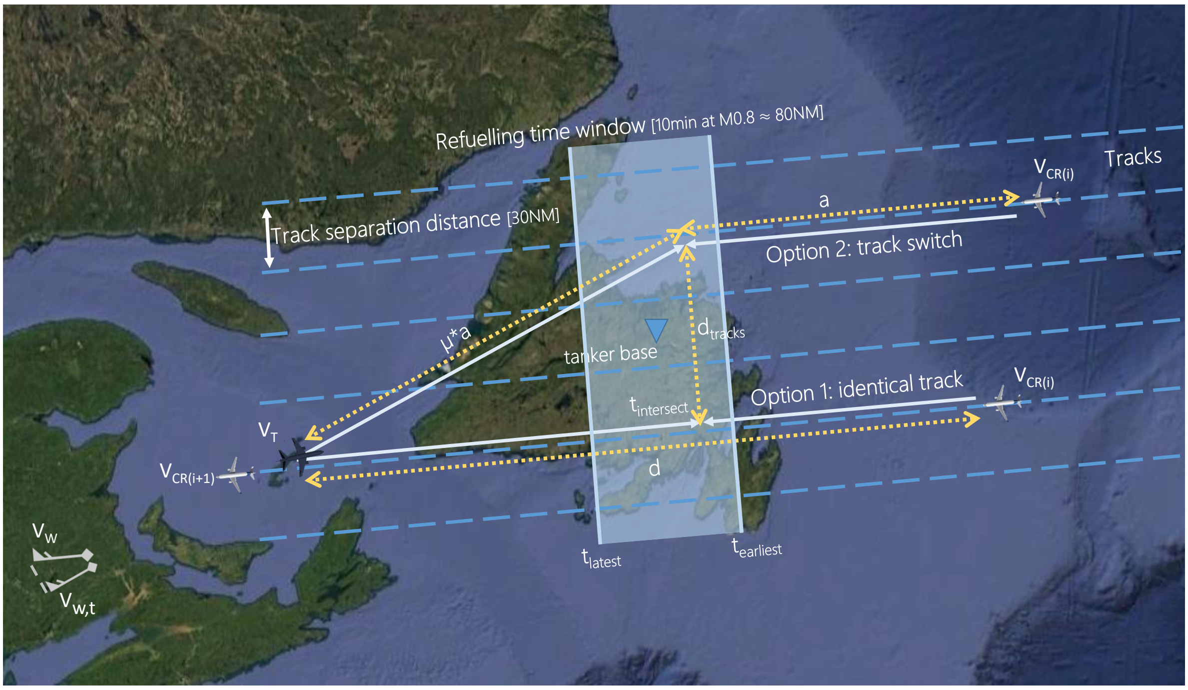


Figure 5.15: Top view of tracks oriented over the base with the tanker having the option to refuel a next cruiser on the same track as previous cruiser or switch to a cruiser on a different track

Table 5.4: Notation and definition of variables

Notation	Definition
Δt	Inter-arrival time between cruisers at time window entry
$\Delta tracks$	Track number difference between current and target track
μ	Ratio between tanker and cruiser ground speeds
a	Cruiser distance to rendezvous point
C	Set of tanker cycles
d	Distance between tanker position after refuelling and next cruiser in the tanker cycle
$d_{separation}$	Fixed track separation distance [30 NM]
d_{tracks}	Distance between tanker current track and refuelling track
I	set of cruisers in tanker cycle c
$t_{i,c_{intersect}}$	Time it takes before tanker and cruiser i intersect measured from moment tanker finished previous cruiser $i-1$ refuelling
$t_{i,c_{tw-entry}}$	Time it takes for tanker to travel to time window entry boundary from moment tanker finished previous cruiser $i-1$ refuelling*
$t_{i,c_{tw-exit}}$	Time it takes for tanker to travel to time window exit boundary from moment tanker finished previous cruiser $i-1$ refuelling*
$T_{i,c_{actual}}$	Actual starting time of refuelling cruiser i in tanker cycle c
$T_{i,c_{entry}}$	Arrival time at time window entry boundary of cruiser i in tanker cycle c
$T_{i,c_{exit}}$	Arrival time at time window exit boundary of cruiser i in tanker cycle c
T_{rf}	Fixed cruiser refuelling time [25 min]
T_w	Time window duration at tanker cruise speed [10 min]
V_{cr_i}	Cruise speed of cruiser i
V_t	Cruise speed of tanker
V_w	Wind velocity along track direction

*Time window entry and exit boundary are seen from cruiser's perspective and can be on either side of the time window depending on cruiser travel direction

5.5.1. Option 1: identical tracks

Since it is determined that cruisers on the same track have identical cruise speeds, the gap between consecutive cruisers remains constant along their flight trajectory. This simplifies calculating the point of interception for the next cruiser. As can be seen in Figure 5.15, the tanker base is located in the middle of the refuelling time window since this is the most ideal location considering tanker travel time. The white arrows in the figure indicate velocity vectors of both cruiser and tanker. Yellow dotted lines are used to indicate distances. Since in this example scenario traffic is travelling with head wind in westbound direction, the tanker velocity vector is larger compared to that of the cruiser. For the first option, where the tanker serves a cruiser on the same track as the previous cruiser, the point of intersection is determined according to Equation 5.8.

$$t_{i,c_{intersect}} = \frac{\Delta t \left(V_{cr_i} \pm V_w\right)}{V_{cr_i} + V_t} \tag{5.8}$$

where all velocities are in meters per second and the distance between both cruisers is determined by $\Delta t \left(V_{cr_i} \pm V_w\right)$ with Δt in seconds. The $\pm$ sign indicates the wind direction with respect to the cruiser heading, where a plus indicates equal directions and a minus opposite directions. For the example of Figure 5.15 a minus sign is used. The found time of intersection is added to the time the refuelling procedure of the previous cruiser was terminated. Since the rendezvous point between tanker and cruiser has to lie within the refuelling time window to be a feasible tanker cycle, tanker travel time to both boundaries of the window has to be determined as well. Equations 5.10 and 5.10 show the travel times of a tanker from its location after refuelling a previous cruiser to the start and end of the time window respectively.

$$t_{tw-entry} = \frac{\left(T_{rf} + T_{i-1,c_{actual}} - T_{i-1,c_{entry}}\right) \cdot \left(V_{cr_i} \pm V_w\right)}{V_t \mp V_w} \tag{5.9}$$

$$t_{tw-exit} = \frac{\left(T_{rf} + T_{i-1,c_{actual}} - T_{i-1,c_{entry}}\right) \cdot \left(V_{cr_i} \pm V_w\right) - \left(V_t \cdot T_w\right)}{V_t \mp V_w} \tag{5.10}$$

Difference between both equations is the time window distance ($V_t \cdot T_w$) that is not included in the tanker cruise duration to the time window exit boundary. Since only for the first cruiser in a tanker cycle the refuelling location is fixed (i.e. at the earliest moment), the distance between the actual refuelling moment ($T_{i-1,c_{actual}}$) and earliest refuelling moment ($T_{i-1,c_{entry}}$) of a previous cruiser is of influence for the refuelling moment of the next cruiser. For a cruiser refuelled at its earliest refuelling moment, $T_{i-1,c_{actual}} = T_{i-1,c_{entry}}$ and will therefore cancel each other out. When the rendezvous point is later than the latest refuelling time $T_{i,c_{exit}}$, the option can be discarded. In case the rendezvous point lies before the earliest refuelling time ($T_{i,c_{entry}}$), the tanker circles at the time window boundary until the cruiser arrives and $T_{i,c_{entry}}$ is taken as refuelling moment.

5.5.2. Option 2: track switch

The second option for two consecutive cruisers in a tanker cycle is that track number differs. This means that, after finishing the refuelling procedure of a cruiser, the tanker has to head to a different track to rendezvous with the next cruiser in the tanker cycle. Determining the point of intersection between tanker and cruiser flying on dissimilar tracks is more complex compared to identical tracks. For a track switch, the same restriction holds as used for identical tracks; the rendezvous point between tanker and cruiser has to lie inside the refuelling time window or before the earliest refuelling moment for a cruiser to be accepted in the tanker sequence. The determination of cruise duration for a tanker to arrive at both time window boundaries differs compared to the identical track situation since the difference in track number has to be accounted for. Direct flight paths for the tanker are assumed as well as a wind vector along the tanker flight trajectory.

$$t_{tw-entry} = \frac{\sqrt{{d_{tw-entry}}^2 + {d_{tracks}}^2}}{V_t \mp V_{w,t}} \tag{5.11}$$

where $d_{tw-entry}$ is the distance from the tanker to the earliest refuelling moment, d_{tracks} is the separation distance from the initial track to the target track and $V_{w,t}$ is the wind velocity along the tanker flight trajectory. The $\mp$ sign indicates the wind direction with respect to the tanker heading. For the example of Figure 5.15 a positive sign is used. The parameters of Equation 5.11 are further explored in the following equations.

$$d_{tw-entry} = \left(T_{rf} + T_{i-1,c_{actual}} - T_{i-1,c_{entry}}\right) \cdot \left(V_{cr_{i-1}} \pm V_w\right) \tag{5.12}$$

$$d_{tracks} = \Delta tracks \cdot d_{separation} \tag{5.13}$$

and

$$V_{w,t} = V_w cos\left(tan^{-1}\left(\frac{d_{tracks}}{d_{tw-entry}}\right)\right) \quad , \tag{5.14}$$

where $d_{separation}$ is the standard separation distance between tracks and $\Delta tracks$ being the difference in track number between current and target track. The latest refuelling start time is determined in an identical way, where $d_{tw-entry}$ in Equations 5.11 and 5.14 is replaced by $d_{tw-exit}$ which is displayed in Equation 5.15.

$$d_{tw-exit} = \left(T_{rf} + T_{i-1,c_{actual}} - T_{i-1,c_{entry}}\right) \cdot \left(V_{cr_{i-1}} \pm V_w\right) - \left(V_t \cdot T_w\right) \tag{5.15}$$

To determine the point of intersection between tanker and cruiser, a reference is made to Figure 5.15 where a and μa represent respectively the cruiser and tanker velocity vectors. The factor μ expresses the tanker velocity with respect to the cruiser velocity: $\frac{V_t \mp V_{w,t}}{V_{cr_i} \pm V_w}$. The tanker cruise duration to reach the point of interception is computed according to Equations 5.16 and 5.17.

$$t_{intersect} = \frac{d_{intersect}}{V_t \mp V_{w,t}} \tag{5.16}$$

with

$$d_{intersect} = \mu a = \mu \frac{\sqrt{{d_{tracks}}^2 \mu^2 - {d_{tracks}}^2 + d^2 \mu^2} - d}{\mu^2 - 1} \tag{5.17}$$

and

$$d = \left(T_{i-1,c_{actual}} - T_{i-1,c_{entry}} + T_{rf}\right) \cdot \left(V_{cr_{i-1}} \pm V_w\right) + \left(T_{cr_i} - \left(T_{i-1,c_{actual}} + T_{rf}\right)\right) \cdot \left(V_{cr_i} \pm V_w\right) \tag{5.18}$$

The chosen method used to find the rendezvous point between tanker and cruiser makes use of the assumption that $V_{w,t}$ is known. In practice, it is only the case for tanker cruise duration calculations to both time window boundaries. To compare arrival times for cruiser and tanker at both time window edges, it can be determined if the rendezvous lies before, in or after the time window. In case the interception point lies within the time window, Equation 5.16 is used. Because the exact cruiser heading is not known beforehand, the unknown $V_{w,t}$ has to be estimated. To test at what point in time intersection occurs within the time window, a fixed $V_{w,t}$ is chosen that is set to be the average of both wind velocities towards the time window boundaries. Since the time window is relatively small compared to the cruiser refuelling time, the divergence in tanker heading to both sides of the time window is small as well. This results in a small margin of error compared to the exact method using vector decomposition. By splitting up the tanker velocity vector in a $x-$ and $y-$component, the exact moment two aircraft intersect, and therefore the associated wind component, can be computed. Both methods are compared in Chapter 6 and it is shown that the used method produces almost identical results as the exact method. Since the formula for the exact method is complex to solve for tanker cruise duration to rendezvous, it is decided to assume a set wind velocity along the tanker flight trajectory to determine cruiser intersection within the refuelling time window.

Besides the used assumption for rendezvous point calculation between cruiser and tanker, some operational assumptions apply. To conclude this section, these assumptions are touched upon briefly.

- Hard time window boundaries are used. This means that if the rendezvous point lies only one centimetre after the time window exit point, the cruiser will not be refuelled and the tanker cycle is discarded as feasible option.
- Instant tanker heading change is assumed each time the tanker changes flight direction (after finishing the refuelling procedure or at cruiser rendezvous).
- A fixed refuelling procedure time is used with the assumption that transferring the fuel volume from tanker to cruiser is not a limiting factor in the procedure.
- A single refuelling altitude is assumed which can lead to conflicts among tankers. Since tankers have to cross tracks while travelling from one cruiser to another, it can lead to encounters with other tankers serving cruisers on these tracks. This study does not take conflict free tanker movement in between refuelling into account.

Now that the operational concept is clarified and the two main constraints for tanker operations are discussed in detail, the optimization models used for both tanker routing and scheduling are thoroughly explained in upcoming sections.

5.6. Tanker routing optimization model

This section extensively reviews the working method of the tanker routing optimization model. The purpose of the model is to find the optimal set of tanker cycles in terms of tanker operating time that covers all passing cruisers for refuelling. From Figure 5.2 the tanker routing optimization model can be viewed in relation to the overall methodology. Model input is determined during scenario generation and takes the arrival times and cruise speeds from the generated cruiser flight schedule. Model outputs are the number of tanker cycles needed to provide all cruisers with fuel, the start and end time of each cycle and the operating time and fuel consumption of the tankers. The schematic of Figure 5.12 already showed that with the use of constraints, infeasible tanker cycles from the column matrix are discarded.

Only feasible tanker cycles remain from which an optimal subset it selected according to the applied objective function. The methodology used to solve the vehicle routing problem is by means of a SP formulation. This alternative formulation is explored since a previous study which used a traditional VF formulation for solving the vehicle routing problem for a simpler model was not entirely successful [Lith et al., 2014]. This feasible tanker cycle column matrix $A_{N,C}$, functions as elementary constraint of the SP formulation for problem solving. The mathematical notation and the formulation of objective function, decision variable and constraints are explained step by step in Sections 5.6.1, 5.6.2, 5.6.3 and 5.6.4 respectively.

5.6.1. Notation

The notation as stated in Table 5.5 is used for the tanker routing model. There is no restriction on the number of tankers included in the model since this first optimization does not assign any tankers to the optimal set of cycles found. This tanker routing problem can be described using a traditional SP formulation as used by Munari [2016]. The decision variable, objective function and constraints used to perform the optimization are discussed next.

Table 5.5: Notation and definition for the tanker routing model

Notation	Definition
$A_{N+2,C}$	column matrix which includes the set of feasible tanker cycles C for set of cruiser nodes N and tanker nodes 0 and $N+1$
$D_{i,c}$	Fuel demand of cruiser i on cycle c
$F_{N+2,C}$	column matrix with tanker arrival time at nodes for set of feasible tanker cycles of $A_{N+2,C}$
Q_T	Tanker fuel capacity
t_c	tanker operating time of tanker cycle c
$U_{(i-1,i),c}$	Tanker fuel usage in between refuelling cruisers $i-1$ and i on tanker cycle c
$U_{i,c}$	Tanker fuel usage during refuelling of cruiser i on cycle c

5.6.2. Decision variable

The goal of the optimization is to find the subset of feasible tanker routes that can be optimized on tanker operating time with the objective function. The tanker routing model makes use of only a single decision variable:

x_c: feasible tanker cycle c starting and ending at the tanker base with at least one cruiser refuel included

x_c is a binary decision variable which has a value of one when the feasible tanker cycle is included in the optimal solution and zero otherwise.

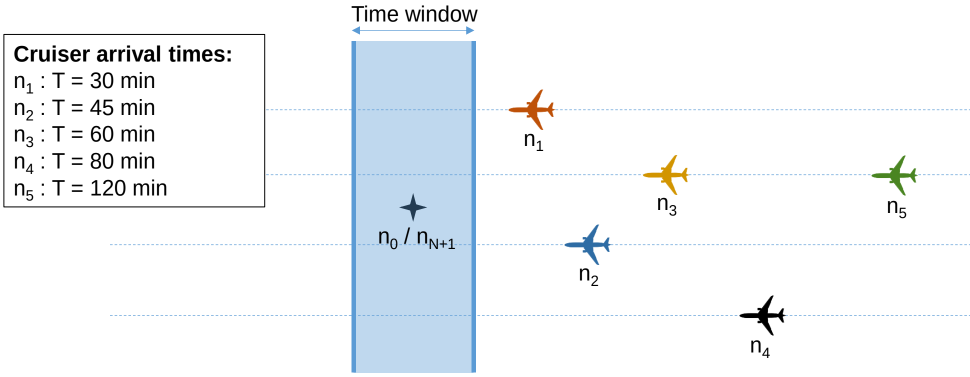
$$x_c = \{1, 0\} \quad , \qquad \forall c \in C \tag{5.19}$$

5.6.3. Objective function

In this representation of the VRP, the decision variable is associated with each feasible tanker cycle. The objective function of this optimization is to minimize the total cost (i.e. tanker operating time) for a selected number of feasible tanker routes.

$$\text{Minimize tanker operating time:} \sum_{c \in C} t_c x_c \tag{5.20}$$

The tanker operating time t_c for each feasible tanker cycle c is determined from the moment the tanker leaves the tanker base till the moment of return. The set of cruisers consist of N amount of cruisers and can be seen as nodes in the model. As mentioned before, there are two additional nodes included for tanker route cost calculations, since the tanker base is included as starting and finishing node for every tanker cycle c. For every column of the matrix with feasible tanker cycles $A_{N,C}$, the tanker operating time is determined. For every cruiser node that is active in the cycle, the refuelling starting time is determined according to the method described in previous section. Depending on the arrival time of the first cruiser in the tanker cycle, and the start time of the refuelling procedure of the final cruiser in the cycle, tanker departing and arrival time at the tanker base is determined. Figure 5.16 shows an example of a simplified cruiser schedule with associated cruiser arrival time at time window entry. For this flight schedule, the column matrix $A_{N,C}$ containing feasible cycles and matrix $F_{N+2,C}$ which includes tanker arrival time at each node for every feasible cycle of $A_{N,C}$ are displayed.



$$\mathbf{A}_{N+2,C}$$

$$\begin{array}{cc}
 & \begin{array}{ccccccccccc} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 & c_8 & c_9 & c_{10} & c_{11} \end{array} \\
\begin{array}{c} n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_{N+1} \end{array} &
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}
\end{array}$$

$$\mathbf{F}_{N+2,C}$$

$$\begin{array}{cc}
 & \begin{array}{ccccccccccc} c_1 & c_2 & c_3 & c_4 & c_5 & c_6 & c_7 & c_8 & c_9 & c_{10} & c_{11} \end{array} \\
\begin{array}{c} n_0 \\ n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_{N+1} \end{array} &
\begin{bmatrix}
10 & 30 & 45 & 60 & 105 & 10 & 10 & 30 & 45 & 60 & 10 \\
30 & 0 & 0 & 0 & 0 & 30 & 30 & 0 & 0 & 0 & 30 \\
0 & 45 & 0 & 0 & 0 & 0 & 0 & 45 & 0 & 0 & 0 \\
0 & 0 & 60 & 0 & 0 & 0 & 0 & 0 & 60 & 0 & 0 \\
0 & 0 & 0 & 80 & 0 & 80 & 0 & 0 & 0 & 80 & 80 \\
0 & 0 & 0 & 0 & 120 & 0 & 120 & 120 & 120 & 123 & 123 \\
74 & 88 & 105 & 122 & 165 & 122 & 165 & 165 & 165 & 170 & 170
\end{bmatrix} \\
\boldsymbol{t_c = n_{N+1} - n_0} & \begin{array}{ccccccccccc} \mathbf{64} & \mathbf{58} & \mathbf{60} & \mathbf{62} & \mathbf{60} & \mathbf{112} & \mathbf{155} & \mathbf{135} & \mathbf{120} & \mathbf{110} & \mathbf{160} \end{array}
\end{array}$$

Figure 5.16: Example cruiser flight schedule with accompanying feasible tanker cycle column matrix and tanker operating time per cycle

As already mentioned, matrix $F_{N+2,C}$ is extended with two tanker base nodes. The numbers in the matrix indicate tanker arrival times at each node. Only for n_0 the tanker departing time at the tanker base is indicated. The tanker operating time per cycle is determined by the difference between tanker departure from and return at the tanker base. Tanker arrival time at the nodes is defined in minutes and is continuous. Only the final sum of operating times of selected tanker routes is rounded to the nearest integer. Depending on the cruiser track number and arrival time, tanker departure time is computed according to methods described in previous sections. For the tanker return time at the base, cruiser track number, cruise speed and refuelling start time are of influence. By means of decision variable x_c a subset of columns is selected for which the tanker operating time is added up. The goal of this optimization is to select a subset of columns that consist of minimal aggregated tanker time and fulfils the set-partitioning constraint, which is discussed next.

5.6.4. Constraints

Set-partitioning constraint

The primary constraint of a set-partitioning problem formulation which distinguish itself from a comparable set-cover formulation is the use of an equality constraint where the identical constraint for a set-cover formulation uses an inequality. This includes the feasible route column matrix $A_{N,C}$. The constraint in Equation 5.21 ensures that every cruiser in the schedule is served by the tanker exactly once. It limits the number of selected tanker routes to at most the number of cruisers in the model.

$$\sum_{c \in C} A_{n,c} x_c = 1 \qquad \forall n \in N \tag{5.21}$$

where $A_{N,C}$ represents the column matrix with feasible tanker cycles for all cruiser nodes. Cruisers n included in tanker cycle c are assigned with a value of one and zero otherwise, as can be seen in Figure 5.16. A possible subset of columns that can be selected from this example that fulfils this constraint is $[c_2, c_3, c_{11}]$.

Operational constraints
With the traditional formulation of the objective function, decision variable and applied constraint, the tanker routing optimization is relatively straight forward. However, the challenge lies in the creation of the feasible tanker cycle column matrix $A_{N,C}$ among the many possible tanker routes. The algorithm used to generate tanker cycles and the process of applying constraints to limit the number of feasible cycles has already been discussed in Section 5.4. There are two main operational limitations that apply; tanker fuel capacity and tanker-cruiser rendezvous, both also already been explained in detail in previous sections of this chapter. This section specifies the mathematical formulation of these and other operational constraints that define the feasible tanker cycles of matrix $A_{N+2,C}$.

In- and outflow constraint
Equations 5.22 and 5.23 ensure that each tanker cycle starts and terminates at the tanker base which are indicated with nodes 0 and $N+1$. These nodes are not included in $A_{N,C}$ but are needed to compute the tanker operating per cycle as is displayed in Figure 5.16.

$$A_{0,c} = 1 \qquad \forall c \in C \tag{5.22}$$

$$A_{N+1,c} = 1 \qquad \forall c \in C \tag{5.23}$$

Constraint to prevent empty tanker route
All feasible tanker cycles C must at least contain one cruiser, this is described by Equation 5.24.

$$\sum_{n \in N} A_{n,c} \geq 1 \qquad \forall c \in C \tag{5.24}$$

Time window duration constraint
As is shown in previous section, the time window is determined to be 10 minutes at a tanker cruise speed of 0.8 Mach without the presence of wind. The model uses normalized cruiser ground speed with respect to this tanker cruise speed to determine time window duration for cruisers with deviant speed. Equation 5.25 determines the time window duration for all cruisers. In this way both boundaries of the time window are located on the same position for all cruisers which prevents exceeding the tanker operating range. Depended on wind direction with respect to cruiser heading, a $+$ or $-$ sign is used to compute the cruiser ground speed.

$$T_{i,c_{exit}} = T_{i,c_{entry}} + T_w * \left(V_{cr_i} \pm V_w\right)/V_t \qquad \forall i \in I, \forall c \in C \tag{5.25}$$

Refuelling within time window constraint
All cruisers in a tanker cycle have to be refuelled within the applied time window for a tanker cycle to be feasible. Equation 5.26 describes that the refuelling start time of every cruiser lies between cruiser time window entry and exit.

$$T_{i,c_{entry}} \leq T_{i,c_{actual}} \leq T_{i,c_{exit}} \qquad \forall i \in I, \forall c \in C \tag{5.26}$$

Entry boundary time window constraint
A cruiser can not be served before its arrival at the time window entry point (i.e. earliest refuelling moment). If the tanker is at this point before the cruiser, the tanker has to wait at the time window boundary until the cruiser arrives after which the refuelling process can be started. For the cruiser to be refuelled not earlier than the time window entry point Equation 5.27 must hold.

$$T_{i,c_{actual}} = T_{i,c_{entry}} \qquad \forall i \in I, \forall c \in C, \text{ if } \; T_{i-1,c_{actual}} + T_{rf} + t_{i,c_{tw-entry}} < T_{i,c_{entry}} \tag{5.27}$$

Exit boundary time window constraint
Since a time window is applied for the refuelling of cruisers, a tanker cycle can only be feasible if the refuelling procedure of all cruisers in the cycle starts within the time window. Equation 5.28 ensures that the next cruiser can only be refuelled by the tanker if the arrival time of the tanker at the time window exit boundary is smaller or equal than the arrival time of the cruiser at this identical location.

$$T_{i-1,c_{actual}} + T_{rf} + t_{i,c_{tw-exit}} \leq T_{i,c_{exit}} \qquad \forall i \in I, \forall c \in C \tag{5.28}$$

Point of intersection before exit boundary time window constraint
For a tanker cycle to be feasible, the tanker-cruiser rendezvous point for all cruisers in the cycle has to be located before the latest refuelling moment (i.e. exit boundary of the time window). How this point of intersection between tanker and cruiser is determined for aircraft on identical tracks as well as dissimilar tracks has already been discussed in Section 5.5. Equation 5.29 constraints the intersection time to be before the time window exit boundary.

$$T_{i-1,c_{actual}} + T_{rf} + t_{i,c_{intersect}} \leq T_{i,c_{exit}} \qquad \forall i \in I, \forall c \in C \tag{5.29}$$

Tanker fuel capacity constraint
The final constraint prevents that the total amount of fuel used per tanker cycle exceeds the tanker fuel capacity. This total fuel can be decomposed in the combined offload fuel for all cruisers in the cycle and the fuel usage by the tanker itself. Both cruiser and tanker fuel calculations have been explained in Section 5.2.3. This fuel capacity constraint is displayed in Equation 5.30.

$$\sum_{i \in I} D_{i,c} + \sum_{i \in I} U_{i,c} + \sum_{i \in I} U_{(i-1,i),c} + U_{(I,I+1),c} \leq Q_T \qquad \forall c \in C \tag{5.30}$$

Since the column matrix with feasible tanker cycles is built up adding a cruiser in each iteration, these described constraints have to be applied every iteration. It can be interesting to know how the growing size of the column matrix impacts the computational time of the problem. Since the amount of columns added the to matrix in each iteration is not only depended on the number of cruisers in the scenario but also on cruiser schedule specifics as inter-arrival times, track location and cruise speed, no precise computation is possible on the problem computational time. However, what can be exactly computed is the total number of columns added to the problem in this iterative approach compared to predefining all tanker sequences beforehand. In Chapter 4 a comparison between these two approaches for the number of columns added to the column matrix $A_{N,C}$ is discussed.

5.6.5. Variable operating costs
With the result of optimized aggregated tanker operating time, part of the direct operating cost can be determined for both staged concept and direct flight. According to Belobaba et al. [2009] DOC can be defined as the total of flight operations costs, maintenance and overhaul costs, depreciation and amortisation. This DOC is further split into variable and fixed cost. Fixed cost are discussed in more detail in Section 5.7.5. Considered under variable operating cost are: fuel, flight crew, airport/navigation taxes and fees, and airframe, engine and tanker boom maintenance. According to [IATA, 2016] fuel cost gain a 20% share of total operating cost. Since fuel cost take up this large share and this study investigates the feasibility of the in-flight refuelling concept, it is decided to first include only fuel cost in the variable cost calculations. If the concept seems profitable, other costs can be added to get better insight in total cost. The total amount of fuel needed for identical flight schedules in both direct operations and air-to-air refuelling are calculated and compared. Results of this fuel usage comparison between the refuelling concept and traditional flight operations are elaborated on in Chapter 7.

5.6.6. Assumptions and model limitations
This designed model makes use of a number of assumptions which limit the model of replicating a real-life traffic environment. Most of these assumptions are made to make the model more accessible and generate computational results in reasonable time without being too far-removed from reality.

- This model can be defined as static and deterministic since tanker routes do not change while they are in execution and all input variables are known in advance. Therefore, this model is not able to deal with real-life dynamic processes such as delays or other schedule disruptions. Keeping in mind the goal of this study, to investigate the feasibility of the refuelling concept in a real-life traffic environment, it still can be a good first step to test concept's profitability. With positive concept outcomes, dynamic and stochastic aspects can be added to make scenarios more realistic. However, it will lead to inferior results. For now, the following assumptions are made regarding uncertainty:
  - In case of a missed cruiser by a tanker due to a schedule disruption, the cruiser can always land at the tanker base to get refuelled.
  - It can occur that due to bad weather conditions cruiser refuelling can not take place. When this is known well in advance, cruisers can take all fuel needed for a direct flight on-board. If conditions worsen with the cruiser already en-route, it can be decided that refuelling takes place further from the tanker base or the cruiser can fly to another airport and land to get refuelled on the ground.
- Instant tanker direction changes are assumed just like instant tanker cruise speed change between refuelling segments.
- Hard time window boundaries apply. Since time in the model is continuous it implies that if a cruiser can be refuelled one second past the latest refuelling moment, this combination is not accepted and removed from the set of feasible solutions.
- It is decided to use homogeneous cruiser speeds along the same track. This not only simplifies the computation but since variations in cruise speeds among cruisers are relatively small and tanking procedure duration is limited, no large impact on tanker operations is expected.
- The model is based on modelling one flow of traffic at a time. However, fixed cost are calculated per day. To simulate a day of traffic, fuel cost are computed for a westbound and eastbound traffic flow.
- The cruiser sequence in the generated cruiser flight schedule is not optimized. An optimization of arrival times, cruiser types, OD-pairs and cruiser track number can possibly improve concept's results.
- It is chosen to split up the tanker optimization in two separate parts. First tanker routing followed by tanker scheduling. This implies that there is no restriction on the number of available tankers. Since feasibility is tested, an unlimited number of available tankers is assumed.
- There are multiple tanker types included in the model, however only a single tanker type can be selected for tanker operations. This limits the model to the use of a homogeneous tanker fleet during operations.

5.6.7. Model output

With the set of optimal tanker cycles found, coinciding tanker fuel consumption can be computed by subtracting fuel offload volumes from the total fuel used for a particular tanker route. Adding cruiser fuel used during the first flight stage, the total amount of fuel for the cruiser-feeder system can now be compared with the fuel amount of direct cruiser flight. Results on fuel usage and the impact of several input parameters on concept performance are thoroughly presented in Chapter 7. Besides fuel consumption and the total tanker operating time, the start and finish time of each selected tanker cycle are the other outputs of this tanker routing optimization. Taking the example of Figure 5.16, the minimal total tanker operating time is 278 minutes when cycles c_2,c_3 and c_{11} are selected. The next step is to determine the amount of tankers that is needed to complete these cycles. This question forms the basis of the tanker assignment optimization model which is described next.

5.7. Tanker assignment model

The second optimization stage, where tankers are assigned to a set of optimal tanker cycles in terms of tanker operating time is discussed in this section. The purpose of this optimization is to determine the minimum number of tankers required to serve all tanker cycles. From Figure 5.2 the tanker assignment optimization model can be viewed in relation to the overall methodology. Similar to the tanker routing optimization, this assignment model makes use of a set-partitioning formulation. However, complexity is modest compared to the first stage of optimization. The mathematical notation and the formulation of decision variable, objective function and constraints is explained step by step in Sections 5.7.1, 5.7.2, 5.7.3 and 5.7.4 respectively.

5.7.1. Notation

The notation as stated in Table 5.6 is used for the tanker assignment optimization model. The number of selected tanker cycles is known and tankers have have to be assigned to these cycles according to a traditional SP formulation as used in the tanker routing model. As mention before, it is assumed that an unlimited number of tankers can be assigned. The decision variable, objective function and constraints used to perform the optimization are discussed next.

Table 5.6: Notation and definition for the tanker assignment model

Notation	Definition
$B_{R,S}$	column matrix including set of feasible tanker schedules S for set of optimal tanker cycles R
S	set of tanker schedules including one or more optimal tanker cycles tanker
R	set of optimal tanker cycles $\subset C$
$T_{r_{start}}$	starting time of tanker cycle r
$T_{r_{end}}$	finishing time of tanker cycle r
TAT	fixed tanker turnaround time [30 min]

5.7.2. Decision variables

The goal of the tanker assignment optimization is to find the minimum number of tankers that is needed to complete the set of optimal tanker cycles found in the first optimization. The tanker assignment model makes use of only a single decision variable:

y_s: feasible tanker schedule s with at least one tanker cycle r included starting and terminating at the tanker base.

y_s is a binary decision variable which has a value of one when the feasible tanker schedule is included in the optimal solution and zero otherwise.

$$y_s = \{1, 0\} \quad , \qquad \forall s \in S \tag{5.31}$$

5.7.3. Objective function

In this scheduling problem, the decision variable is associated with a tanker schedule that includes one or more cycles resulting from the tanker routing optimization. A tanker schedule is defined as the schedule of tanker cycles assigned to one tanker. The objective function of this optimization is to minimize the total cost (i.e. number of tankers in homogeneous fleet) to complete the set of optimal tanker cycles.

$$\text{Minimize number of tankers} = \sum_{s \in S} y_s \tag{5.32}$$

The number of tankers needed is equal to the number of selected tanker schedules y_s to complete all tanker cycles r. Since a homogeneous tanker fleet is used, tanker costs are constant for all required tankers. The minimization of the number of tankers will lead to minimum tanker cost. Therefore, no cost factor per selected tanker schedule is included in Equation 5.32. How tanker cost are determined is discussed later in this section.

Figure 5.17 shows an example of a set of tanker cycles R that provide the minimum tanker operating time in the first optimization. Each of these cycles has a starting time $T_{r_{start}}$ and finishing time $T_{r_{end}}$. Tanker cycles are ordered on tanker cycle start time. Column matrix $B_{R,S}$ includes the feasible tanker schedules S incorporating one or more tanker cycles. The start and finishing times of each tanker route are defined in minutes and are continuous.

Tanker cycle start and end times:

r_1 : T_{start} = 30 min T_{end} = 134 min
r_2 : T_{start} = 65 min T_{end} = 176 min
r_3 : T_{start} = 92 min T_{end} = 194 min
r_4 : T_{start} = 168 min T_{end} = 276 min
r_5 : T_{start} = 182 min T_{end} = 255 min

$\mathbf{B_{R,S}}$

$$
\begin{array}{c} \\ r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \end{array}
\begin{array}{c} \begin{array}{ccccccc} s_1 & s_2 & s_3 & s_4 & s_5 & s_6 & s_7 \end{array} \\
\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix} \end{array}
$$

Figure 5.17: Example of generating the column matrix with feasible tanker schedules S from a subset of tanker cycles that is the result of the tanker routing optimization

What can be noticed is that column matrix $B_{R,S}$ has a limited number of tanker schedule columns which not include all combinations of tanker cycles. Applied constraints restrict the number of generated feasible tanker schedules. These constraints are now discussed in more detail.

5.7.4. Constraints

Set-partitioning constraint

The same constraint as during the tanker routing optimization is applied in this model. The equality constraint that ensures that every tanker cycle is assigned to a tanker schedule. This constraint includes the column matrix $B_{R,S}$ where the set of feasible tanker schedules are the columns in the matrix and all rows represent the tanker cycles. Tanker cycles R included in a tanker schedule s are given a value of one and zero otherwise.Equation 5.33 show this equality constraint that ensures that the number of tankers to complete all cycles is at most equal to the number of tanker cycles.

$$\sum_{s \in S} B_{r,s} y_s = 1 \qquad \forall r \in R \tag{5.33}$$

For the example of Figure 5.17, a possible combination of selected columns that fulfils this requirement would be $[s_2, s_3, s_4, s_7]$. This implies that four tankers are needed for all tanker cycles to be served by a tanker.

Constraint to prevent empty tanker schedules

The set of tanker schedules must at least contain one tanker cycle to prevent the generation of empty schedules. This is described by Equation 5.34.

$$\sum_{r \in R} B_{R,S} \geq 1 \qquad \forall s \in S \tag{5.34}$$

Turnaround time constraint

A tanker cycle can not be included in a tanker schedule when this tanker cycle start time lies before the end time of a previous cycle. Besides, as is described by Equation 5.35, a fixed turnaround time TAT of 30 minutes at the tanker base must be accounted for in between multiple cycles in a tanker schedule. This is the time needed to prepare the tanker for the next cycle. Since tanker cycles are arranged on ascending cycle start time, it is prevented that tankers serve earlier starting cycles after finishing a cycle with later starting time.

$$T_{r,s_{end}} + TAT \leq T_{r+1,s_{start}} \qquad \forall r \in R, \forall s \in S \tag{5.35}$$

5.7.5. Fixed operating cost

With the minimum number of tankers needed to complete all tanker cycles selected from the tanker routing optimization, the total cost of the civil aerial refuelling concept can be estimated. Besides fuel cost as representation of variable operating cost, fixed costs are accounted for as well. Flight crew salaries, tanker depreciation, aircraft rentals, insurances, and part of the maintenance cost can all be categorized as fixed operational cost. In this study only tanker depreciation cost is accounted for to represent fixed operating costs.

To determine tanker depreciation cost, aircraft list prices are required for all tankers taken up in the model: two conceptual tanker designs and three existing military tankers. For the two conceptual designs list prices are not available. For the three military tankers, the use of available list prices would be misleading due to costly high-end military systems on-board of those tankers. Therefore, it is decided to use list prices of existing equivalent commercial aircraft. For both RECREATE tankers an up-to-date reference aircraft is chosen of similar range and size. Since the Boeing 737-600, used for performance data, is a fairly old commercial aircraft, this is not selected for list price indication. Instead, a Boeing 737-7 MAX is selected, which is slightly larger but of comes close to the technology level of both conceptual tankers. The list price of this aircraft is US$90,7 million [Boeing, 2016]. Other tankers that are included in the model are the A310MRTT, KC-46 and A330MRTT. All of these existing military tankers are based on a commercial equivalent, namely the A310, B767 and A330 respectively. To translate acquisition cost into a daily depreciation cost, the assumption is made that a tanker's lifetime is 20 years. Depreciation cost are computed per day so they can be added to the daily variable costs (i.e. fuel cost). Both acquisition and depreciation cost of all tanker types can be viewed in Appendix C.

To recap this chapter on methodology, the overall structure of the model is discussed. Applied methods used for scenario generation of cruiser flight schedules and both optimization stages are explained in detail. Before scenarios can be tested and results can be compared, methods used in this study are verified if they are correct. Next chapter will analyse adopted approaches to confirm if used methods can be justified.

6 Verification and validation

In this chapter verification and validation of used methods in the methodology and model results are discussed. Where verification checks if the model fulfils all requirements, validation is performed to ensure that the results provided by the model meets all needs and that model specifications were correct in the first place.

6.1. Scenario generation

6.1.1. Fuel calculations

The model uses multiple fuel calculation methods or tools since all tools have their own benefits over other methods. For cruiser fuel computations Fuelplanner [2016] is used to compute both trip and reserve fuel as well as cruiser flight time. Since this tool displays the reserve fuel for all cruiser types in the model, it can be easily used to compute stage fuel for cruisers between OD-pairs. However, the calculation methods behind the Fuelplanner tool are unclear. Therefore it is investigated if the outputs of the tool make sense compared to the two other methods used. In Table 6.1 the various fuel calculation methods are compared based on a flight between JFK and LHR. Two different aircraft types are used for this comparison, an A330-300 and B747-400 respectively.

Table 6.1: Validation of various fuel calculation methods

JFK-LHR [2989 NM]	Trip fuel [kg]	Delta trip fuel [%] w.r.t. Fuel planner	Cruise fuel [kg]	Delta cruise fuel [%] w.r.t. BADA	Reserve fuel [kg]	Total fuel [kg]
A330-300						
Fuel planner	44,205	0%	-	-	7,187	51,392
BADA	38,225	-13.5%	32,836	0%	-	-
Breguet	44,100	-0.2%	32,712	-0.4%	-	-
B747-400						
Fuel planner	72,358	0%	-	-	11,765	84,123
BADA	60,922	-15.8%	53,196	0%	-	-
Breguet	67,529	-6.7%	50,827	-4.5%	-	-

It can be concluded from Table 6.1 that the Fuelplanner tool and Breguet equation method show similar results for both aircraft comparing trip fuel, while BADA results are more off. BADA does not include fuel fractions other than cruise, climb and descent into their calculations. This could be the reason for BADA results to diverge. This suspicion is affirmed looking at cruise fuel, where BADA and Breguet perform similar. Comparing results, it can be concluded that all three methods can be used next to each other. Where the Fuelplanner tool is used for comparison of cruiser fuel for direct and staged operations, the Breguet endurance equation is applied for tanker endurance calculations. BADA is particularly very useful to compute accurate integrated masses for climb and descent, which is used to determine tanker fuel for climb and descent. Furthermore, additional fuel used by cruisers to descent to refuelling altitude and climb back to cruise flight level is also computed using BADA. Another implementation of BADA is to check, based on aircraft flight envelopes, if the used cruiser types are physically able to maintain cruise ground speeds at lower refuelling altitude.

As mentioned in previous chapter, cruisers use additional fuel during the complete refuelling procedure at reduced altitude since the cruiser has to climb back to cruise altitude after just being refuelled. To check if this additional fuel is relevant and has to be accounted for in the fuel offload volume, two situations are compared. As can be seen in Figure 6.1, cruiser refuelling at cruise altitude and at reduced refuelling altitude, including a descent and climb phase are compared. Table 6.2 shows the comparison in cruiser fuel consumption between both operations.

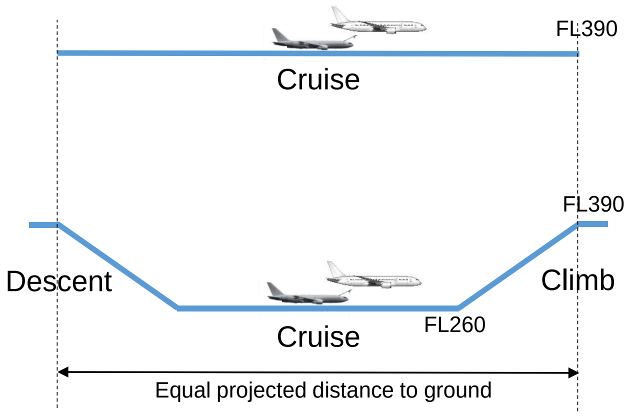


Figure 6.1: Schematic of two situations where refuelling takes place at cruise altitude or at a lower refuelling altitude

Table 6.2: Comparison of cruiser fuel usage during the refuelling segment for refuelling at reduced altitude and cruise altitude

A330-300 LHR-ORD	**Segment**	**Distance (NM)**	**Fuel used (kg)**
Remain at cruise level (FL390)			
	CRUISE	332	3357
Descent to lower altitude (FL260)			
	DESCENT	40	76
	CRUISE	195	2648
	CLIMB	97	1698
	TOTAL	332	4422
Δ fuel between altitudes [%]			**32%**
Cruiser offload volume [kg]			19,686
Additional fuel as percentage of cruiser offload volume			**5%**
A330-300 LHR-LAX	**Segment**	**Distance (NM)**	**Fuel used (kg)**
Remain at cruise level (FL390)			
	CRUISE	318	3215
Descent to lower altitude (FL260)			
	DESCENT	40	76
	CRUISE	194	2648
	CLIMB	84	1469
	TOTAL	318	4193
Δ fuel between altitudes [%]			**30%**
Cruiser offload volume [kg]			7,848
Additional fuel as percentage of cruiser offload volume			**12%**

Two different OD-pairs are selected in combination with the A330 cruiser to compute the amount of fuel needed for the cruiser. Results show that refuelling at lower altitude leads to a third more fuel usage by the cruiser. Looking at the impact the additional amount of fuel has on the total cruiser fuel offload volume, it can be concluded that the impact is significant. Obviously, impact increases for shorter second stage lengths as is confirmed by the results in Table 6.2. Since this fuel is predominantly used in the cruiser climb back to refuelling altitude, it has to be accounted for in the cruiser fuel offload volume.

6.1.2. Wind model

The model wind is based on three data sources which are compared to check if presented values are valid. Most detailed information is provided by Windytv [2016] which makes use of an interactive wind map where wind speeds all around the globe can be viewed. The wind map is based on a combined forecast of both global and local wind model sources. The wind map used for wind modelling on both refuelling and cruise altitude is based on two global models:

- ECMWF (European Centre for Medium-Range Weather Forecasts), which provides a resolution of ~9 km. The forecast output is produced every three hours.
- GFS (Global Forecast System), which has a resolution of ~13 km. The forecast output is produced every hour.

The benefit of this wind model is the fact that historical wind data can easily be accessed. In this way a statistical overview can be made of wind direction and velocity. The information provided by Windytv [2016] is compared to jet stream wind information provided by Turbulence-forecast [2016] for an altitude of 30,065 ft (9166 m). Also here, information is based on the use of the GFS model. The third method used, to confirm if both models provide accurate forecasts, is by comparing aircraft ground speed differences for opposite traffic across the North Atlantic [Flightradar24, 2016]. Appendix A provides an overview of results found by these methods. The conclusion can be drawn that results are comparable and that data from Windytv [2016] can be used for retrieving wind data used for the model. As mentioned in Chapter 5, the wind field applied to the model is homogeneous to simplify computations and reduce computational effort. Since refuelling time is limited and wind speed and direction is more or less constant in the refuelling area, as can be seen in Appendix A.

6.1.3. Point of interception

The method used to determine the point and time cruiser and tanker meet to start the refuelling procedure is explained in detail in Chapter 5. It was mentioned that the formula used for computing the rendezvous point between cruiser and tanker on different tracks was not exact. The used method in this study is compared with the exact vector decomposition method by means of a numerical example. Figure 6.2 depicts the schematic with a tanker and cruiser on different tracks. Tanker velocity can be decomposed in an x and y component as stated in Equation 6.1.

$$V_{t_{act}} = \sqrt{V_{t_x}^2 + V_{t_y}^2} = \sqrt{V_t^2 + 2V_w V_t cos(\alpha) + V_w^2} \quad (6.1)$$

$$V_{t_{act}} t_{intersect} = \sqrt{V_t^2 + 2V_w V_t cos(tan^{-1}(\frac{c}{b})) + V_w^2} t_{intersect} = (V_{cr} \pm V_w) t_{intersect} \quad (6.2)$$

A numerical example with typical values for known parameters is provided in Table 6.3. Comparing both methods for this numerical example provides identical results. Since time windows are relatively small in combination with tracks running closely next to each other, the difference in angle α to both time window boundaries is also small. Therefore taking the average of both angles as the $V_{w,t}$ will give good results. The reason for not using vector decomposition is due to the large complexity of rewriting Equation 6.2 for $t_{intersect}$. However, what can be done, with all other variables known, is to check the value for $t_{intersect}$ and compare results with the approximation used in the model.

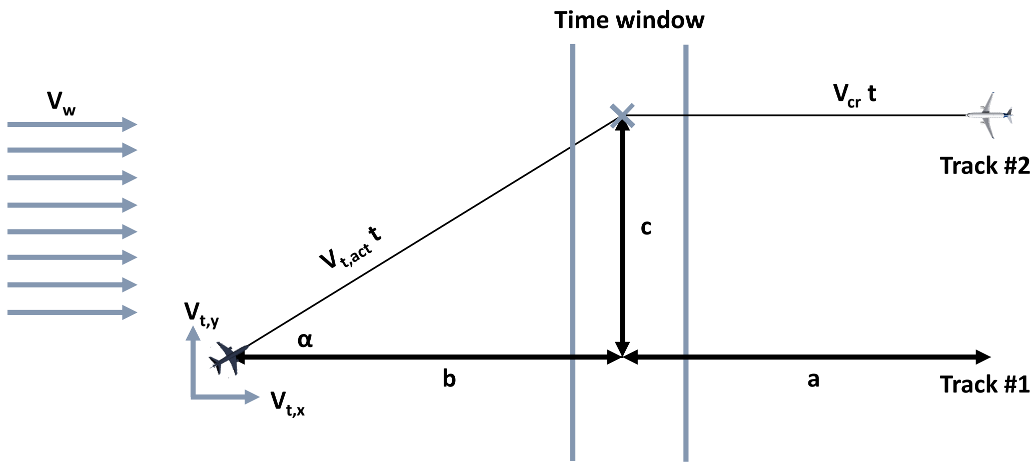


Figure 6.2: Schematic top view with tanker and cruiser on various tracks

Table 6.3: Result of numerical example for a comparison between methods determining tanker and cruiser rendezvous point for dissimilar tracks

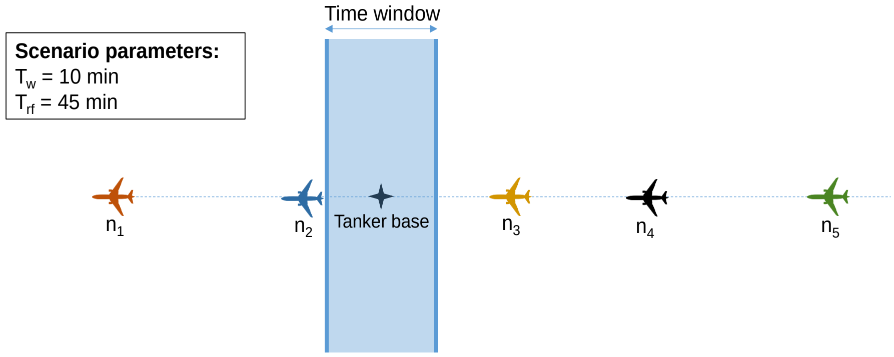
Input parameters	
T_{rf} [min]	25
T_w [min]	10
c [NM]	30
$a+b$ [NM]	390
V_w [m/s]	30
V_t [m/s]	250
V_{cr} [m/s]	240

	Vector decomposition	**Used method**	**Δ [%]**
$t_{tw-entry}$ [min]	22.1	22.1	0%
$V_{t_{actual}}$ [m/s]	274.7	274.6	-0.04%
$t_{tw-exit}$ [min]	13.3	13.3	0%
$V_{t_{actual}}$ [m/s]	277.2	277.1	-0.04%
$t_{intersect}$ [min]	23.4	23.4	0%
$V_{t_{actual}}$ [m/s]	274.7	274.6	-0.04%

6.2. Optimization models

As mentioned in Chapter 4, the presented model is the result of an iterative process where the model is gradually built with growing complexity. The basis of this research is the work by Lith [2012], who tried to solve a simplified traffic representation of cruiser traffic over the Atlantic. To check if the model functions as it is required to, the basic model is tested. An identical case is built as was done by Lith [2012], with the only difference being the problem formulation. Figure 6.3 depicts the scenario situation of the basic problem. This simple representation includes 11 cruisers flying on a single track with uniform cruise speed. No wind is incorporated in the scenario. Cruiser arrival times at time window entry are included in the figure. Furthermore, a 10 minute time window and 25 fixed refuelling time apply in the scenario.

Figure 6.4 shows the results of the optimization for the scenario created by Lith [2012]. In the figure, the arrival times of the tanker at each node including base departing time and return time at base are indicated. Results show that four tanker cycles are needed to serve all cruisers in the schedule. Besides uniform cruiser speed and the use of a single track, the assumption is made that the fuel offload provided by the tanker is uniform and up to three offloads can be provided per cycle. The objective of this optimization is similar to described in the methodology: to find the minimum aggregated tanker time of the individual cycles including all cruisers. The solution to this problem found by Lith [2012] was 721 minutes, which is five minutes worse than this research found. The cycles are checked by hand to ensure the found solution is valid. This shows that the created model provides results that comply with



Cruiser	Arrival time [min]
1	49
2	60
3	91
4	113
5	137
6	166
7	200
8	220
9	254
10	273
11	304

Figure 6.3: Schematic of the basic model scenario including 11 cruisers on single track with uniform cruise speed

all active constraints. The improved result that is found can be explained by the fact that Lith [2012] had one or more errors in its model that restricted the problem more than intended.

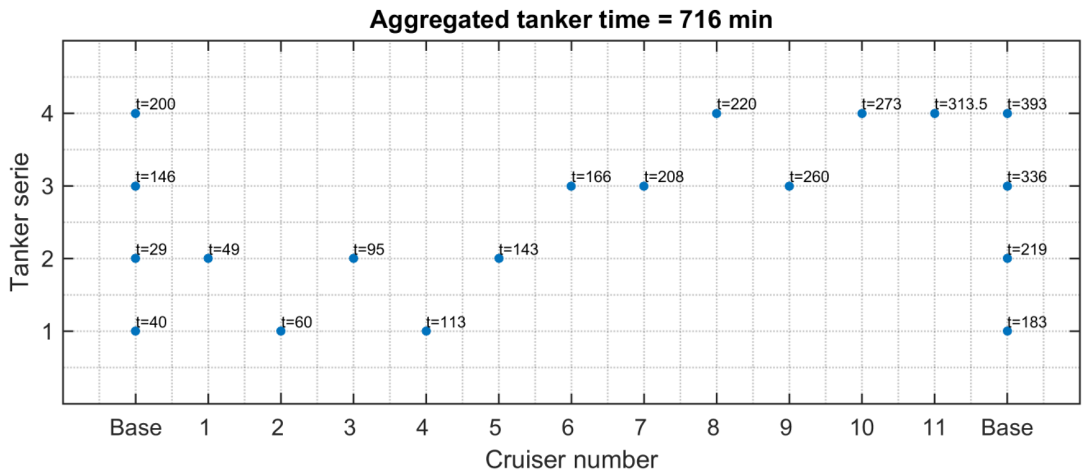


Figure 6.4: Tanker routing optimization for problem as solved by [Lith, 2012]

From this initial problem, complexity is added to the model, including multiple tracks, variety in cruiser speeds, differing fuel offloads and influence of wind. While implementing this model additions, the model is constantly checked for errors between each addition. Small problem sizes can be checked by hand which can be done up until a certain problem complexity. Increasing complexity means increased error sensitivity and more solutions have to be checked to ensure all combinations are covered. When this is completed, a large scale problem size is taken and solutions are checked on three main parameters. First, the set of tanker cycle results is checked to see if no cruisers are within the refuelling time of previous cruisers. Another focus point is to check if all cruisers are refuelled within their time window. Last, offload volumes are checked for each series. An example of this is displayed in Table 6.4 for a scenario including 50 cruisers in combination with the A310MRTT tanker.

What can be noticed is the tanker efficiency, which is the ratio between the fuel offload volume of a tanker cycle and the fuel used by the tanker itself. It can be detected that this ratio is rather low for the A310MRTT tanker. Tanker efficiencies lie in a range between 1 and 3 independent of the number of cruisers included in the cycle. Comparing tanker efficiency of this tanker with results found by Li and Rocca [2014] for the identical tanker, similar values are found. However, comparing the performance

Table 6.4: Tanker and offload fuel for a scenario including 50 cruiser travelling in westbound direction with a A310MRTT tanker

Tanker cycle	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Takeoff weight	113221	160829	159629	159249	158455	160702	156985	155494	157887	163985	128314	148502	163931	160514	162063	162491	163185	163224	162178	157397	155029
Landing weight	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064	92064
Total fuel	21157	68765	67565	67185	66391	68638	64921	63430	65823	71921	36250	56438	71867	68450	69999	70427	71121	71160	70114	65333	62965
Cruisers in	45	1	2	4	6	8	11	12	26	33	38	40	3	5	7	9	10	14	18	19	23
tanker cycle		15	13	22	20	25	24	27	41	46	49	50	21	16	17	28	29	32	30	31	34
													37	36	35	39	42	43	44	47	48
Offload weight per	11907	34213	27027	14119	34018	14119	27027	27027	34018	4133	8530	8530	27027	7848	8084	16389	19686	31412	7969	15626	14119
cruiser [kg]		15626	21920	33496	11907	33496	14119	14119	11968	46703	7969	27530	8084	27530	27530	16032	8530	4133	8530	9476	8530
													4133	4133	8530	4133	11968	5889	27530	11907	11907
Total offload weight	11907	49839	48947	47615	45925	47615	41145	41145	45986	50835	16499	36060	39244	39512	44145	36553	40184	41434	44029	37008	34555
Tanker fuel weight	9250	18926	18618	19570	20466	21023	23776	22285	19837	21086	19751	20378	32624	28939	25854	33873	30937	29726	26085	28325	28410
Tanker efficiency	1.29	2.63	2.63	2.43	2.24	2.26	1.73	1.85	2.32	2.41	0.84	1.77	1.20	1.37	1.71	1.08	1.30	1.39	1.69	1.31	1.22

of the RECREATE conceptual conventional tanker design results are further apart. According to Li and Rocca [2014], the designed tanker efficiency of this tanker lies between 7 and 8. Found efficiencies of this tanker are shown in Table 6.5 for a scenario with 21 cruisers. Results show inferior efficiencies for this tanker. Depending on the fuel offload volume and the number of cruisers included in the tanker cycle, efficiency can come close to ratios found by Li and Rocca [2014]. It can be concluded that for this smaller tanker, efficiency fluctuates. This indicates a major difference compared to previous studies that use uniform fuel offloads and a constant number of cruisers included per cycle.

Compared to the A310MRTT tanker, this conceptual tanker can be more efficient. Since tanker size of these conceptual designs is tailor-made for the use in combination with conceptual cruisers, tanker size can be insufficient for flight schedules with current aircraft types. Therefore it will not always be possible to deploy the RECREATE tankers for a generated cruiser flight schedule.

In general, as the number of cruisers in the tanker cycle increases, tanker efficiencies drop for all tankers. This makes sense due to longer airtime and limited fuel capacity. As mentioned before, the two RECREATE tankers can not be used for all cruiser OD-pairs due to lacking fuel capacity. Since currently available (larger) tankers are not optimized in size and performance for civil refuelling operations, efficiencies are low.

Table 6.5: Tanker and offload fuel for a scenario including 21 cruiser travelling in westbound direction with a RECREATE conventional tanker

Tanker cycle	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Take-off weight [kg]	61059	34672	61929	60465	30720	42877	54500	55214	50661	59953	62764	66080	60369	58281
Landing weight [kg]	21561	21561	21561	21561	21561	21561	21561	21561	21561	21561	21561	21561	21561	21561
Total fuel [kg]	39498	13111	40368	38904	9159	21316	32939	33653	29100	38392	41203	44519	38808	36720
Cruisers in cycle	1	4	8	10	12	14	20	2	3	5	6	7	9	11
								13	15	17	16	18	19	21
Offload weight per	34213	8084	34018	33496	4133	16032	27530	14119	14119	18495	21920	27530	14119	8530
cruiser [kg]								8530	4133	8530	8530	5889	11907	15626
Total offload weight [kg]	34213	8084	34018	33496	4133	16032	27530	22649	18251	27025	30450	33420	26026	24155
Tanker fuel weight [kg]	5285	5026	6350	5408	5026	5285	5408	11005	10848	11367	10753	11099	12782	12565
Tanker efficiency	6.47	1.61	5.36	6.19	0.82	3.03	5.09	2.06	1.68	2.38	2.83	3.01	2.04	1.92

7 Case study

This chapter presents the results of this research. By means of a case study the process of result generation is displayed. First, in Section 7.1 a general overview is given of the generated results by means of a case. Step-by-step the produced results are gone over. Section 7.2 provides a detailed observation and analysis of case results. Furthermore, a sensitivity analysis is performed to get insight on the factors of influence for the in-flight refuelling operational concept.

7.1. Description and context

In previous chapter, the working principles of the modelled operational concept are explained. In this case study, a larger amount of cruisers is included in the model to provide results for more realistic traffic numbers. The input parameters that are discussed in Chapter 5 are listed in Table 7.1 including values that are used for the case study.

Table 7.1: Case study specific variables for scenario generation

Definition	Case study values
# Days in simulation	1
# Cruisers in scenario	125
# Active refuelling tracks	8
# Traffic directions per day	2
Track location	Base
# OD-pairs	12
# Tanker types	1 (A310MRTT)
# Cruiser types	7
Wind direction & speed	No wind

This case study simulates a single day of trans-Atlantic traffic including 125 cruisers in both traffic directions. A single day of traffic consists of one eastbound and one westbound traffic flow. All twelve OD-pairs are included for each day of simulation with tracks outlined directly over the tanker base, where eastbound traffic having a 70° heading and westbound 250°. A single tanker type is used, the A310MRTT, which has sufficient capacity to ensure that every flight can be refuelled. The combination of the use of large passenger aircraft with a long second stage length makes that both RECREATE designs can not be used in this case study due to insufficient fuel capacity. The flights between OD-pairs are distributed over the seven available cruiser types resulting in the OD demand matrix of Table 7.2, which shows the distribution of flights for this typical scenario of the case study. Additional scenarios are generated to investigate the concept performance under various conditions and are discussed in detail in Section 7.2. For now, this case study serves as an example of the process of result generation and provides a first insight in concept performance.

Table 7.2: OD demand matrix per aircraft type for a scenario of the case study

OD-pairs	Aircraft type							
	B738	**B752**	**B763**	**A333**	**B744**	**B788**	**B772**	**Total**
LHR-JFK	3	5	2	3	4	4	5	26
LHR-ORD	-	3	3	2	5	2	4	18
LHR-MIA	-	2	3	-	3	2	1	11
LHR-LAX	-	-	1	1	1	1	4	8
CDG-JFK	2	-	-	3	3	1	3	12
CDG-ORD	-	-	6	-	1	1	1	9
CDG-MIA	-	-	1	-	-	1	3	5
CDG-LAX	-	-	-	2	1	-	-	3
FRA-JFK	-	-	2	2	2	1	6	13
FRA-ORD	-	2	2	-	3	-	3	10
FRA-MIA	1	1	1	-	2	-	-	5
FRA-LAX	-	-	1	-	2	-	1	4
Total	6	13	25	8	27	13	33	125

For the scenario, four main tracks are active with two cruise flight levels per traffic direction. Referring to Figure 5.9, every main track has two refuelling side tracks, one for each cruise flight level. Since various cruiser types are included in the scenario with a difference in cruise speed, cruiser flights are grouped based on cruise speed. With the assumption that all cruisers on identical main track and flight level have similar cruise speed, it means in practice that the slowest cruisers fly at a different track than faster cruisers. How aircraft are divided over the main tracks and cruise flight levels is displayed in Table 7.3. This table shows the cruiser distribution over the side tracks for traffic in eastbound direction. Since for this case study identical flight schedules are generated for both flight directions to allow a fair comparison, the data of Tables 7.2 and 7.3 is valid in either direction. Cruiser arrival times at time window entry for this scenario can be found in Appendix D. Also here applies that arrival times are similar for both traffic directions.

Table 7.3: Cruisers divided over refuelling tracks with original flight level and cruise speed

Side track	**Cruise altitude**	**Cruise speed [M]**	**Aircraft type**							
			B738	**B752**	**B763**	**B788**	**B772**	**B744**	**A333**	**Total**
1	FL390	0.84				2	9	5		16
2	FL370	0.84				3	10	3		16
3	FL390	0.80		6	13					19
4	FL370	0.84				3	8	5		16
5	FL390	0.82							16	16
6	FL370	0.82							17	17
7	FL390	0.78	6							6
8	FL370	0.80		7	12					19

Cruiser fuel offload volumes for this scenario are determined without the effect of wind during cruiser flight. In Table 7.4, cruiser fuel usage of staged operations is compared to fuel needed for direct operations between the same OD-pairs. The detour that is needed to receive a refuelling over Gander is incorporated in the calculations. A cruiser fuel gain is achieved of around 7% compared to direct operations depending on the direction of traffic. Tanker fuel usage is not included in these calculations. The difference in fuel gain for both traffic directions can be attributed to the location of Gander as tanker base with respect to the OD-pairs included in the model. Since West European airports included in the model have more or less similar distance to Gander, the average second stage length of towards these airports for eastbound flight is similar to the individual airports. Distances to US airports vary more, with the average distance of the second stage length in westbound direction being smaller compared to opposite traffic. Looking at the weighted average stage length of both flight directions, it can be seen that for eastbound flights the refuelling moment lies before the halfway point of total stage length. For westbound flight it is opposite. The optimal refuelling moment is at the point where for both stages an equal amount of fuel is used by the cruiser. Due to the fact that take-off requires more fuel than landing, the optimum refuel point lies before half the total flight distance, which is the case for eastbound flight. Therefore, when all OD-pairs are included, refuelling flights in eastbound direction will benefit more than in opposite direction. What can be seen as well from Table 7.4, is that the average detour of the complete stage length compared to direct flight is 1.9%. The effect of detours for concept's performance will be discussed in detail in Section 7.2.

Table 7.4: Comparison of total cruiser fuel consumption for 125 cruisers in direct and in-flight refuelling operations

	Weighted average direct operations [NM]	Weighted average 1st stage length [NM]	Weighted average 2nd stage length [NM]	Average detour as % of direct flight	Refuelling location as % of total distance	Total cruiser fuel direct [kg]	Total cruiser fuel staged [kg]	Delta [%]
Eastbound	3,592	1,487	2,161	1.5%	40.8%	7,698,736	7,101,497	-7.8
Westbound	3,592	2,161	1,487	1.5%	59.2%	7,698,736	7,214,944	-6.3

Figure 7.1 depicts the results for traffic in westbound direction for this scenario. The number of tanker cycles that is needed to provide all cruisers with fuel, the number of cruisers per cycle, the arrival time of a tanker at a node (i.e. cruiser or base) and the track number of each cruiser included in a tanker cycle can be retrieved from this figure. The aggregated tanker time is the combined duration of all tanker cycles. A similar plot for eastbound traffic is made and is shown in Figure 7.2. Comparing both figures, some noteworthy dissimilarities can be detected. First of all, the aggregated tanker operating time is larger for traffic in eastbound direction. This is the result of the increased number of tanker cycles that is needed to serve all cruisers. Each time the tanker has to travel back and forth towards the tanker base, tanker operating time increases. The reason for the larger number of cycles in eastbound direction can be found in the larger average second stage length in this direction. Tanker capacity limits the number of cruisers that can be taken up in a tanker cycle, which is on average lower for eastbound direction as can be seen in Table 7.5. The total number of tanker cycles is split up into the amount of cruisers in a cycle I. What can be noticed is that on average almost one additional cruiser is included in a cycle for westbound direction compared to opposite travel direction.

Table 7.5: Case study comparison of number of cruiser included in tanker cycles for both traffic directions

Westbound			Eastbound		
I	**# tanker cycles**	**% from total number of cycles**	**I**	**# tanker cycles**	**% from total number of cycles**
1	6	12%	**1**	36	47%
2	17	35%	**2**	31	41%
3	19	39%	**3**	9	12%
4	7	14%	**4**	0	0%
Total number of cycles		49	**Total number of cycles**		76
Average number of cruisers per cycle		**2.55**	**Average number of cruisers per cycle**		**1.64**

Investigating the tanker cycles of the tanker routing optimization for this case study in more detail, a statistical analysis is applied on cruiser track numbers of cruisers included in the tanker cycles. Track numbers of consecutive cruisers in a cycle are compared and the average track difference between cruisers in a cycle is displayed in Figure 7.3. Results are distracted from case study routing optimization results shown in Figures 7.1 and 7.2. Tanker cycles for both traffic directions with an I larger than one

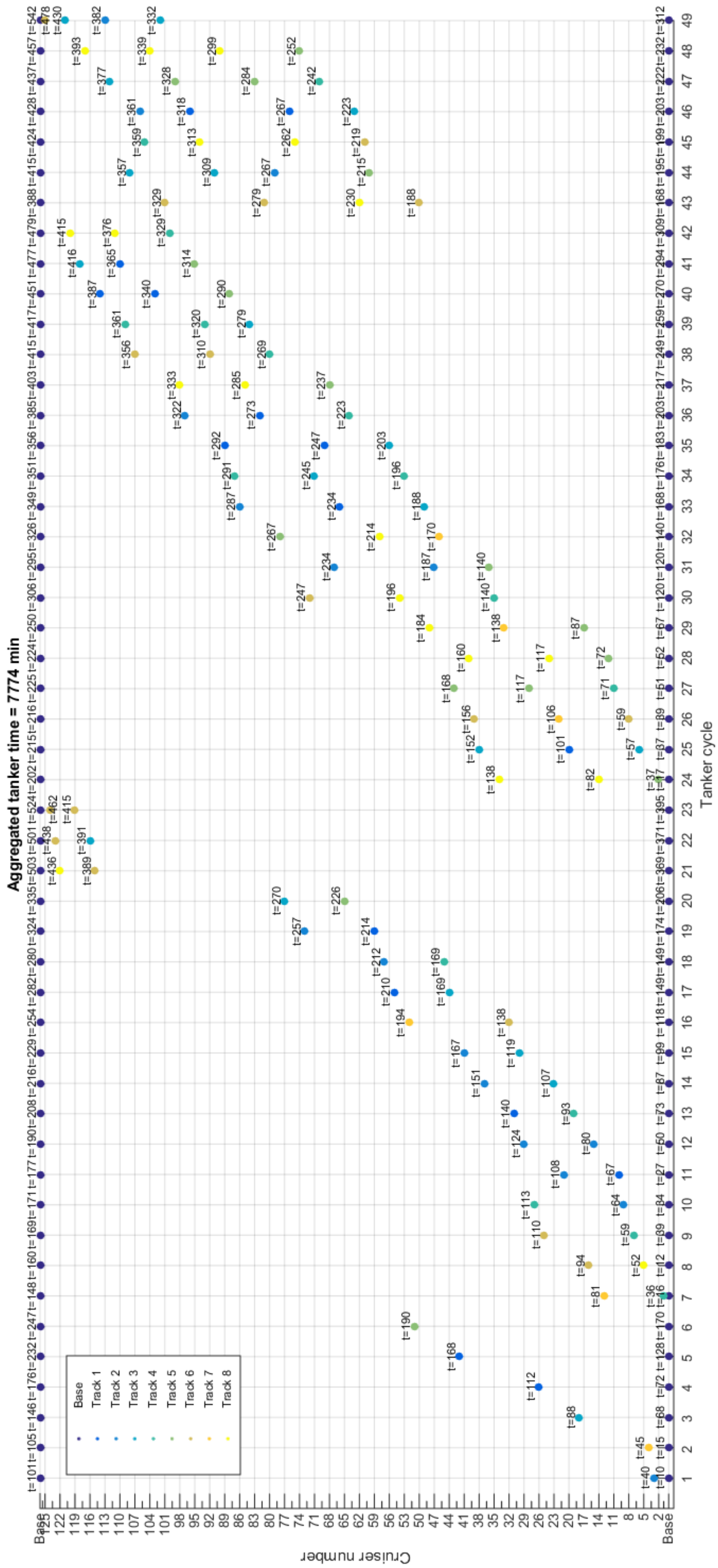


Figure 7.1: Optimization results of tanker routing for 125 cruisers in westbound direction

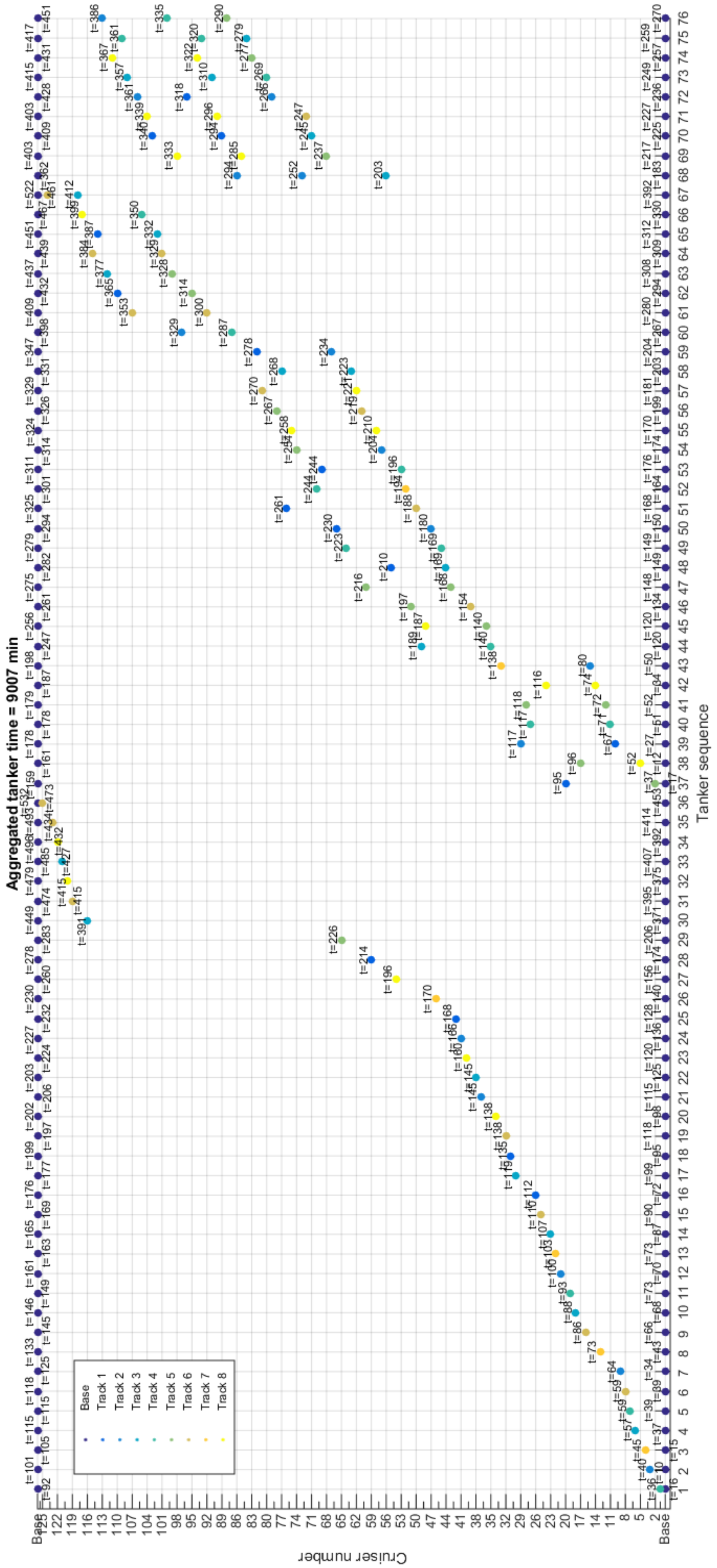


Figure 7.2: Optimization results of tanker routing for 125 cruisers in eastbound direction

are included in the figure. Results show that as the number of cruisers in the cycle becomes larger, track difference among cruisers reduces. Not only the average track distance among cruisers becomes smaller for increased number of cruisers, the standard deviation that is displayed in the same figure reduces as well. This means that there is less dispersion for cycles with larger number of cruisers included compared to shorter tanker cycles. To include more cruisers in a tanker cycle, not only fuel offload volume of individual cruisers has to be confined but fuel used by the tanker itself is restricted as well.

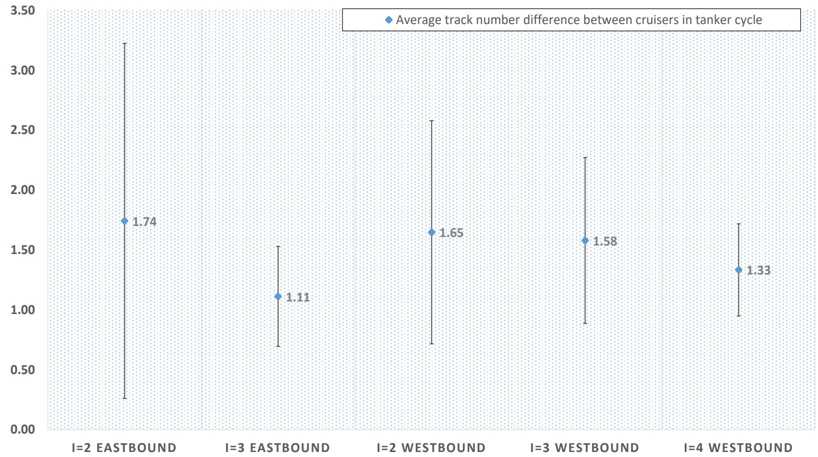


Figure 7.3: Optimization results of tanker routing for 125 cruisers in westbound direction

After the first stage of optimization, which results in the optimal subset of feasible tanker cycles, tankers have to be assigned to these tanker cycles. To determine the minimal number of tankers needed to fulfil this refuelling task, tankers can be assigned to one or more cycles, as explained in Chapter 5. The tanker departure and arrival times from and to the tanker base for each cycle are indicated in Figures 7.1 and 7.2. As explained in Chapter 5 an identical approach is used for the second optimization as is used for the first. Figures 7.4 and 7.5 depict the optimized set of tanker schedules that has to be flown with equivalent number of tankers for the optimized subset of tanker cycles from the tanker routing optimization for flights in both travel directions.

Results show that for westbound direction, the 49 tanker cycles can be optimally allocated over a minimum of 30 tankers. For eastbound direction, the larger amount of 76 tanker cycles are distributed over a minimum of 38 tankers. Since this case study simulated a day of traffic by generating cruiser schedules in both flight directions, the larger amount of tankers of the two direction is leading for cost calculations. Dividing the number of cycles over the number of tankers required, provides the efficiency of cycle allocation. For eastbound traffic this ratio is 2.00 while for westbound direction a lower ratio of 1.63 applies. This can be explained by the fact that the average tanker cycle duration for eastbound traffic is lower. While opposite traffic has an average tanker cycle duration of 159 minutes, for eastbound direction this is 118 minutes.

In the end, both optimization stages are performed to test the feasibility of the in-flight refuelling concept. Table 7.6 provides an overview of the results for both flight directions of this case study. With the assumption made in Chapter 5 that variable and fixed operating costs are represented by total fuel and tanker depreciation cost respectively, costs are incorporated conservatively. Fuel cost are determined using fuel data from IATA [2016], taking the 2016 fuel price per kg, which is US$0.228. Tanker depreciation cost are based on a tanker lifespan of 20 years and determined per day. Tanker list prices of tankers used in the model can be found in Appendix C. Finally, concept costs are compared to costs of direct operations for a single day of traffic.

Examining case study results, cruiser fuel usage for both stages of the refuelling concept is what stands out first. While total cruiser fuel is almost equal for both flight directions, the second stage cruiser offload volume for eastbound direction is more than 50% as large as is needed for opposing traffic. Furthermore, stage fuel is more equally divided for eastbound traffic. The combination of OD-

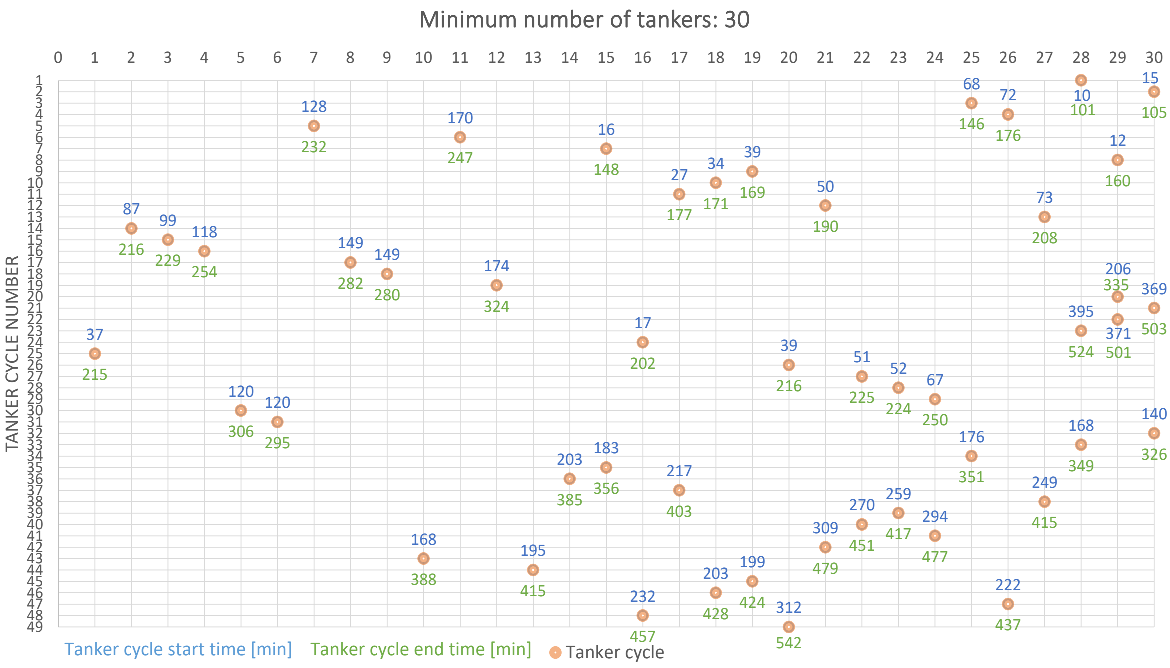


Figure 7.4: Optimization results of tanker allocation for optimized subset of tanker cycles from the tanker routing optimization for flights in westbound direction

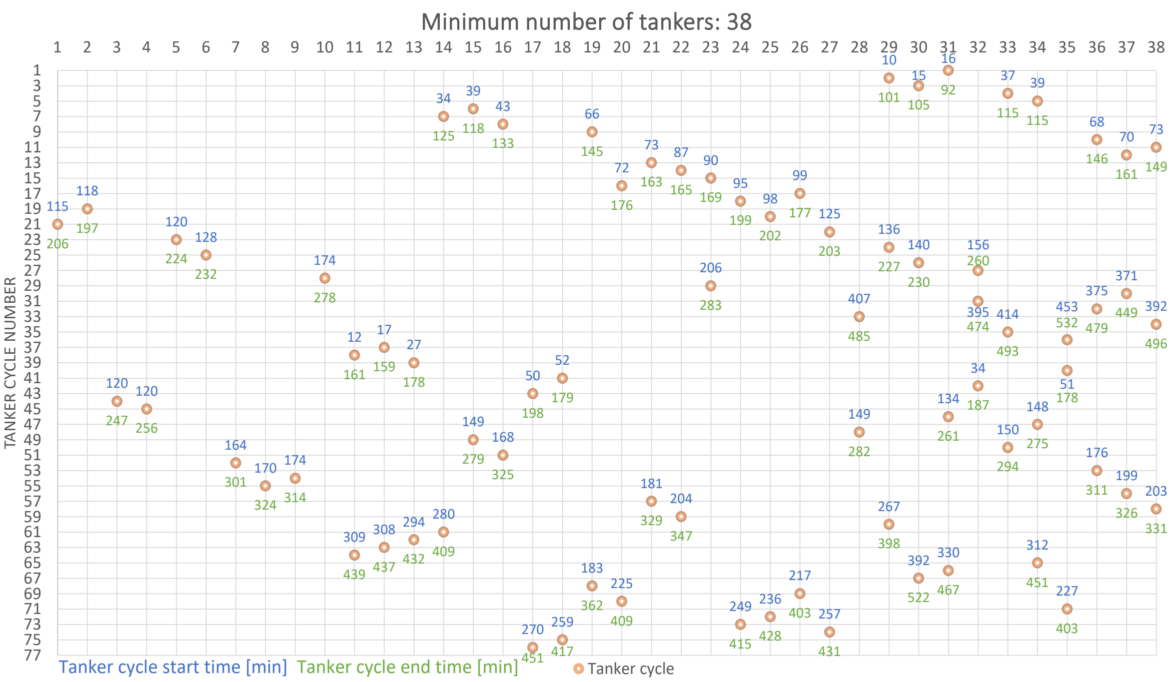


Figure 7.5: Optimization results of tanker allocation for optimized subset of tanker cycles from the tanker routing optimization for flights in eastbound direction

pair selection and tanker base location is the reason for this inequality. Due to more tanker cycles, tanker fuel usage for eastbound direction is slightly higher. However, tanker efficiency benefits from the higher transferred fuel volume in this same direction. Higher offload volumes per cruisers means less space for additional cruisers in the tanker cycle, which positively effects tanker efficiency. Here, tanker selection plays an important role, which has to be sufficiently large to incorporate all cruisers individually in a tanker cycle. This is the reason why the A310MRTT is selected in this case study. Where fuel is gained considering a comparison of cruiser fuel for both direct and staged operations, this is converted into a fuel loss when concept tanker fuel is added. For both directions a significant fuel loss is made, resulting in a total fuel loss of US$322,382 compared to direct operations. Adding fixed cost in the form of tanker depreciation, results become even worse. Taking the direction in which the required number of tankers that is needed to fulfil all cycles is largest, costs are further increased by US$621,224. In the end, westbound traffic performs slightly better under zero wind conditions for both fuel and tanker costs. It is decided to not include other costs, since this will not have any added value. For the concept to be at least break-even with a similar number of tankers, fuel savings should be around 2.7 million kg (=17.7% reduction of total fuel). Based on this case study it can be concluded that the AAR concept does not seem profitable.

Table 7.6: Result of simulating one day of traffic for 125 cruiser aircraft

	Westbound	**Eastbound**	**Total**
Aggregated tanker time [min]	7,774	9,007	16,781
First stage fuel [kg]	5,102,870	3,894,554	8,997,424
Second stage fuel [kg]	2,052,457	3,206,943	5,259,400
Total cruiser fuel [kg]	7,155,327	7,101,497	14,256,824
Tanker fuel [kg]	1,226,714	1,327,888	2,554,603
Tanker efficiency	1.67	2.42	2.06
Total concept fuel [kg]	8,382,042	8,429,385	16,811,427
Direct total fuel [kg]	7,698,736	7,698,736	15,397,473
Concept fuel increase [%]	8.9%	9.5%	9.2%
Concept fuel loss [$/day]	-155,794	-166,588	-322,382
# Tankers	30	38	38
Depreciation cost per tanker [$/day]	16,348	16,348	16,348
Total depreciation cost [$/day]	-	-	-621,224
Total concept loss [$/day]			**-943,606**

To get a more detailed insight in the performance of the refuelling concept, multiple scenarios are tested and results compared. Furthermore, performance of individual parameters are scrutinized in the following section.

7.2. Results

A more detailed look in results is provided in this section, simulating multiple days of traffic. Moreover, the effect of individual parameters on results and computational time are tested.

7.2.1. Effect of wind

The effect of wind is investigated by implementing effective cruiser range due to presence of wind in combination with wind effecting tanker and cruiser ground speeds during refuelling operations. Due to wind, cruiser effective range increases or decreases depending on wind and traffic flow direction as discussed in Chapter 5. The presence of wind changes the effective range of each stage length and therefore directly impacts cruiser fuel offload needs. Besides changes in cruiser fuel offload volumes, tanker refuelling operations are affected by wind as well. Alteration in aircraft ground speed due to wind affects aircraft rendezvous location during tanker operations. To investigate the impact of wind, two scenarios are created. One includes a high wind velocity of 60 m/s, the other is with calmer conditions using a wind speed of 30 m/s. Since wind is primarily coming from the west, wind direction is kept constant at 250°. This is parallel to the tracks over the tanker base. Besides wind, all other scenario parameters are kept constant with respect to the case study. Table 7.7 shows the results of simulating these two scenarios including wind.

Comparing results from Table 7.7 with Table 7.6, results show that wind does effect tanker operations. It can be identified that for both scenarios including wind total cost are decreased compared the scenario of the case study. Common denominator of all scenarios is that the concept is not profitable comparing to direct operations. However, the presence of wind reduces concept costs slightly. Adding wind to the model changes absolute cruiser fuel and tanker consumption for both direct and staged operations. To make a fair comparison between scenarios, fuel is compared with the ratio between concept and direct total fuel volumes. Total concept fuel of traffic in both directions combined provides a better result for the 30 m/s wind condition compared to the case study result without the presence of wind. For the stronger wind condition of 60 m/s total concept fuel as a percentage of direct fuel gives an identical result as the case study. Investigating both traffic directions individually, concept fuel losses grow for eastbound traffic while a decrease in fuel losses can be detected for westbound traffic. An explanation for this result is the growing cruiser fuel offload volume in combination with the used tanker. Cruiser traffic heading in westbound direction with headwind require more fuel for the second stage length compared to the no wind situation. Since the A310MRTT tanker is used, which is identical to the case study tanker, tanker fuel capacity is better utilized. For traffic in eastbound direction the opposite applies. Another reason that improves performance for a situation with cruiser head wind is the reduced ground speed. More time is needed for the cruiser to cross the refuelling zone which gives the tanker more time to rendezvous with the cruiser in time. In combination with an increased tanker ground speed travelling in opposite direction in between refuels, more feasible tanker cycles are generated. On the other hand, cruisers heading East have increased ground speed and a shorter rendezvous period with the tanker exist. In combination with reduced fuel offload volumes, concept performance decreases in this direction. Another observation that is made is that the scenario with less wind outperforms the scenario with stronger wind. It can be concluded that at a given wind speed decreased performance in eastbound direction is larger than the benefit that is created in westbound direction. This also indicates that cruiser fuel offload volume, tanker fuel capacity and effective time window duration due to the presence of wind are three important influential factors for concept performance.

Table 7.7: Effect of wind on the refuelling concept for two scenarios with different wind speeds

	30 m/s			60 m/s		
	Westbound	**Eastbound**	**Total**	**Westbound**	**Eastbound**	**Total**
Aggregated tanker time [min]	7,162	7,901	15,063	6,889	7,653	14,543
First stage fuel [kg]	5,601,481	3,527,306	9,128,787	6,121,449	3,255,014	9,376,463
Second stage fuel [kg]	2,305,435	2,689,733	4,995,168	2,649,138	2,192,929	4,842,067
Tanker fuel [kg]	1,133,697	1,405,011	2,538,708	1,335,585	1,551,952	2,887,537
Tanker efficiency	2.03	1.91	1.97	1.98	1.41	1.68
Total concept fuel [kg]	9,040,612	7,622,050	16,662,663	10,106,172	6,999,895	17,106,067
Direct total fuel [kg]	8,685,828	6,985,416	15,671,244	9,548,502	6,119,180	15,667,682
Concept fuel increase [%]	4.1%	10.1%	6.3%	5.8%	14.4%	9.2%
Concept fuel loss [$/day]	-80,891	-145,153	-226,043	-127,149	-200,803	-327,952
# Tankers	24	33	33	22	34	34
Depreciation cost per tanker [$/day]	16,348	16,348	16,348	16,348	16,348	16,348
Total depreciation cost [$/day]	-	-	-539,484	-	-	-555,832
Total concept loss [$/day]			-765,527			-883,784

A logical trend is present considering the number of tankers needed for both travel directions. The difference in needed tankers for both directions becomes larger for increased wind speed. Since the total amount of essential tankers is determined upon the direction in which most tankers are needed, efficiency in eastbound direction is leading. Compared to the scenario without wind, the number of tanker reduces. Due to the higher ground speed in eastbound direction, it is more difficult to include multiple cruisers per cycle. This reduces the number of included cruisers per cycle as well as the cycle duration. While more tanker cycles are needed to serve all cruisers, more cycles can be assigned to the same tanker. This results in reduced total amount of tankers. Cost wise, a lesser number of tankers is beneficial for the concept. However, to growing difference in the number of tankers between both travel directions for increased wind speed is not preferred since more tankers stay put when the westbound traffic flow is active.

7.2.2. Inter-arrival times

To test the influence of varying inter-arrival times on the concept's viability a set of 50 cruisers is considered. Since traffic flows are tidal and have a duration of approximately seven hours in both traffic directions, cruisers have to be distributed over this time period. Depending on the number of cruisers and active tracks applied, the average cruiser inter-arrival time can be computed that is needed to fulfil the requirement that all cruisers cross the refuelling time window in this seven hour time period. Since random integers according to an uniform distribution are used to generate cruiser inter-arrival times, determining the average inter-arrival time of the selected time interval is straightforward. Keeping in mind that the lower boundary of this time interval has to be at least ten minutes according to separation standards, the upper limit can be shifted to change its average. Figure 7.6 presents the result of a stepwise increase of cruiser inter-arrival times until the difference in arrival time between the first and last cruiser is seven hours. With only 50 cruisers included in the scenario, stretching out cruisers over the entire time period simulates refuelling cruisers for just one or two airlines. Other input parameters as OD-pairs, cruiser type usage and the number of tracks and their location are kept constant. Figure 7.6 provides the results for a westbound traffic flow, neglecting wind and using a fixed tanker type.

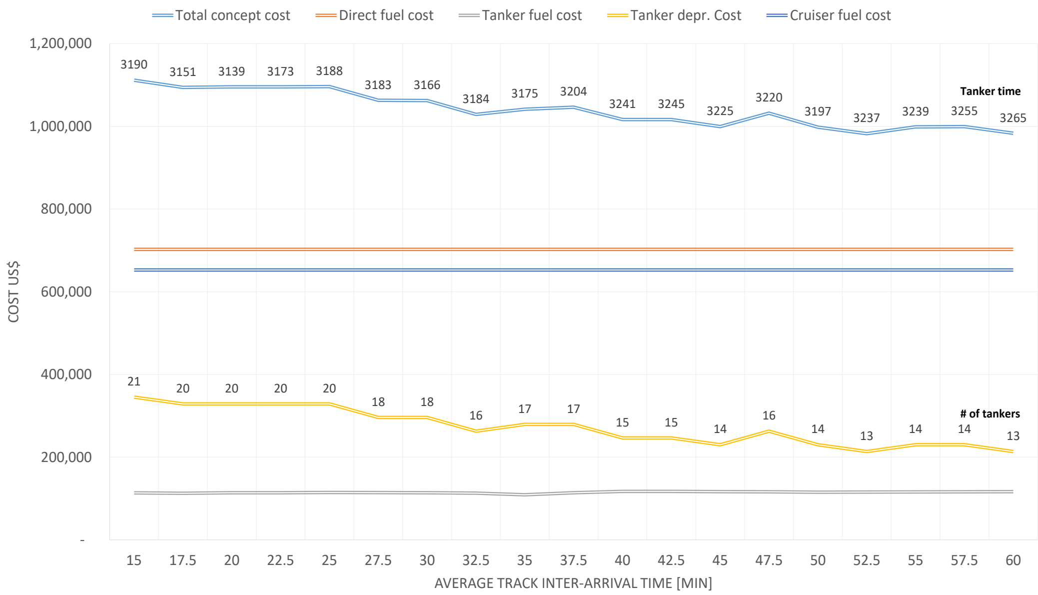


Figure 7.6: Overview of concept performance with increasing inter-arrival times for a flow of 50 cruisers in westbound direction

Results show that the minimum tanker time not necessarily provide the lowest total concept cost. Furthermore, enlarging inter-arrival time reduces the number of tankers needed to provide all cruisers with fuel, while tanker fuel cost remains almost constant. Therefore, the lowest total cost is found when the time between cruisers is fully stretched over the seven hour traffic flow duration. This optimal cost solution yields a 4% increase in aggregated tanker travel time and a 2.4% fuel increase compared to the minimum value. However, total concept cost is dropped by 10.3%. If time duration of active tracks is assumed to be very large, the number of tankers will reach a minimum. However, there will never be a point where the concept in this scenario is more beneficial than direct operations, since total fuel cost will always exceed direct fuel cost. In an ideal world, selecting a proper inter-arrival time can lead to reduced concept cost. However, cruiser flight schedules are determined by the airlines. Nonetheless, AAR operations remain to be around 9.5% more expensive in term of fuel than direct operations for this smaller amount of cruisers. Including tanker depreciation cost will further decrease AAR concept feasibility.

7.2.3. Detours, stage length and cruiser types

The influence of detours, stage length and used cruisers is further highlighted in this section. Since fluctuations can be spotted in cruiser fuel savings gained due to implementation of AAR operations, the effect of both aspects is further looked into. Theoretically, the most effective location for cruiser refuelling is when for both flight legs a similar amount of fuel is burned. This will be slightly before halfway the total travel distance, since more fuel is burned during take-off than landing. This section tries to investigate the effect of dissimilar stage length on cruiser fuel savings. Furthermore, flights on some OD-pairs have to make detours to get refuelled over the tanker base. These detours can have influence on the concept's efficiency. Additionally, the effect of spread in fuel offload volume for different cruisers on various OD-pairs in the cruiser schedule is researched. Starting with the effect on detours, three OD-pairs are investigated with no, small and larger additional distance due to AAR. Since 2nd stage lengths for eastbound traffic are more or less similar, westbound traffic is investigated. OD-pairs LHR-JFK, LHR-MIA and LHR-LAX are included in this comparison with 0%, 1% and 5% extra travel distance respectively. For each of these OD-pairs scenarios are created with different tanker type usage and interspersed wind conditions. Figures 7.7, 7.8 and 7.9 provide results of this comparison.

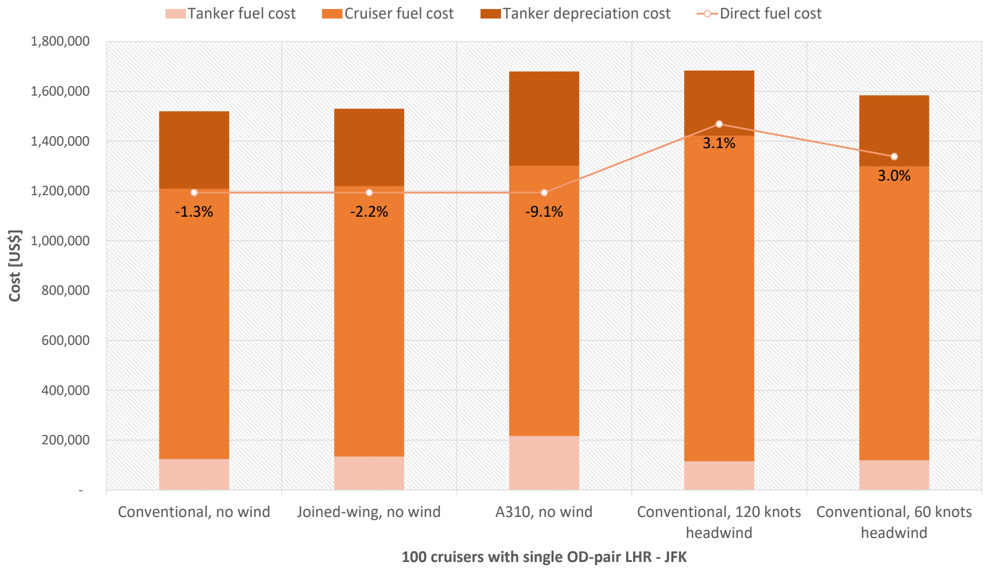


Figure 7.7: Results of simulating 100 cruisers in westbound direction with a single OD-pair LHR-JFK for multiple tankers and wind conditions

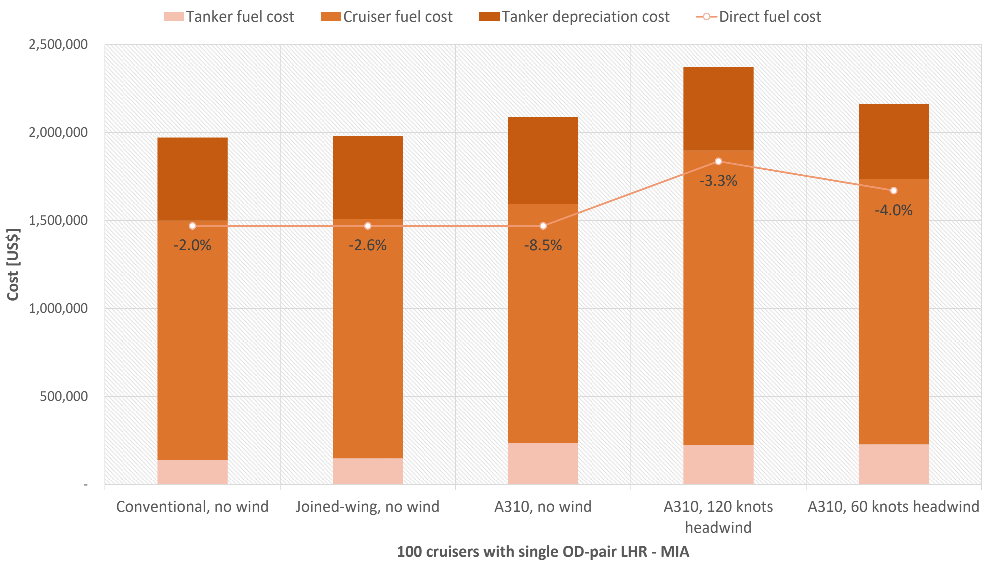


Figure 7.8: Results of simulating 100 cruisers in westbound direction with a single OD-pair LHR-MIA for multiple tankers and wind conditions

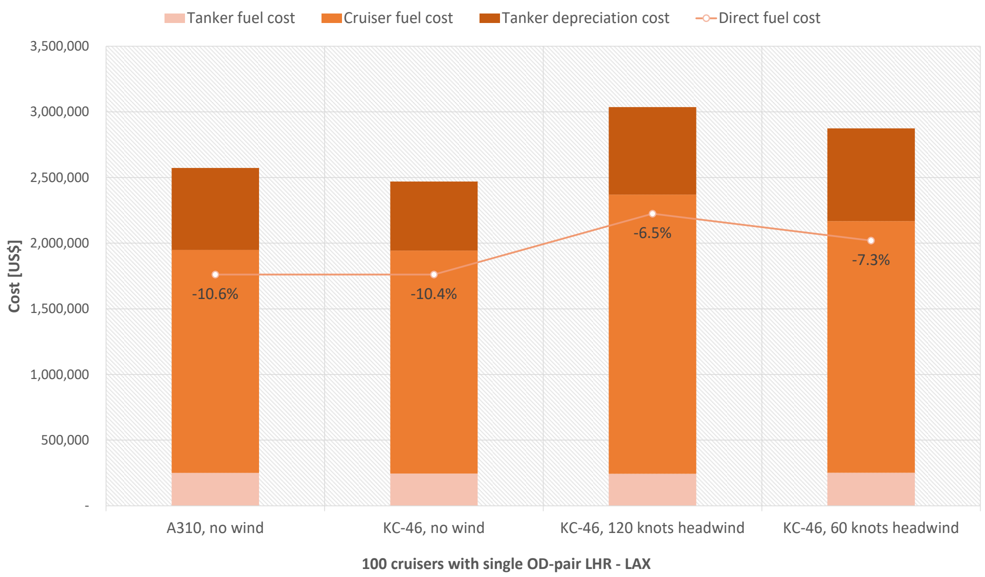


Figure 7.9: Results of simulating 100 cruisers in westbound direction with a single OD-pair LHR-LAX for multiple tankers and wind conditions

It is found that the refuelling concept can be beneficial fuel wise for flights between LHR and JFK when making use of the conceptual RECREATE tankers (concept fuel savings around 3%). Since tanker capacity of these RECREATE tankers is not sufficient for longer stage lengths in combination with the cruiser types included in the flight schedule, this tanker type can barely be used. As can be seen in Figure 7.7, the impact of technology is significant.

For longer second stage lengths in combination with increased detours, cruiser fuel gains drop. Larger, less efficient tankers are needed to capacitate increasing fuel volumes for increased stage lengths. This further reduced concept performance and makes potential fuel gains completely vanish. For all scenarios the same conclusion can be drawn, irrespective of the fuel gains/losses of the concept. When tanker depreciation costs are added to fuel cost, non of the scenarios gives profitable results for the AAR concept. However, it can be concluded that a shorter first stage compared to second stage is more beneficial for cruiser fuel savings. Furthermore, a logical conclusion is that detours have a negative effect on cruiser fuel savings. The performance efficiency of the used tanker is of importance as well. This is further elaborated upon in the next section.

The influence of the used type of cruiser on concept performance can be solely attributed to technology level and aircraft size. The foundation of this concept is to reduce the snowball effect of burning additional fuel to carry fuel. Since fuel comparisons made are based on relative performance in stead of absolute fuel savings in kg, an older heavier aircraft will benefit more from the refuelling concept than a small light weight aircraft. In Table 7.8 a comparison is made which shows the performance of various aircraft types for AAR operations relative to direct operations. An OD-pair without detour of the AAR concept is selected to make a fair comparison. Furthermore, the RECREATE cruiser, which is not included in the model, is taken up in this comparison to prove that concept results will not improve with the implementation of this cruiser. All cruisers behave more or less similar irrespective of size and technology level. Explanation for this result can be the lack of detailed aircraft flight performance data to calculate accurate savings. However, what can be concluded is that aircraft behave similar and that the used type of cruiser in this model will not have significant impact on fuel savings relative to direct operations.

Table 7.8: Concept fuel savings compared to direct operations for various cruiser types

LHR - JFK	B757-200	B767-300	B777-200	A330-300	B747-400	B787-8	B737-800	RECREATE cruiser
Fuel direct operations [kg]	32,705	45,695	67,823	51,392	84,121	50,552	23,194	27,458
Fuel AAR operations [kg]	29,633	41,143	61,146	45,158	75,189	44,785	20,972	24,987
Fuel reduction for AAR operations [%]	9%	10%	10%	12%	11%	11%	10%	9%

7.2.4. Tanker type

To investigate the effect of tanker selection on concept performance, tankers have to be chosen that provide excessive fuel capacity over the largest cruiser offload volume in the schedule. The tanker size of the selected tanker does not only influence concept performance but impacts computational time as well. This is further explained in detail in the next section. To test multiple tanker types, two scenarios with opposite travel direction are generated. Depending on fuel offload volumes in both directions, the three tanker types that are most suitable are compared. For all scenarios, 100 cruisers on 8 different tracks are included. Eastbound scenarios are modelled with 60 m/s of tailwind. This provides the opportunity to include both RECREATE tankers due to lower cruiser offload volumes. For the westbound traffic scenario, no wind is included in the scenario and the tanker types that are used are the A310MRTT, KC-46 and A330MRTT. In this way, all five tanker types that can be selected in the model are included in this comparison. Table 7.9 provides an overview of the results between various cruiser types.

Table 7.9: Comparison between tanker types for constant cruiser schedules tested for both travel directions

	Westbound			Eastbound		
	A310	KC-46	A330	A310	RECREATE conventional	RECREATE joined-wing
Aggregated tanker time [min]	6407	5946	5845	6902	7967	8171
Direct total fuel [kg]	6,140,356	6,140,356	6,140,356	4,880,816	4,880,816	4,880,816
Concept total cruiser fuel [kg]	5,712,079	5,712,079	5,712,079	4,363,190	4,363,190	4,363,190
Concept cruiser fuel reduction [%]	-7.0%	-7.0%	-7.0%	-10.6%	-10.6%	-10.6%
Tanker fuel [kg]	1,012,769	925,178	936,785	1,337,844	802,663	859,888
Total concept fuel [kg]	6,724,848	6,637,257	6,648,864	5,701,034	5,165,854	5,223,079
Concept total fuel increase [%]	9.5%	8.1%	8.3%	16.8%	5.8%	7.0%
Concept fuel cost $/day	1,533,265	1,513,295	1,515,941	1,299,836	1,177,815	1,190,862
Direct operations fuel cost [$/day]	1,400,001	1,400,001	1,400,001	1,112,826	1,112,826	1,112,826
Fuel cost loss [$/day]	-133,264	-113,293	-115,940	-187,010	-64,989	-78,036
# Tankers needed	22	20	20	30	32	36
Total tanker depreciation cost [$/day]	359,656	403,836	636,164	490,440	397,589	447,288
Total concept loss [$/day]	-492,920	-517,129	-752,104	-677,450	-462,578	-525,324

Results show that for westbound traffic the KC-46 tanker is most beneficial considering fuel costs of this scenario, however differences compared to other tankers are small. The two largest tanker type, KC-46 and A330MRTT respectively, allow more cruisers to be included in a tanker cycle and therefore less cycles are needed. The KC-46 tanker is of more recent technology level compared to the A310MRTT and smaller in tanker capacity compared to the A330MRTT, which both have inferior tanker flight performance characteristics. These superior flight characteristics contribute to an increased tanker fuel efficiency. However, comparison of depreciation costs for this given scenario shows that the A310MRTT is most beneficial, even when a larger tanker fleet is necessary. In the end, considering both tanker fuel and depreciation cost, the smallest tanker is most beneficial. Nonetheless, the concept remains unprofitable for all tanker types. Investigating tanker fuel usage for the eastbound traffic scenario including tailwind, both RECREATE tanker designs perform significantly better than the

A310MRTT. With the conventional RECREATE tanker slightly outperforming the joined-wing design. Due to smaller tanker capacity of both RECREATE designs, a larger number of tankers is needed to serve all cruisers in the scenario. Since depreciation cost per tanker are lower for both RECREATE designs, even though more tankers are needed total depreciation cost is lower compared to the A310MRTT. The smallest RECREATE tanker with a joined-wing design performs well in terms of tanker fuel, however due to additional tankers that are required compared to the conventional RECREATE design, total cost rise. Reduced tanker fuel for both RECREATE designs can be attributed to enhanced tanker flight performance characteristics. Still, the concept remains less efficient compared to direct operations.

This comparison shows the importance of tanker flight performance characteristics. Designing a state-of-the-art tanker, with only purpose to refuel commercial flight can enhance concept's performance. With such a tanker, fuel cost can be brought around the break even point. However due to the presence of tanker depreciation cost and other costs that are not included in this model, concept performance is worse compared to direct operations. Another operational challenge of this concept is that depending on the generated scenario, different tanker types perform best. Already between traffic directions, contrasting tanker types are preferred. To capitalize on tanker efficiency, the use of a heterogeneous tanker fleet where a tanker type can be selected that performs best for certain scenario conditions is preferred. However, a heterogeneous tanker fleet will increase operating costs.

7.3. Algorithm performance and computational time

Now that the influence of various input parameters on concept performance are discussed, a closer look is taken at the influence of these parameters on computational time and algorithm performance. How the used algorithm behaves, including the addition and reduction of feasible columns to the column matrix is discussed in Chapter 5. In this section, algorithm performance is displayed through a scenario comparison. This is followed by examining the effect of various parameters on computational time, which is related to the number of columns of the final feasible column matrix.

As mentioned in Chapter 5, the used algorithm applies all constraints before tanker cycles are extended with an additional cruiser. After each iteration of applying constraints, infeasible columns are discarded and feasible solutions are used for adding a cruiser to the cycle. In this way, all possible solutions are considered in a more effective way. In Table 7.10, the number of added columns to the solution matrix is displayed for multiple scenarios and compared to an algorithm that applies constraints at the end when all possible cycles are generated. In the table, the number of added columns represent the columns that are appended to the column matrix before column reduction takes place by applied constraints. All eight scenarios that are included in the comparison are examined in contrast to the algorithm that applies constraints only once all combinations are generated. Generation of these combinations is performed according to Equation 5.7. Delta is defined as the number of added columns applying the used algorithm for a given scenario as percentage of the total number of combinations.

Table 7.10: Algorithm performance of the used algorithm for 8 different scenarios with varying traffic direction and used tanker

125 cruisers and no wind		Eastbound & A310 tanker		Eastbound & A330 tanker		Westbound & A310 tanker		Westbound & KC-46 tanker	
# Cruisers in tanker cycle l	# Added columns (all combinations)	# Added columns per iteration	Delta	# Added columns per iteration	Delta	# Added columns per iteration	Delta	# Added columns per iteration	Delta
1	125	125	100.0%	125	100.0%	125	100.0%	125	100.0%
2	7,750	7,750	100.0%	7,750	100.0%	7,750	100.0%	7,750	100.0%
3	317,750	140,874	44.3%	221,562	69.7%	141,071	44.4%	204,568	64.4%
4	9,691,375	397,757	4.1%	2,648,432	27.3%	403,418	4.2%	1,817,891	18.8%
5	234,531,275	50,150	0.0%	1,014,929	0.4%	54,572	0.0%	3,153,095	1.3%
Total:	**244,548,275**	**596,656**	**0.24%**	**3,892,798**	**1.59%**	**606,936**	**0.25%**	**5,183,429**	**2.12%**

125 cruisers and 60 knots wind		Eastbound & A310 tanker		Eastbound & A330 tanker		Westbound & A310 tanker		Westbound & KC-46 tanker	
# Cruisers in tanker cycle l	# Added columns (all combinations)	# Added columns per iteration	Delta	# Added columns per iteration	Delta	# Added columns per iteration	Delta	# Added columns per iteration	Delta
1	125	125	100.0%	125	100.0%	125	100.0%	125	100.0%
2	7,750	7,750	100.0%	7,750	100.0%	7,750	100.0%	7,750	100.0%
3	317,750	61,755	19.4%	213,252	67.1%	211,661	66.6%	213,785	67.3%
4	9,691,375	11,462	0.1%	827,598	8.5%	2,009,591	20.7%	2,244,731	23.2%
5	234,531,275	0	0.0%	64,288	0.0%	4,178,468	1.8%	6,262,131	2.7%
Total:	**244,548,275**	**81,092**	**0.03%**	**1,113,013**	**0.46%**	**552,017**	**0.23%**	**8,728,522**	**3.57%**

Comparing traffic flow in both directions, a clear distinction in performance can be identified between eastbound and westbound traffic. The number of added columns for eastbound traffic is significantly less compared to traffic in other direction. The introduction of wind, tailwind for eastbound traffic, enlarges this distinction. This can be clarified by the reduced number of cycles options for higher cruiser ground speed in combination with reduced tanker ground speed in between refuels. The opposite applies for westbound traffic.

Looking at the tanker type used for these scenarios, differences can be noticed as well. The chosen tanker type has to be significantly large to refuel the cruiser with the largest fuel request. Incorporating wind, for westbound traffic direction this implies the use of a different tanker type with enlarged capacity. The opposite is true for eastbound direction, where due to tailwind possibly a smaller tanker type can be used. For these scenarios this is not the case. Using a tanker capacity which is just larger than the largest fuel offload tightens the optimization by reducing the number of tankers that can be incorporate in a tanker cycle. This reduces the number of added columns and therefore computational time. However, a larger tanker can add more cruisers to its cycle what could be beneficial for concept performance considering costs. In previous section, it is proved that selecting a tanker which fuel capacity is too 'tight' or too 'lose' will both negatively affect concept cost. For computational performance the use of a 'tight' tanker is always more beneficial. The larger tanker capacity is reflected in the iteration with the largest number of added columns for westbound traffic, since tanker capacity is the limiting factor in this direction. For eastbound traffic this is not that clear, since the number of cruisers and arrival time are limiting cruiser addition to tanker sequence.

7.3.1. Model computational time

The model can be split up into multiple model segments according to Figure 5.2. These segments exist of a scenario generation and two optimization stages. From the three segments, the middle segment influence total computational time most. Building the feasible column matrix for the tanker routing optimization is the most time consuming part of the model. Where optimization of both model parts takes no more than a few seconds, generating the column matrix can go up to more than an hours for large problem sizes. Computational time is in most cases not the limiting factor, most problems that take longer than 30 minutes run out of computational memory. The model is run on a computer with a 2.40 GHz processor consisting of 4 cores and 8 GB physical memory. Software that is used to built the model is MATLAB version R2014B and CPLEX version 12.6 is used as optimization solver where approximately 4 GB of memory can be addressed.

The computational time is tested for various scenarios, with increasing number of cruisers and constant inter-arrival time. Figure 7.10 provides an overview of the computational time for six scenarios with varying wind speed and traffic direction. Computational performance of the six scenarios differs depending on the tanker that is used. Taking westbound traffic as an example, the performance of the scenario without wind outperforms the other two scenario. This scenario uses a smaller tanker that is just capable of providing the largest fuel offload volume to a cruiser. Addition of wind increases the fuel offload volumes and a larger tanker is selected to provide all cruisers with a fuel offload. However, difference between the largest offload volume and the tanker fuel capacity is increased. This causes the number of feasible columns for the column matrix to grow. Increasing wind to 60 m/s will increase fuel volumes even further and reduces the difference between the largest fuel offload volume and tanker fuel capacity, enhancing computational performance.

What can be detected is that eastbound traffic outperforms traffic in opposite direction when the number of cruisers increases. This is in line with the results displayed in Table 7.10. This immediately outlines a parameter that affects computational time tremendously. A tight 'fit' between tanker and largest cruiser offload, will be most beneficial for scenario computational time. Using a tanker with surplus capacity, more cruisers can be added to the tanker cycle and computational times dramatically increase. As can be spotted in Figure 7.10 a difference in performance between both travel directions exists. Where an increased headwind enlarges cruiser offload volumes in westbound direction which lead to a tighter tanker fit if the same tanker type can be used, hence reducing computational times. The tailwind in eastbound direction also provides better results. However, the reason for this to happen is a different one. For eastbound traffic, tanker fit becomes less tight but enlarged cruiser ground speed ensures less tanker cycle options which results in lower computational time.

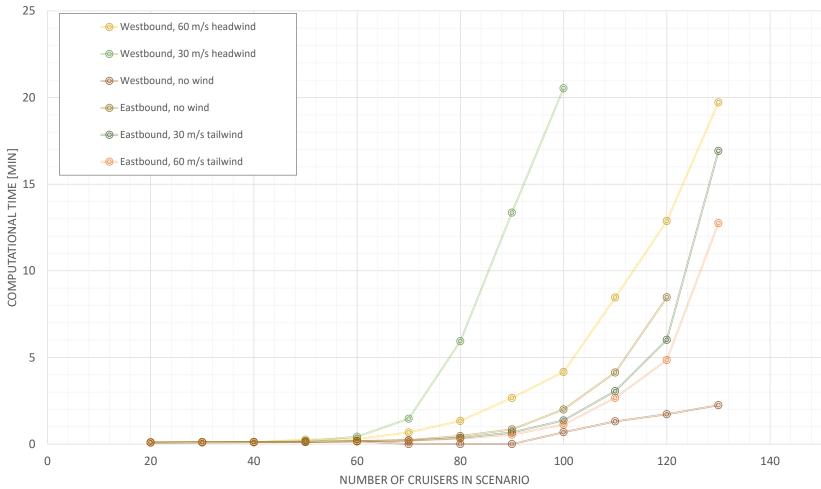


Figure 7.10: Computational time for increasing number of cruisers for six different scenarios with varying wind speed and traffic direction

Other factors that influence that impact the throughput (i.e. number of cruisers per hour) over the tracks like inter-arrival time and number of active tracks are investigated as well. Results show that if traffic density increases, due to the number of tracks or inter-arrival times, computational times decrease due to a reduced number of cruisers which can be added to the tanker cycle. The opposite applies when traffic density is decreased. Track location does not influence computational times when the tanker is sufficiently large. However, when due to the extra tanker travel distance tanker capacity becomes insufficient to provide the largest offload volume, the use of a larger tanker impacts computations significant as shown in Figure 7.10. Two parameters that affect cruiser offload volume are the cruiser types and OD-pairs included in the scenario. If the spread in offload volume is large, computational time in negatively affected.

As mentioned in Chapter 5, a realistic number of cruisers to be modelled lies around 250 cruiser flights between North America and Western Europe on a daily basis per flight direction. The model is capable in some conditions to include this number of cruisers, however most scenarios are infeasible due to excessive computational time or running out of memory. Therefore, it is chosen to reduce the number of tracks and limit the number of cruisers included in the model while traffic density can be maintained. when this number of cruisers is extended to model larger amounts of traffic, including all traffic over the North Atlantic, the computation would amount to approximately 27 hours for 250 flights, assuming plentiful computational memory. Figure 7.11 shows the exponentially growing computational time with increasing number of cruisers in the model. A trend-line is added to provide insight in the computational time of cruiser numbers larger than 150.

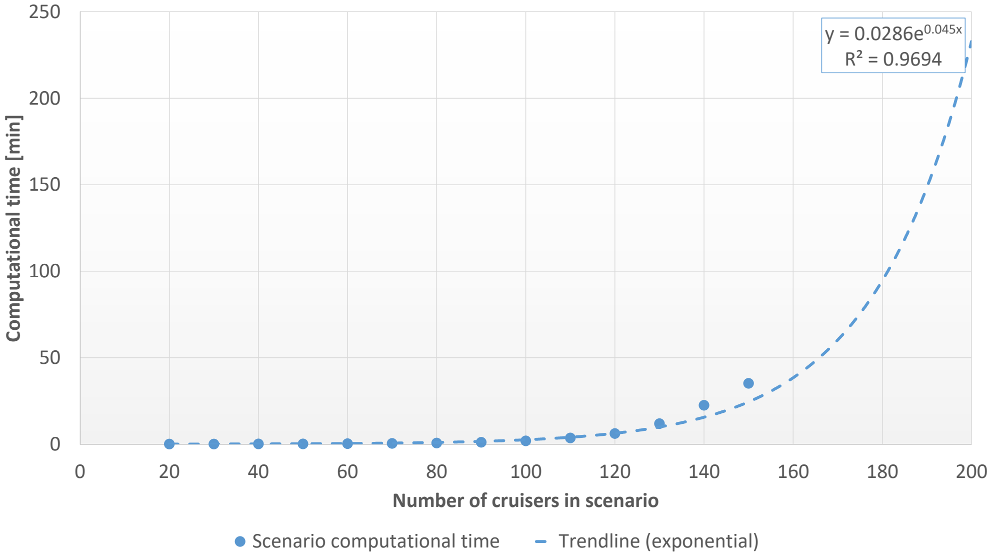


Figure 7.11: Computational time for increasing number of cruisers in the model including exponential trend line

8

Conclusions and recommendations

In this final chapter an extensive overview of the main conclusions of this research are presented. First, the main conclusions of this study are discussed in Section 8.1 followed by its limitations (Section 8.2). Based on these limitations and conclusions, recommendations for further research are addressed.

8.1. Conclusions

The two main components of the research problem statement include the viability of the AAR concept in a real-life traffic environment and the efficiency of the SP formulation for this particular tanker routing problem. Both aspects are thoroughly discussed in this conclusion.

Starting of by addressing the AAR concept performance while implemented in a real-life traffic environment, results show that this concept is not beneficial considering operational costs. For most scenarios, cruiser fuel saved due to AAR operations is annihilated by tanker fuel consumption during the refuelling process. For most cases, the cruiser fuel savings are even transmuted into a fuel loss of the overall concept compared to direct flight. Where cruiser fuel savings show a benefit of 6-10% depending on cruiser type and OD-pair served, tanker efficiency remains low (around 2) for existing tanker types included in the model. However, even a tanker efficiency promised during the RECREATE project of 7-8 with the use of RECREATE tankers is not sufficient for the concept to be break even in cost since the small gains in total fuel cost are annihilated due to tanker depreciation cost. Even while the overall concept seems unattainable, some important findings are highlighted.

8.1.1. Tanker usage

Several factors can be outlined, which influence concept performance. First of all, the used tanker is of high importance. All previous research, highlighted in Chapter 2 make use of conceptual tanker designs. This tanker is explicitly developed for the refuelling concept over the Atlantic. However, tanker fuel capacity of these tankers is designed in combination with the use of a new conceptual cruiser design applying uniform fuel offload volumes. Since it is not realistic to replace all current traffic by this new cruiser, the choice is made not the implement this cruiser design in the model. As a consequence the conceptual tanker can be used only for a limited number of scenarios. Furthermore, previous chapter showed that incorporating the new cruiser will not improve results compared to direct operations. In stead, existing military tankers are used with reduced flight performance characteristics. This results in lower tanker efficiency and higher tanker fuel consumption. However, as mentioned before, the RECREATE tankers increase performance but not sufficient for the concept to be viable. The use of variable fuel offload volumes further decrease of concept performance.

Matching cruiser fuel needs and tanker fuel capacity is important to ensure maximum tanker efficiency. However due to cruiser schedules, this can not always be assured. The combination of cruiser arrival time, velocity and fuel need can cause situations in which departing tankers are do not have to be completely filled with fuel. This tends to an implementation of heterogeneous tanker fleet, which is not accounted for in this study. The reason for this are the additional cost of fleet heterogeneity as maintenance and crew cost, which are not taken into account in this study. Another reason not to include heterogeneous tanker fleet is a practical one since the use of a single tanker type is easier in case of tanker failure or schedule rearrangement. Furthermore, computational time in combination with the SP formulation increases due to the fact that the column matrix has to be made for multiple tanker types.

The influence of wind on tanker operations is significant comparing both travel directions. Results are as expected, where tanker time for westbound traffic is lower due to cruiser headwind that implicates lower ground speed. Fuel losses are decreased, however not enough for the concept to be profitable. Increased tailwind for eastbound traffic results in higher total fuel cost while using a fixed tanker type. Adapting the tanker type to the circumstances, improves fuel usage. Due to higher cruiser ground speed, larger tankers are less beneficial considering the longer travel times, reduced tanker sequence options and lower cruiser fuel offload needs. However, a tight tanker capacity fit for westbound traffic is not beneficial since lots of cruisers can be included in the sequence, tanker travel time is short and offload needs by cruisers are increased. Downside of using large tankers are the higher depreciation costs. Therefore, proportionate tanker capacity has to be found to under these circumstances. This indicates a difference in operational limitations between both travel directions including wind, which is cruiser offload fuel for westbound traffic and time window duration for eastbound traffic. Which implies different tanker needs for both travel directions.

8.1.2. Cruiser schedule

Even while cruiser schedule including various cruiser types and OD-pairs show no profitable results for the AAR concept, specific routes and cruiser types perform better than others. On the route between LHR and JFK, around 3% of fuel can be gained due to limited second stage length and absence of cruiser detour a small and efficient RECREATE tanker can be deployed. This highlights immediately three important aspects considering AAR operations: stage length, detour distance and tanker usage. However, in a schedule with multiple OD-pairs and cruiser types which cause large fluctuations in cruiser offload volume, these fuel savings vanish. While this concept can be fuel beneficial under certain conditions, cost benefits can not be achieved so far.

8.1.3. Computational performance

Concluding on computational performance, the SP formulation is more effective than the VF formulation used by Lith [2012]. However, problem sizes up to a certain number of cruisers can be dealt with within reasonable computational time. Cruiser inter-arrival time, number of cruisers, wind direction and velocity, and the fuel offload volume in combination with tanker capacity all influence computational time. Since the SP formulation works well for a restricted number of cruisers in a tanker sequence, it is important to match tanker capacity to cruiser offload volume. The variety in cruiser offload volume has a negative effect on the computational time. Since tanker capacity must be sufficiently large to refuel the cruiser with largest supply need, the number of feasible columns increases rapidly for cruisers with lower offload needs. Therefore, to reduce computational time, spread in cruiser offload volumes need to be condensed.

The implementation of wind enlarges the effect just described. Headwind for westbound traffic causes offload volumes for various tanker types and OD-pairs to be stretched out further. In combination with a lower cruiser ground speed, possible sequences and therefore computational time is enlarged significantly. For eastbound traffic just the opposite applies. For this reason it is important to select a tanker with a capacity that is just able to provide the cruiser with the largest fuel offload volume need with fuel. The implementation of a heterogeneous tanker fleet will negatively influence computational time, since the column matrix has to be created for all included tanker models.

8.2. Limitations and recommendations for future work

This section provides the limitations of this research. Some limitations are expected to be overcome with minor work others need more rigorous change of perspective. Both are stated in this section.

8.2.1. Traffic and aircraft data

First, the available data used for modelling the NAT cruiser schedule is discussed. Besides, used tanker and cruiser data is evaluated and fuel calculations are debated.

To start off, data that is used to model cruiser air-traffic for the AAR concept lacks accuracy. Due to unavailability, no use is made of a real-life cruiser traffic schedule of flights crossing the Atlantic over the track system. Instead, a rough estimation on the number of flight is made and with statistical data, the spread of traffic per cruiser type and OD-pair is estimated. Multi-day real-life cruiser traffic data will give more accurate data on track use and separation time. As a result of combining statistical data on cruiser types, OD-pairs, track clearance and operational restrictions on tracks, it was able to model a reasonable representation of daily traffic.

Tanker performance data that was not freely accessible, especially detailed tanker performance of exiting military tankers, can be a cause of reduced performance of the refuelling concept compared to research highlighted in Chapter 2. Fuel calculations are based on these performance characteristics and therefore efficiency can be affected. More accurate data on aircraft flight performance can change research outcome. However, comparing tanker efficiency of conceptual tanker designs, results lie close to presented values in other research.

The number of flights that can be simulated in the model is lower than in real life. On busy days, ATC provides track clearance to around 300 aircraft per flight direction. To maintain reasonable computational time, this number is cut in half. To preserve track density, the amount of main refuelling tracks is reduced as well.

Investing in the design of a tanker with the specific purpose to refuel commercial flights can be interesting. The tanker should have larger tanker capacity than both RECREATE tankers. With enhanced tanker performance, concept small fuel gains can be achieved. However, additional cost will presumably still make the concept unprofitable. Therefore it is also important the investigate the monetary value of possible indirect benefits as airline fleet flexibility to mitigate the costs of AAR operations.

8.2.2. Tanker operations

The problem is geographically limited to traffic over the North-Atlantic making use of the NATs because of its highly structured layout and dense traffic. This makes concept implementation in a real-life traffic environment easier. A single tanker base is used to test the AAR concept. Downside of this single base is that most cruiser flights have to make detours between OD-pairs. Potential fuel savings are therefore already partly lost. The introduction of a multi tanker base system mitigates this problem. On the other hand, more tankers will be required.

Selecting Gander International as tanker base location is a logical one based on geographical location. Looking from a practical perspective, it can be criticized. The track system begins/ends just on this longitude. This gives a problem for westbound traffic since refuelling procedures end in less structured airspace which can increase workload for local ATC to guide aircraft safely back to refuelling altitude.

No tanker trajectory optimization is included into the model. It is assumed that tankers fly in straight lines between cruisers, make immediate turns after ending refuelling procedures and change speed instantly after intercepting a cruiser. Tanker trajectory can be modelled in more detail to gain a better insight in tanker operations. This is also important considering another aspect not included in this research. Since tankers maintain a single flight level, refuelling altitude, it can occur that conflicts between tankers occur when crossing each other's flight trajectory while travelling from one cruiser to another. This safety aspect of AAR operations must be taken into account in future work.

A completely different form of refuelling operations can be tried where the tanker flies along with the cruiser over the Atlantic in a twin-tanker base system. Including a tanker base on both oceanic entry points, the tanker flies from one base to another travelling along with the stream of cruisers. On its way refuelling one or more cruisers to arrive in the end at the other tanker base. The benefit of this system over a multi-base system is that tankers are always at the right base, following traffic flow. In a multi-base system tankers have to be moved from one base to another in-between traffic flows depending on track location. Downside can be the operating time, since tankers have to make is from one base to another burning fuel themselves.

8.2.3. Fuel calculations

Compared to other studies, fuel savings calculations are less positive, while applying similar fuel calculation methods as most other studies. Used fuel calculation methods are also verified in previous chapter. The question arises if this work is too negative or other work too positive considering fuel savings. To answer this question methods and assumptions used in other research is compared to this research. There are several factors that influence concept efficiency. The chosen cruiser type is important in combination with the tanker used. Most studies use a new designed cruiser to enhance concept benefits, the same goes for the tanker that is used. Another finding that is not always considered are that detours play a significant role in the cruiser fuel savings. This could be solved by the introduction of more tanker bases on strategical locations. Furthermore, some other studies lack detailed tanker routing and tanker fuel calculations. Moreover, fixed offload volumes are applied while cruiser type and OD-pairs vary from cruiser to cruiser in a real-life traffic environment. Finally, tanker efficiencies that are stated in other literature can be achieved only for single offload operations. When more cruisers are included in the sequence this efficiency drops. All in all it can be concluded that assumptions can change concept profitability outcomes significantly.

8.2.4. Cost determination

This study includes two major cost components: fuel cost and tanker depreciation. However, some other cost that are left out in this study are important as well. The number of needed tankers influences not only depreciation costs, cost of tanker maintenance and crew cost are important costs as well to be incorporated in the model. The same applies to AAR specific cost as boom depreciation and maintenance. For now, including these cost is less relevant since the refuelling concept proofs to be unprofitable while even not all cost are taken into account. Next to costs, there are also indirect profits that are not incorporated into this model since they are hard to express in numbers. The AAR concept can enhance airline fleet flexibility due to the fact that short haul aircraft can be operated on long-haul OD-pairs. Furthermore, this concepts works as an enabler for point-to-point networks, which can open up new markets. These aspects are outside the scope of this research but can be interesting to investigate.

8.2.5. Problem formulation and solution method

It is chosen to use a static and deterministic problem where all input variables are known in advance and chosen vehicle routes will not change during their execution. However, this study does make use of stochastic input variables, known in advance, to determine these input variables to change scenarios. In reality, problems are hardly static and deterministic due to presence of uncertainty and interference. For the AAR concept this can be cruiser arrival time at the time window boundary or failure of a tanker. This uncertainty is not accounted for in the model. The presence of uncertainty will not enhance concept profitability, on the contrary. Furthermore, computational times increase due to the fact that solution route choices have to be reassessed over time. However, it can be interesting to research effects of uncertainty on concept implementation.

It can be concluded that the solution method chosen for this tanker routing and assigning problem is more effective than a VF formulation. In this study an exact SP formulation method is used. The reason why this works well is the use of strict time window constraints in combination with tankers that have a 'tight' fuel capacity. This limits the number of cruisers that can be included in a tanker sequence. Downside of this exact problem formulation is that larger tankers increase computational times significantly. To reduce computational times for larger tankers that can include more cruisers in its tanker sequence, other methods for column matrix generation are advised. Other studies, for example in the field of crew scheduling make use of heuristics like column generation in combination with the SP formulation to mitigate the problem of rapid growing size of this column matrix for larger sequences. This can be tried as well for the tanker routing problem.

A

Scenario generation data

A.1. Location of active oceanic tracks

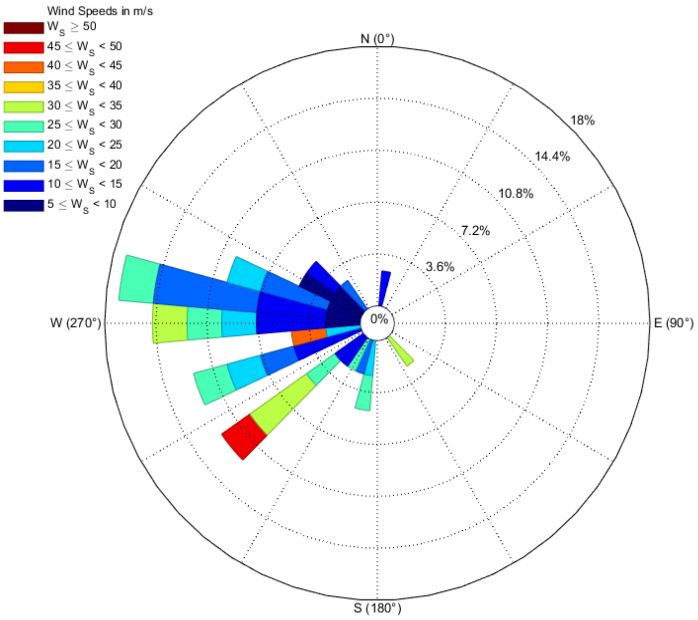
Overview of eastbound way-point count on active oceanic tracks

Way-point name	Latitude [°]	Longitude [°]	Position wrt tanker base	Way-point on active track count	Percentage of total count
SAVRY	59.3	-58.0	North	2	0.9%
DORYY	56.0	-57.0	North	1	0.4%
HOIST	55.0	-57.0	North	1	0.4%
LOMSI	53.1	-56.5	North	4	1.8%
NEEKO	52.2	-55.5	North	7	3.1%
RIKAL	51.5	-54.3	North	10	4.5%
TUDEP	51.1	-53.1	North	14	6.3%
ALLRY	51.0	-50.0	North	17	7.6%
UMESI	50.5	-52.4	North	3	1.3%
BUDAR	50.0	-52.0	North	6	2.7%
ELSIR	49.3	-52.0	North	19	8.5%
IBERG	49.0	-52.0	North	3	1.3%
JOOPY	48.3	-52.0	South	25	11.2%
MUSAK	48.0	-52.0	South	3	1.3%
NICSO	47.3	-52.0	South	21	9.4%
OMSAT	47.0	-52.0	South	5	2.2%
PORTI	46.3	-52.0	South	15	6.7%
RELIC	46.0	-52.0	South	6	2.7%
URTAK	45.5	-51.0	South	2	0.9%
SUPRY	45.3	-52.0	South	13	5.8%
RAFIN	44.5	-51.5	South	10	4.5%
BOBTU	44.1	-52.5	South	1	0.4%
DOVEY	41.7	-67.0	South	14	6.3%
JOBOC	40.7	-67.0	South	7	3.1%
SLATN	39.7	-67.0	South	1	0.4%
SOORY	38.3	-60.2	South	13	5.8%

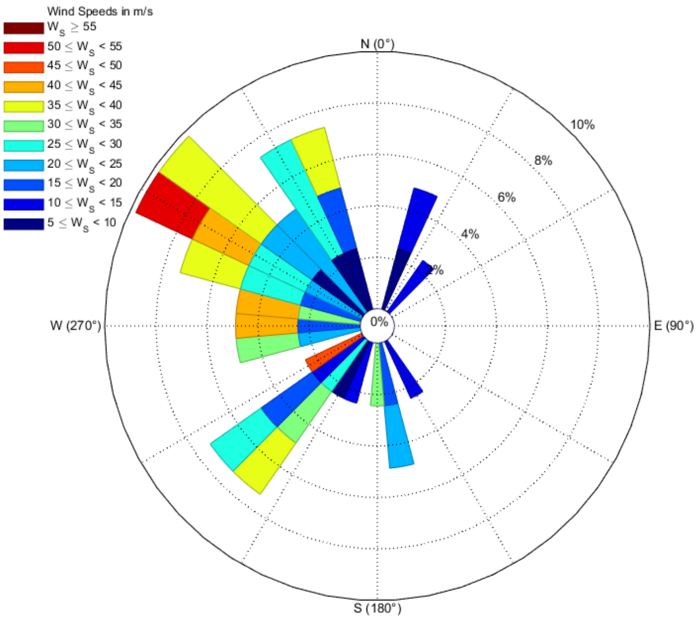
Overview of westbound way-point count on active oceanic tracks

Way-point name	Latitude [°]	Longitude [°]	Position wrt tanker base	Way-point on active track count	Percentage of total count
ADSAM	69.6	-63.1	North	1	0.5%
AVPUT	65.0	-60.0	North	1	0.5%
CLAVY	64.1	-59.0	North	2	1.0%
EMBOK	63.3	-58.0	North	0	0.0%
KETLA	62.3	-58.0	North	2	1.0%
MAXAR	61.3	-58.0	North	4	2.0%
PIDSO	60.3	-58.0	North	2	1.0%
SAVRY	59.3	-58.0	North	3	1.5%
URSAP	58.4	-57.3	North	0	0.0%
ALTOD	57.4	-57.0	North	0	0.0%
CUDDY	56.4	-57.0	North	4	2.0%
DORYY	56.0	-57.0	North	9	4.5%
ENNSO	55.3	-57.0	North	2	1.0%
HOIST	55.0	-57.0	North	15	7.5%
IRLOK	54.3	-57.0	North	6	3.0%
JANJO	54.0	-57.0	North	16	8.0%
LOMSI	53.1	-56.5	North	13	6.5%
MELDI	52.4	-56.2	North	3	1.5%
NEEKO	52.2	-55.5	North	10	5.0%
PELTU	52.1	-55.1	North	1	0.5%
RIKAL	51.5	-54.3	North	11	5.5%
SAXAN	51.3	-53.5	North	1	0.5%
TUDEP	51.1	-53.1	North	12	6.0%
UMESI	50.5	-52.4	North	3	1.5%
ALLRY	50.3	-52.0	North	10	5.0%
BUDAR	50.0	-52.0	North	3	1.5%
ELSIR	49.3	-52.0	North	9	4.5%
IBERG	49.0	-52.0	North	1	0.5%
JOOPY	48.3	-52.0	South	8	4.0%
MUSAK	48.0	-52.0	South	1	0.5%
NISCO	47.3	-52.0	South	6	3.0%
PORTI	46.3	-52.0	South	5	2.5%
RELIC	46.0	-52.0	South	1	0.5%
URTAK	45.5	-51.0	South	6	3.0%
SUPRY	45.3	-52.0	South	5	2.5%
RAFIN	44.5	-51.5	South	3	1.5%
BOBTU	44.1	-52.5	South	3	1.5%
JEBBY	43.0	-57.5	South	2	1.0%
DOVEY	41.7	-67.0	South	5	2.5%
JOBOC	40.7	-67.0	South	5	2.5%
SLATN	39.7	-67.0	South	1	0.5%
SOORY	38.3	-60.2	South	4	2.0%
BALOO	34.2	-62.8	South	2	1.0%

A.2. Additional wind roses



Wind rose for wind speed and direction measured 500 NM south of the tanker base at FL240



Wind rose for wind speed and direction measured 500 NM north of the tanker base at FL240

A.3. Ground speed measurements of trans-Atlantic flights

Overview of ground speeds measured for flights over the North Atlantic on December 15 2016, based on data from Flightradar24 [2016]

		Aircraft ground speed [km/h]			
		Atlantic		Land	
Callsign	**AC type**	**Westbound**	**Eastbound**	**Westbound**	**Eastbound**
AA704	A332	806	1022	767	1009
EI100	A332	806	1032	817	1015
AF23	A332	796	1017	806	933
AF639	A332	769	1035	819	964
EI124	A332	734	998	766	952
AA722	A332	779	992	814	966
DL43	B763	787	982	732	945
AA207	B763	770	981	754	983
UA30	B763	737	1027	741	989
DL496	B763	722	972	735	900
DL10	B763	743	1043	729	929
UA944	B763	736	1036	709	909
EI130	B752	725	905	675	877
EI118	B752	715	933	733	881
EI135	B752	749	922	715	887
UA127	B752	782	957	687	874
AA203	B752	759	926	674	922
UAL70	B752	770	907	772	898
DL275	B744	857	1017	770	1004
BA275	B744	843	1037	774	994
BA192	B744	806	1039	765	937
BA212	B744	804	1100	799	988
KL692	B744	809	1088	791	947
UA2281	B744	811	1079	790	963
Average ground speed [km/h]		775	1002	756	944
Delta average ground speed [km/h]		227		188	

B

Cruiser data

B.1. Cruiser performance overview

Tanker performance data and characteristics of tankers included in the model

	B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
Range [NM]	3,915	5,980	7,065	6,350	7,585	7,355	3,060
Range [km]	7,250	11,070	13,080	11,750	14,047	13,621	5,665
MTOW [kg]	115,680	186,880	297,550	242,000	396,890	227,930	79,010
WF [kg]	34,792	73,104	137,107	78,024	173,472	101,322	20,816
Max fuel capacity [lbs]	76,703	161,167	302,270	172,013	382,440	223,378	45,891
OEW [kg]	59,160	90,011	138,100	122,780	183,520	119,950	41,413
Payload [kg]	16,820	21,950	26,323	28,174	34,986	20,352	13,456
Typical payload (single passenger) [kg]	100	100	100	100	100	100	100
Seats	200	261	313	335	416	242	160
Load factor	0.841	0.841	0.841	0.841	0.841	0.841	0.841
MZFW [kg]	75980	111961	164423	150954	218506	140302	54869
Flight performance							
Cruise altitude [ft]	42000	43100	43100	41,000	45000	43100	41000
Vcruise [Mach]	0.8	0.8	0.84	0.82	0.84	0.84	0.78
L/D [cruise]	17.27	16.77	17.43	19.90	15.99	17.68	16.56
CD0 [cruise]	0.017	0.021	0.018	0.020	0.020	0.021	0.025
K [cruise]	0.049	0.042	0.045	0.032	0.049	0.037	0.036
CLmd [cruise]	0.595	0.708	0.643	0.788	0.638	0.758	0.843
K/CD0 [cruise]	2.821	1.995	2.417	1.609	2.458	1.742	1.407

B.2. Cruiser cruise speed conversion

Cruise speed conversion of cruisers from cruise altitude to refuelling altitude while maintaining ground speed

	Cruise speed at cruise and refuelling altitude [Mach]						
	B757-200	**B767-300ER**	**B777-200ER**	**A330-300**	**B747-400**	**B787-8**	**B737-800**
FL400	0.80	0.80	0.84	0.82	0.84	0.84	0.78
FL260	0.75	0.75	0.79	0.77	0.79	0.79	0.73
FL390	0.80	0.80	0.84	0.82	0.84	0.84	0.78
FL260	0.76	0.76	0.79	0.77	0.79	0.79	0.74
FL380	0.80	0.80	0.84	0.82	0.84	0.84	0.78
FL260	0.76	0.76	0.80	0.78	0.80	0.80	0.74
FL370	0.80	0.80	0.84	0.82	0.84	0.84	0.78
FL260	0.76	0.76	0.80	0.78	0.80	0.80	0.74

B.3. Cruiser fuel consumption direct operation

Cruiser fuel needed in direct operations, no wind

	Distance [NM]	Total fuel [kg]						
	LHR	B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
JFK	2991	32,705	45,695	67,823	51,392	84,121	50,552	23,194
ORD	3423	36,587	51,118	75,872	57,491	94,105	56,552	25,947
MIA	3839	40,283	56,281	83,536	63,297	103,609	62,263	28,568
LAX	4730	48,250	67,414	100,059	75,817	124,103	74,579	34,218
	CDG							
JFK	3150	34,126	47,680	70,769	53,623	87,775	52,747	24,201
ORD	3596	38,136	53,282	79,084	59,924	98,088	58,946	27,045
MIA	3980	41,550	58,053	86,165	65,290	106,871	64,223	29,467
LAX	4915	49,908	69,730	103,496	78,422	128,366	77,141	35,394
	FRA							
JFK	3341	35,836	50,070	74,316	56,311	92,174	55,392	25,415
ORD	3761	39,611	55,344	82,144	62,243	101,884	61,226	28,092
MIA	4191	43,435	60,687	90,074	68,252	111,719	67,137	30,803
LAX	5033	50,964	71,205	105,686	80,081	131,083	78,774	36,143

*Red numbers indicate fuel offload volume exceeds RECREATE tanker fuel capacity

Cruiser fuel needed in direct operations, 60 knots tailwind

Eastbound	Distance [NM]	Total fuel [kg]						
	LHR	B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
JFK	2617	29,537	41,269	61,252	46,412	75,972	45,655	20,948
ORD	2995	33,143	46,306	68,729	52,078	85,246	51,228	23,504
MIA	3359	36,615	51,157	75,929	57,534	94,176	56,595	25,967
LAX	4139	44,051	61,547	91,351	69,219	113,303	68,089	31,241
	CDG							
JFK	2756	30,864	43,123	64,004	48,498	79,385	47,706	21,889
ORD	3147	34,587	48,324	71,724	54,347	88,960	53,460	24,528
MIA	3483	37,791	52,801	78,370	59,383	97,203	58,414	26,801
LAX	4301	45,595	63,704	94,553	71,645	117,274	70,475	32,336
	FRA							
JFK	2923	32,458	45,350	67,310	51,003	83,486	50,170	23,019
ORD	3291	35,964	50,248	74,579	56,511	92,502	55,588	25,505
MIA	3667	39,553	55,262	82,022	62,150	101,732	61,136	28,050
LAX	4404	46,580	65,080	96,595	73,192	119,807	71,998	33,034

Cruiser fuel needed in direct operations, 60 knots headwind

Westbound	Distance	Total fuel [kg]						
LHR		B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
JFK	3365	36,670	51,234	76,043	57,620	94,317	56,679	26,006
ORD	3851	41,305	57,711	85,656	64,904	106,240	63,845	29,293
MIA	4319	45,769	63,948	94,914	71,918	117,722	70,745	32,459
LAX	5321	55,330	77,306	114,741	86,942	142,314	85,523	39,240
CDG								
JFK	3544	38,376	53,618	79,581	60,301	98,706	59,317	27,216
ORD	4046	41,305	57,711	85,656	64,904	106,240	63,845	29,293
MIA	4478	47,282	66,062	98,051	74,296	121,614	73,083	33,532
LAX	5529	57,315	80,080	118,858	90,061	147,420	88,591	40,647
FRA								
JFK	3759	40,425	56,481	83,832	63,521	103,977	62,485	28,669
ORD	4231	44,932	62,778	93,178	70,603	115,569	69,451	31,865
MIA	4715	49,546	69,225	102,747	77,854	127,437	76,583	35,138
LAX	5662	58,582	81,849	121,483	92,051	150,677	90,549	41,545

Cruiser fuel needed in direct operations, 120 knots tailwind

Eastbound	Distance	Total fuel [kg]						
LHR		B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
JFK	2617	25,971	36,286	53,857	40,809	66,800	40,143	18,418
ORD	2995	29,061	40,604	60,266	45,665	74,749	44,920	20,610
MIA	3359	32,037	44,762	66,437	50,341	82,403	49,520	22,721
LAX	4139	38,411	53,668	79,656	60,357	98,798	59,372	27,241
CDG								
JFK	2756	27,108	37,875	56,216	42,596	69,725	41,901	19,225
ORD	3147	30,299	42,333	62,832	47,610	77,932	46,833	21,488
MIA	3483	33,046	46,171	68,529	51,926	84,997	51,079	23,436
LAX	4301	39,735	55,517	82,400	62,437	102,202	61,418	28,180
FRA								
JFK	2923	28,475	39,785	59,049	44,743	73,240	44,013	20,194
ORD	3291	31,479	43,982	65,280	49,464	80,968	48,657	22,325
MIA	3667	34,556	48,280	71,659	54,298	88,880	53,412	24,506
LAX	4404	40,579	56,696	84,151	63,763	104,373	62,722	28,778

Cruiser fuel needed in direct operations, 120 knots headwind

Westbound	Distance	Total fuel [kg]						
LHR		B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
JFK	3365	40,236	56,216	83,439	63,223	103,490	62,192	28,535
ORD	3851	45,386	63,413	94,120	71,317	116,738	70,153	32,188
MIA	4319	50,346	70,343	104,406	79,111	129,495	77,819	35,705
LAX	5321	60,970	85,185	126,436	95,804	156,819	94,240	43,239
CDG								
JFK	3544	42,131	58,865	87,370	66,202	108,366	65,122	29,879
ORD	4046	45,386	63,413	94,120	71,317	116,738	70,153	32,188
MIA	4478	52,028	72,692	107,892	81,752	133,819	80,418	36,897
LAX	5529	63,176	88,267	131,010	99,270	162,493	97,649	44,803
FRA								
JFK	3759	44,409	62,047	92,092	69,781	114,223	68,642	31,494
ORD	4231	49,416	69,043	102,477	77,649	127,103	76,382	35,046
MIA	4715	54,543	76,207	113,109	85,705	140,290	84,307	38,681
LAX	5662	64,582	90,233	133,928	101,480	166,111	99,824	45,801

B.4. Cruiser fuel consumption staged operation

Fuel needed between OD-pairs for AAR operations, 0 knots tailwind

Eastbound OD-pair	Distance [NM]	Fuel per stage [kg]						
		B757-200	**B767-300ER**	**B777-200ER**	**A330-300**	**B747-400**	**B787-8**	**B737-800**
JFK - Base	956	13,693	19,131	28,395	21,516	35,219	21,165	9,711
Base - LHR	2,036	14,966	20,652	30,731	22,111	37,466	22,115	10,570
Total	**2,992**	**28,659**	**39,783**	**59,126**	**43,626**	**72,685**	**43,279**	**20,281**
% of direct ops	*100%*	*87%*	*86%*	*86%*	*84%*	*85%*	*85%*	*86%*
ORD - Base	1,455	18,452	25,781	38,265	28,995	47,461	28,522	13,086
Base - LHR	2,036	14,966	20,652	30,731	22,111	37,466	22,115	10,570
Total	**3,491**	**33,419**	**46,433**	**68,996**	**51,105**	**84,928**	**50,636**	**23,656**
% of direct ops	*102%*	*90%*	*89%*	*89%*	*87%*	*89%*	*88%*	*90%*
MIA - Base	1,836	22,087	30,859	45,802	34,705	56,808	34,139	15,664
Base - LHR	2,036	14,966	20,652	30,731	22,111	37,466	22,115	10,570
Total	**3,872**	**37,053**	**51,511**	**76,533**	**56,816**	**94,275**	**56,253**	**26,234**
% of direct ops	*101%*	*90%*	*90%*	*90%*	*88%*	*89%*	*88%*	*90%*
LAX - Base	2,925	32,474	45,372	67,342	51,027	83,525	50,194	23,030
Base - LHR	2,036	14,966	20,652	30,731	22,111	37,466	22,115	10,570
Total	**4,961**	**47,440**	**66,024**	**98,073**	**73,138**	**120,992**	**72,309**	**33,600**
% of direct ops	*105%*	*95%*	*95%*	*95%*	*94%*	*95%*	*94%*	*95%*
JFK - Base	956	13,693	19,131	28,395	21,516	35,219	21,165	9,711
Base - CDG	2,195	16,415	22,676	33,736	24,388	41,193	24,354	11,598
Total	**3,151**	**30,108**	**41,808**	**62,131**	**45,903**	**76,412**	**45,519**	**21,308**
% of direct ops	*100%*	*87%*	*86%*	*87%*	*84%*	*86%*	*85%*	*87%*
ORD - Base	1,455	18,452	25,781	38,265	28,995	47,461	28,522	13,086
Base - CDG	2,195	16,415	22,676	33,736	24,388	41,193	24,354	11,598
Total	**3,650**	**34,868**	**48,458**	**72,001**	**53,382**	**88,655**	**52,876**	**24,684**
% of direct ops	*102%*	*90%*	*89%*	*89%*	*87%*	*89%*	*88%*	*90%*
MIA - Base	1,836	22,087	30,859	45,802	34,705	56,808	34,139	15,664
Base - CDG	2,195	16,415	22,676	33,736	24,388	41,193	24,354	11,598
Total	**4,031**	**38,502**	**53,535**	**79,537**	**59,093**	**98,002**	**58,493**	**27,261**
% of direct ops	*101%*	*91%*	*90%*	*90%*	*88%*	*90%*	*89%*	*90%*
LAX - Base	2,925	32,474	45,372	67,342	51,027	83,525	50,194	23,030
Base - CDG	2,195	16,415	22,676	33,736	24,388	41,193	24,354	11,598
Total	**5,120**	**48,889**	**68,048**	**101,078**	**75,415**	**124,719**	**74,549**	**34,628**
% of direct ops	*104%*	*95%*	*95%*	*95%*	*93%*	*94%*	*94%*	*95%*
JFK - Base	956	13,693	19,131	28,395	21,516	35,219	21,165	9,711
Base - FRA	2,386	18,156	25,108	37,346	27,123	45,671	27,045	12,832
Total	**3,342**	**31,849**	**44,240**	**65,741**	**48,639**	**80,890**	**48,210**	**22,543**
% of direct ops	*100%*	*87%*	*87%*	*87%*	*85%*	*86%*	*86%*	*87%*
ORD - Base	1,455	18,452	25,781	38,265	28,995	47,461	28,522	13,086
Base - FRA	2,386	18,156	25,108	37,346	27,123	45,671	27,045	12,832
Total	**3,841**	**36,608**	**50,890**	**75,611**	**56,118**	**93,132**	**55,566**	**25,918**
% of direct ops	*102%*	*91%*	*90%*	*90%*	*88%*	*90%*	*89%*	*90%*
MIA - Base	1,836	22,087	30,859	45,802	34,705	56,808	34,139	15,664
Base - FRA	2,386	18,156	25,108	37,346	27,123	45,671	27,045	12,832
Total	**4,222**	**40,243**	**55,967**	**83,147**	**61,828**	**102,479**	**61,184**	**28,496**
% of direct ops	*101%*	*90%*	*90%*	*90%*	*88%*	*89%*	*89%*	*90%*
LAX - Base	2,925	32,474	45,372	67,342	51,027	83,525	50,194	23,030
Base - FRA	2,386	18,156	25,108	37,346	27,123	45,671	27,045	12,832
Total	**5,311**	**50,630**	**70,480**	**104,688**	**78,150**	**129,196**	**77,239**	**35,862**
% of direct ops	*106%*	*96%*	*96%*	*96%*	*95%*	*96%*	*95%*	*96%*

Fuel needed between OD-pairs for AAR operations, 0 knots headwind

Westbound OD-pair	Distance [NM]	Fuel per stage [kg]						
		B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
LHR - Base	2,036	23,994	33,524	49,758	37,703	61,715	37,087	17,016
Base - JFK	956	5,124	6,900	10,320	6,645	12,151	6,901	3,590
Total	**2,992**	**29,118**	**40,424**	**60,078**	**44,348**	**73,866**	**43,989**	**20,606**
% of direct ops	*100%*	*88%*	*87%*	*88%*	*85%*	*87%*	*86%*	*88%*
LHR - Base	2,036	23,994	33,524	49,758	37,703	61,715	37,087	17,016
Base - ORD	1,455	9,671	13,254	19,751	13,791	23,847	13,930	6,815
Total	**3,491**	**33,666**	**46,778**	**69,508**	**51,493**	**85,563**	**51,018**	**23,831**
% of direct ops	*102%*	*90%*	*90%*	*90%*	*88%*	*89%*	*89%*	*90%*
LHR - Base	2,036	23,994	33,524	49,758	37,703	61,715	37,087	17,016
Base - MIA	1,836	13,144	18,105	26,951	19,247	32,778	19,297	9,277
Total	**3,872**	**37,138**	**51,630**	**76,709**	**56,949**	**94,493**	**56,385**	**26,294**
% of direct ops	*101%*	*90%*	*90%*	*90%*	*88%*	*89%*	*89%*	*90%*
LHR - Base	2,036	23,994	33,524	49,758	37,703	61,715	37,087	17,016
Base - LAX	2,925	23,068	31,972	47,532	34,842	58,305	34,638	16,316
Total	**4,961**	**47,062**	**65,496**	**97,290**	**72,544**	**120,020**	**71,725**	**33,332**
% of direct ops	*105%*	*95%*	*94%*	*94%*	*93%*	*94%*	*93%*	*95%*
CDG - Base	2,195	25,511	35,643	52,903	40,086	65,616	39,432	18,092
Base - JFK	956	5,124	6,900	10,320	6,645	12,151	6,901	3,590
Total	**3,151**	**30,635**	**42,543**	**63,223**	**46,731**	**77,767**	**46,333**	**21,682**
% of direct ops	*100%*	*88%*	*88%*	*88%*	*86%*	*87%*	*87%*	*88%*
CDG - Base	2,195	25,511	35,643	52,903	40,086	65,616	39,432	18,092
Base - ORD	1,455	9,671	13,254	19,751	13,791	23,847	13,930	6,815
Total	**3,650**	**35,182**	**48,897**	**72,653**	**53,877**	**89,463**	**53,362**	**24,907**
% of direct ops	*102%*	*95%*	*94%*	*94%*	*92%*	*93%*	*93%*	*94%*
CDG - Base	2,195	25,511	35,643	52,903	40,086	65,616	39,432	18,092
Base - MIA	1,836	13,144	18,105	26,951	19,247	32,778	19,297	9,277
Total	**4,031**	**38,654**	**53,748**	**79,854**	**59,333**	**98,394**	**58,729**	**27,369**
% of direct ops	*101%*	*91%*	*90%*	*91%*	*89%*	*90%*	*89%*	*91%*
CDG - Base	2,195	25,511	35,643	52,903	40,086	65,616	39,432	18,092
Base - LAX	2,925	23,068	31,972	47,532	34,842	58,305	34,638	16,316
Total	**5,120**	**48,579**	**67,615**	**100,435**	**74,927**	**123,921**	**74,069**	**34,408**
% of direct ops	*104%*	*94%*	*94%*	*94%*	*93%*	*94%*	*93%*	*94%*
FRA - Base	2,386	27,333	38,189	56,681	42,948	70,302	42,248	19,384
Base - JFK	956	5,124	6,900	10,320	6,645	12,151	6,901	3,590
Total	**3,342**	**32,456**	**45,089**	**67,001**	**49,593**	**82,453**	**49,149**	**22,974**
% of direct ops	*100%*	*89%*	*89%*	*89%*	*87%*	*88%*	*87%*	*89%*
FRA - Base	2,386	27,333	38,189	56,681	42,948	70,302	42,248	19,384
Base - ORD	1,455	9,671	13,254	19,751	13,791	23,847	13,930	6,815
Total	**3,841**	**37,004**	**51,443**	**76,431**	**56,739**	**94,149**	**56,178**	**26,199**
% of direct ops	*102%*	*91%*	*91%*	*91%*	*89%*	*90%*	*90%*	*91%*
FRA - Base	2,386	27,333	38,189	56,681	42,948	70,302	42,248	19,384
Base - MIA	1,836	13,144	18,105	26,951	19,247	32,778	19,297	9,277
Total	**4,222**	**40,476**	**56,294**	**83,632**	**62,195**	**103,080**	**61,545**	**28,661**
% of direct ops	*101%*	*91%*	*90%*	*91%*	*89%*	*90%*	*89%*	*91%*
FRA - Base	2,386	27,333	38,189	56,681	42,948	70,302	42,248	19,384
Base - LAX	2,925	23,068	31,972	47,532	34,842	58,305	34,638	16,316
Total	**5,311**	**50,401**	**70,160**	**104,213**	**77,790**	**128,607**	**76,885**	**35,700**
% of direct ops	*106%*	*96%*	*96%*	*96%*	*94%*	*95%*	*95%*	*96%*

Fuel needed between OD-pairs for AAR operations, 60 knots tailwind

Eastbound OD-pair	**Distance [NM]**	**Fuel per stage [kg]**						
		B757-200	**B767-300ER**	**B777-200ER**	**A330-300**	**B747-400**	**B787-8**	**B737-800**
JFK - Base	837	12,553	17,539	26,031	19,724	32,287	19,403	8,902
Base - LHR	1,782	12,647	17,411	25,921	18,466	31,501	18,530	8,925
Total	**2,618**	**25,200**	**34,950**	**51,952**	**38,191**	**63,788**	**37,932**	**17,828**
% of direct ops	*100%*	*85%*	*85%*	*85%*	*82%*	*84%*	*83%*	*85%*
ORD - Base	1,273	16,718	23,358	34,668	26,269	42,999	25,840	11,856
Base - LHR	1,782	12,647	17,411	25,921	18,466	31,501	18,530	8,925
Total	**3,055**	**29,365**	**40,769**	**60,589**	**44,735**	**74,500**	**44,370**	**20,781**
% of direct ops	*102%*	*89%*	*88%*	*88%*	*86%*	*87%*	*87%*	*88%*
MIA - Base	1,607	19,897	27,800	41,262	31,265	51,178	30,755	14,111
Base - LHR	1,782	12,647	17,411	25,921	18,466	31,501	18,530	8,925
Total	**3,388**	**32,544**	**45,212**	**67,183**	**49,732**	**82,679**	**49,285**	**23,036**
% of direct ops	*101%*	*89%*	*88%*	*88%*	*86%*	*88%*	*87%*	*89%*
LAX - Base	2,559	28,986	40,499	60,110	45,547	74,555	44,804	20,557
Base - LHR	1,782	12,647	17,411	25,921	18,466	31,501	18,530	8,925
Total	**4,341**	**41,633**	**57,910**	**86,031**	**64,013**	**106,056**	**63,333**	**29,482**
% of direct ops	*105%*	*95%*	*94%*	*94%*	*92%*	*94%*	*93%*	*94%*
JFK - Base	837	12,553	17,539	26,031	19,724	32,287	19,403	8,902
Base - CDG	1,921	13,915	19,183	28,550	20,459	34,762	20,489	9,824
Total	**2,757**	**26,468**	**36,722**	**54,582**	**40,183**	**67,049**	**39,892**	**18,727**
% of direct ops	*100%*	*86%*	*85%*	*85%*	*83%*	*84%*	*84%*	*86%*
ORD - Base	1,273	16,718	23,358	34,668	26,269	42,999	25,840	11,856
Base - CDG	1,921	13,915	19,183	28,550	20,459	34,762	20,489	9,824
Total	**3,194**	**30,632**	**42,540**	**63,218**	**46,727**	**77,761**	**46,330**	**21,680**
% of direct ops	*102%*	*89%*	*88%*	*88%*	*86%*	*87%*	*87%*	*88%*
MIA - Base	1,607	19,897	27,800	41,262	31,265	51,178	30,755	14,111
Base - CDG	1,921	13,915	19,183	28,550	20,459	34,762	20,489	9,824
Total	**3,527**	**33,812**	**46,983**	**69,812**	**51,724**	**85,940**	**51,245**	**23,935**
% of direct ops	*101%*	*89%*	*89%*	*89%*	*87%*	*88%*	*88%*	*89%*
LAX - Base	2,559	28,986	40,499	60,110	45,547	74,555	44,804	20,557
Base - CDG	1,921	13,915	19,183	28,550	20,459	34,762	20,489	9,824
Total	**4,480**	**42,901**	**59,682**	**88,661**	**66,006**	**109,317**	**65,293**	**30,381**
% of direct ops	*104%*	*94%*	*94%*	*94%*	*92%*	*93%*	*93%*	*94%*
JFK - Base	837	12,553	17,539	26,031	19,724	32,287	19,403	8,902
Base - FRA	2,088	15,438	21,311	31,709	22,852	38,679	22,844	10,904
Total	**2,924**	**27,991**	**38,850**	**57,740**	**42,576**	**70,967**	**42,246**	**19,807**
% of direct ops	*100%*	*86%*	*86%*	*86%*	*83%*	*85%*	*84%*	*86%*
ORD - Base	1,273	16,718	23,358	34,668	26,269	42,999	25,840	11,856
Base - FRA	2,088	15,438	21,311	31,709	22,852	38,679	22,844	10,904
Total	**3,361**	**32,156**	**44,668**	**66,377**	**49,121**	**81,679**	**48,684**	**22,761**
% of direct ops	*102%*	*89%*	*89%*	*89%*	*87%*	*88%*	*88%*	*89%*
MIA - Base	1,607	19,897	27,800	41,262	31,265	51,178	30,755	14,111
Base - FRA	2,088	15,438	21,311	31,709	22,852	38,679	22,844	10,904
Total	**3,694**	**35,335**	**49,111**	**72,971**	**54,117**	**89,857**	**53,599**	**25,016**
% of direct ops	*101%*	*89%*	*89%*	*89%*	*87%*	*88%*	*88%*	*89%*
LAX - Base	2,559	28,986	40,499	60,110	45,547	74,555	44,804	20,557
Base - FRA	2,088	15,438	21,311	31,709	22,852	38,679	22,844	10,904
Total	**4,647**	**44,424**	**61,810**	**91,819**	**68,399**	**113,235**	**67,647**	**31,461**
% of direct ops	*106%*	*95%*	*95%*	*95%*	*93%*	*95%*	*94%*	*95%*

Fuel needed between OD-pairs for AAR operations, 60 knots headwind

Westbound OD-pair	Distance [NM]	Fuel per stage [kg]						
		B757-200	**B767-300ER**	**B777-200ER**	**A330-300**	**B747-400**	**B787-8**	**B737-800**
LHR - Base	2,291	26,422	36,916	54,792	41,517	67,959	40,840	18,738
Base - JFK	1,076	6,213	8,422	12,578	8,356	14,952	8,585	4,362
Total	**3,366**	**32,635**	**45,338**	**67,370**	**49,873**	**82,911**	**49,424**	**23,100**
% of direct ops	*100%*	*89%*	*88%*	*89%*	*87%*	*88%*	*87%*	*89%*
LHR - Base	2,291	26,422	36,916	54,792	41,517	67,959	40,840	18,738
Base - ORD	1,637	11,329	15,570	23,188	16,395	28,111	16,492	7,990
Total	**3,927**	**37,751**	**52,486**	**77,980**	**57,912**	**96,070**	**57,332**	**26,728**
% of direct ops	*102%*	*91%*	*91%*	*91%*	*89%*	*90%*	*90%*	*91%*
LHR - Base	2,291	26,422	36,916	54,792	41,517	67,959	40,840	18,738
Base - MIA	2,066	15,235	21,028	31,288	22,533	38,158	22,530	10,761
Total	**4,356**	**41,657**	**57,943**	**86,080**	**64,050**	**106,117**	**63,370**	**29,499**
% of direct ops	*101%*	*91%*	*91%*	*91%*	*89%*	*90%*	*90%*	*91%*
LHR - Base	2,291	26,422	36,916	54,792	41,517	67,959	40,840	18,738
Base - LAX	3,291	26,400	36,627	54,442	40,078	66,875	39,788	18,679
Total	**5,581**	**52,822**	**73,543**	**109,234**	**81,595**	**134,834**	**80,628**	**37,417**
% of direct ops	*105%*	*95%*	*95%*	*95%*	*94%*	*95%*	*94%*	*95%*
CDG - Base	2,469	28,128	39,300	58,330	44,198	72,347	43,477	19,948
Base - JFK	1,076	6,213	8,422	12,578	8,356	14,952	8,585	4,362
Total	**3,545**	**34,341**	**47,722**	**70,908**	**52,554**	**87,299**	**52,061**	**24,310**
% of direct ops	*100%*	*89%*	*89%*	*89%*	*87%*	*88%*	*88%*	*89%*
CDG - Base	2,469	28,128	39,300	58,330	44,198	72,347	43,477	19,948
Base - ORD	1,637	11,329	15,570	23,188	16,395	28,111	16,492	7,990
Total	**4,106**	**39,457**	**54,870**	**81,518**	**60,593**	**100,458**	**59,969**	**27,938**
% of direct ops	*102%*	*96%*	*95%*	*95%*	*93%*	*95%*	*94%*	*95%*
CDG - Base	2,469	28,128	39,300	58,330	44,198	72,347	43,477	19,948
Base - MIA	2,066	15,235	21,028	31,288	22,533	38,158	22,530	10,761
Total	**4,535**	**43,363**	**60,327**	**89,618**	**66,731**	**110,505**	**66,007**	**30,709**
% of direct ops	*101%*	*92%*	*91%*	*91%*	*90%*	*91%*	*90%*	*92%*
CDG - Base	2,469	28,128	39,300	58,330	44,198	72,347	43,477	19,948
Base - LAX	3,291	26,400	36,627	54,442	40,078	66,875	39,788	18,679
Total	**5,760**	**54,528**	**75,927**	**112,772**	**84,276**	**139,223**	**83,265**	**38,627**
% of direct ops	*104%*	*95%*	*95%*	*95%*	*94%*	*94%*	*94%*	*95%*
FRA - Base	2,684	30,177	42,163	62,580	47,419	77,619	46,645	21,402
Base - JFK	1,076	6,213	8,422	12,578	8,356	14,952	8,585	4,362
Total	**3,760**	**36,390**	**50,585**	**75,159**	**55,775**	**92,571**	**55,229**	**25,764**
% of direct ops	*100%*	*90%*	*90%*	*90%*	*88%*	*89%*	*88%*	*90%*
FRA - Base	2,684	30,177	42,163	62,580	47,419	77,619	46,645	21,402
Base - ORD	1,637	11,329	15,570	23,188	16,395	28,111	16,492	7,990
Total	**4,321**	**41,506**	**57,733**	**85,768**	**63,814**	**105,730**	**63,137**	**29,392**
% of direct ops	*102%*	*92%*	*92%*	*92%*	*90%*	*91%*	*91%*	*92%*
FRA - Base	2,684	30,177	42,163	62,580	47,419	77,619	46,645	21,402
Base - MIA	2,066	15,235	21,028	31,288	22,533	38,158	22,530	10,761
Total	**4,750**	**45,413**	**63,191**	**93,869**	**69,952**	**115,777**	**69,175**	**32,162**
% of direct ops	*101%*	*92%*	*91%*	*91%*	*90%*	*91%*	*90%*	*92%*
FRA - Base	2,684	30,177	42,163	62,580	47,419	77,619	46,645	21,402
Base - LAX	3,291	26,400	36,627	54,442	40,078	66,875	39,788	18,679
Total	**5,975**	**56,578**	**78,790**	**117,022**	**87,496**	**144,494**	**86,433**	**40,080**
% of direct ops	*106%*	*97%*	*96%*	*96%*	*95%*	*96%*	*95%*	*96%*

Fuel needed between OD-pairs for AAR operations, 120 knots tailwind

Eastbound OD-pair	Distance [NM]	Fuel per stage [kg]						
		B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
JFK - Base	717	11,413	15,946	23,667	17,933	29,356	17,641	8,094
Base - LHR	1,527	10,328	14,171	21,111	14,822	25,535	14,945	7,280
Total	**2,244**	**21,741**	**30,117**	**44,779**	**32,755**	**54,891**	**32,586**	**15,374**
% of direct ops	*100%*	*84%*	*83%*	*83%*	*80%*	*82%*	*81%*	*83%*
ORD - Base	1,091	14,983	20,934	31,070	23,543	38,537	23,159	10,626
Base - LHR	1,527	10,328	14,171	21,111	14,822	25,535	14,945	7,280
Total	**2,618**	**25,310**	**35,105**	**52,182**	**38,365**	**64,072**	**38,103**	**17,906**
% of direct ops	*102%*	*87%*	*86%*	*87%*	*84%*	*86%*	*85%*	*87%*
MIA - Base	1,377	17,708	24,742	36,722	27,825	45,548	27,372	12,559
Base - LHR	1,527	10,328	14,171	21,111	14,822	25,535	14,945	7,280
Total	**2,904**	**28,036**	**38,913**	**57,834**	**42,647**	**71,083**	**42,316**	**19,839**
% of direct ops	*101%*	*88%*	*87%*	*87%*	*85%*	*86%*	*85%*	*87%*
LAX - Base	2,194	25,499	35,627	52,878	40,067	65,585	39,413	18,084
Base - LHR	1,527	10,328	14,171	21,111	14,822	25,535	14,945	7,280
Total	**3,721**	**35,826**	**49,797**	**73,989**	**54,889**	**91,120**	**54,358**	**25,364**
% of direct ops	*105%*	*93%*	*93%*	*93%*	*91%*	*92%*	*92%*	*93%*
JFK - Base	717	11,413	15,946	23,667	17,933	29,356	17,641	8,094
Base - CDG	1,646	11,414	15,689	23,365	16,530	28,330	16,624	8,051
Total	**2,363**	**22,827**	**31,635**	**47,032**	**34,463**	**57,686**	**34,265**	**16,145**
% of direct ops	*100%*	*84%*	*84%*	*84%*	*81%*	*83%*	*82%*	*84%*
ORD - Base	1,091	14,983	20,934	31,070	23,543	38,537	23,159	10,626
Base - CDG	1,646	11,414	15,689	23,365	16,530	28,330	16,624	8,051
Total	**2,738**	**26,397**	**36,623**	**54,435**	**40,072**	**66,868**	**39,783**	**18,677**
% of direct ops	*102%*	*87%*	*87%*	*87%*	*84%*	*86%*	*85%*	*87%*
MIA - Base	1,377	17,708	24,742	36,722	27,825	45,548	27,372	12,559
Base - CDG	1,646	11,414	15,689	23,365	16,530	28,330	16,624	8,051
Total	**3,023**	**29,123**	**40,431**	**60,087**	**44,355**	**73,878**	**43,996**	**20,610**
% of direct ops	*101%*	*88%*	*88%*	*88%*	*85%*	*87%*	*86%*	*88%*
LAX - Base	2,194	25,499	35,627	52,878	40,067	65,585	39,413	18,084
Base - CDG	1,646	11,414	15,689	23,365	16,530	28,330	16,624	8,051
Total	**3,840**	**36,913**	**51,316**	**76,243**	**56,597**	**93,916**	**56,038**	**26,135**
% of direct ops	*104%*	*93%*	*92%*	*93%*	*91%*	*92%*	*91%*	*93%*
JFK - Base	717	11,413	15,946	23,667	17,933	29,356	17,641	8,094
Base - FRA	1,790	12,720	17,513	26,072	18,581	31,688	18,642	8,977
Total	**2,507**	**24,133**	**33,459**	**49,740**	**36,514**	**61,044**	**36,283**	**17,071**
% of direct ops	*100%*	*85%*	*84%*	*84%*	*82%*	*83%*	*82%*	*85%*
ORD - Base	1,091	14,983	20,934	31,070	23,543	38,537	23,159	10,626
Base - FRA	1,790	12,720	17,513	26,072	18,581	31,688	18,642	8,977
Total	**2,881**	**27,703**	**38,447**	**57,143**	**42,124**	**70,225**	**41,801**	**19,603**
% of direct ops	*102%*	*88%*	*87%*	*88%*	*85%*	*87%*	*86%*	*88%*
MIA - Base	1,377	17,708	24,742	36,722	27,825	45,548	27,372	12,559
Base - FRA	1,790	12,720	17,513	26,072	18,581	31,688	18,642	8,977
Total	**3,167**	**30,428**	**42,255**	**62,795**	**46,406**	**77,236**	**46,014**	**21,536**
% of direct ops	*101%*	*88%*	*88%*	*88%*	*85%*	*87%*	*86%*	*88%*
LAX - Base	2,194	25,499	35,627	52,878	40,067	65,585	39,413	18,084
Base - FRA	1,790	12,720	17,513	26,072	18,581	31,688	18,642	8,977
Total	**3,983**	**38,219**	**53,140**	**78,950**	**58,648**	**97,274**	**58,056**	**27,060**
% of direct ops	*106%*	*94%*	*94%*	*94%*	*92%*	*93%*	*93%*	*94%*

Fuel needed between OD-pairs for AAR operations, 120 knots headwind

Westbound OD-pair	Distance [NM]	Fuel per stage [kg]						
		B757-200	B767-300ER	B777-200ER	A330-300	B747-400	B787-8	B737-800
LHR - Base	2,545	28,849	40,308	59,826	45,331	74,203	44,592	20,460
Base - JFK	1,195	7,302	9,943	14,837	10,068	17,753	10,268	5,135
Total	**3,740**	**36,151**	**50,251**	**74,663**	**55,399**	**91,956**	**54,860**	**25,594**
% of direct ops	*100%*	*90%*	*89%*	*89%*	*88%*	*89%*	*88%*	*90%*
LHR - Base	2,545	28,849	40,308	59,826	45,331	74,203	44,592	20,460
Base - ORD	1,819	12,986	17,886	26,625	19,000	32,374	19,054	9,166
Total	**4,364**	**41,836**	**58,193**	**86,451**	**64,331**	**106,577**	**63,646**	**29,626**
% of direct ops	*102%*	*92%*	*92%*	*92%*	*90%*	*91%*	*91%*	*92%*
LHR - Base	2,545	28,849	40,308	59,826	45,331	74,203	44,592	20,460
Base - MIA	2,295	17,327	23,950	35,626	25,820	43,537	25,763	12,244
Total	**4,840**	**46,176**	**64,257**	**95,452**	**71,151**	**117,740**	**70,355**	**32,704**
% of direct ops	*101%*	*92%*	*91%*	*91%*	*90%*	*91%*	*90%*	*92%*
LHR - Base	2,545	28,849	40,308	59,826	45,331	74,203	44,592	20,460
Base - LAX	3,656	29,732	41,283	61,352	45,313	75,446	44,938	21,042
Total	**6,201**	**58,582**	**81,590**	**121,178**	**90,645**	**149,649**	**89,530**	**41,502**
% of direct ops	*105%*	*96%*	*96%*	*96%*	*95%*	*95%*	*95%*	*96%*
CDG - Base	2,744	30,745	42,956	63,757	48,310	79,079	47,522	21,804
Base - JFK	1,195	7,302	9,943	14,837	10,068	17,753	10,268	5,135
Total	**3,939**	**38,047**	**52,900**	**78,594**	**58,378**	**96,832**	**57,790**	**26,939**
% of direct ops	*100%*	*90%*	*90%*	*90%*	*88%*	*89%*	*89%*	*90%*
CDG - Base	2,744	30,745	42,956	63,757	48,310	79,079	47,522	21,804
Base - ORD	1,819	12,986	17,886	26,625	19,000	32,374	19,054	9,166
Total	**4,563**	**43,731**	**60,842**	**90,382**	**67,310**	**111,453**	**66,576**	**30,970**
% of direct ops	*102%*	*96%*	*96%*	*96%*	*94%*	*95%*	*95%*	*96%*
CDG - Base	2,744	30,745	42,956	63,757	48,310	79,079	47,522	21,804
Base - MIA	2,295	17,327	23,950	35,626	25,820	43,537	25,763	12,244
Total	**5,039**	**48,072**	**66,906**	**99,383**	**74,130**	**122,616**	**73,285**	**34,048**
% of direct ops	*101%*	*92%*	*92%*	*92%*	*91%*	*92%*	*91%*	*92%*
CDG - Base	2,744	30,745	42,956	63,757	48,310	79,079	47,522	21,804
Base - LAX	3,656	29,732	41,283	61,352	45,313	75,446	44,938	21,042
Total	**6,400**	**60,477**	**84,239**	**125,109**	**93,624**	**154,525**	**92,460**	**42,846**
% of direct ops	*104%*	*96%*	*95%*	*95%*	*94%*	*95%*	*95%*	*96%*
FRA - Base	2,983	33,022	46,138	68,480	51,889	84,936	51,042	23,419
Base - JFK	1,195	7,302	9,943	14,837	10,068	17,753	10,268	5,135
Total	**4,178**	**40,324**	**56,081**	**83,317**	**61,956**	**102,689**	**61,310**	**28,554**
% of direct ops	*100%*	*91%*	*90%*	*90%*	*89%*	*90%*	*89%*	*91%*
FRA - Base	2,983	33,022	46,138	68,480	51,889	84,936	51,042	23,419
Base - ORD	1,819	12,986	17,886	26,625	19,000	32,374	19,054	9,166
Total	**4,801**	**46,009**	**64,024**	**95,105**	**70,889**	**117,310**	**70,096**	**32,585**
% of direct ops	*102%*	*93%*	*93%*	*93%*	*91%*	*92%*	*92%*	*93%*
FRA - Base	2,983	33,022	46,138	68,480	51,889	84,936	51,042	23,419
Base - MIA	2,295	17,327	23,950	35,626	25,820	43,537	25,763	12,244
Total	**5,278**	**50,349**	**70,088**	**104,105**	**77,709**	**128,474**	**76,805**	**35,663**
% of direct ops	*101%*	*92%*	*92%*	*92%*	*91%*	*92%*	*91%*	*92%*
FRA - Base	2,983	33,022	46,138	68,480	51,889	84,936	51,042	23,419
Base - LAX	3,656	29,732	41,283	61,352	45,313	75,446	44,938	21,042
Total	**6,639**	**62,755**	**87,421**	**129,832**	**97,202**	**160,382**	**95,980**	**44,461**
% of direct ops	*106%*	*97%*	*97%*	*97%*	*96%*	*97%*	*96%*	*97%*

C

Tanker performance data

Tanker performance data and characteristics of tankers included in the model

	RECREATE Conventional	RECREATE Joined-wing	A310 MRTT	A330 MRTT	KC-46 pegasus
Dimensions					
Aspect Ratio	9.56	9.07	8.79	10.04	8.17
Length [m]	33.9	21.8	-	-	-
Span [m]	30.9	30.1	43.9	60.3	48.1
Area [m²]	100.0	100.0	219.3	362.0	283.3
Weight					
MTOW [kg]	67,154	63,022	163,998	233,000	188,241
WF [kg]	48,633	48,063	77,500	111,000	96,265
OEW [kg]	18,521	14,959	86,498	125,000	91,976
WF/MTOW	0.72	0.76	0.47	0.48	0.51
Performance					
V [Mach] @ FL260	0.8	0.8	0.8	0.8	0.8
SFC	0.70057	0.6864	0.63947	0.605	0.655
L/D [cruise]	19.06	19.51	15.91	20.00	16.22
Tanker efficiency	7.74	8.38	-	-	-
Number of refuels [14,152 kg]	3	3	5	7	6
CD0 cruise	0.019	0.022	0.025	0.019	0.020
K cruise	0.036	0.031	0.040	0.033	0.049
CLmd	0.725	0.840	0.793	0.758	0.633
K/CD0 cruise	1.903	1.417	1.589	1.739	2.497
e	0.92	1.15	0.91	0.96	0.80
Cost					
Acqusition cost [US$]	90,700,000	90,700,000	120,000,000	232,200,000	147,400,000
Depreciation cost [$/day]	12,425	12,425	16,438	31,808	20,192

D
Additional results

Case study cruiser flight schedule including 125 cruisers in westbound direction

Track #	Cruise speed [Mach]	Refuelling speed [Mach]	Arrival time at T_w [min]	Cruiser type	OD pair	1st stage cruiser fuel [kg]	2nd stage cruiser fuel [kg]	Total concept cruiser fuel [kg]	Total cruiser fuel direct ops [kg]
4	0.82	0.77	36	5	2	62,180	25,048	87,228	94,105
5	0.84	0.80	37	7	4	17,145	16,032	33,177	34,218
2	0.84	0.79	40	6	1	37,367	8,084	45,451	50,552
7	0.78	0.74	45	1	1	24,175	5,889	30,064	32,705
8	0.8	0.75	52	3	6	53,083	20,719	73,802	79,084
3	0.8	0.76	57	2	11	38,156	18,495	56,651	60,687
4	0.82	0.77	59	5	3	62,180	33,496	95,676	103,609
6	0.84	0.79	59	7	7	18,153	9,476	27,629	29,467
2	0.84	0.79	64	5	4	62,180	57,276	119,456	124,103
1	0.82	0.78	67	5	2	62,180	25,048	87,228	94,105
4	0.82	0.77	71	5	9	70,243	14,119	84,362	92,174
5	0.84	0.80	72	7	4	17,145	16,032	33,177	34,218
7	0.78	0.74	73	1	1	24,175	5,889	30,064	32,705
8	0.8	0.75	74	2	10	38,156	13,906	52,062	55,344
2	0.84	0.79	80	5	3	62,180	33,496	95,676	103,609
6	0.84	0.79	86	7	8	18,153	16,032	34,185	35,394
5	0.84	0.80	87	7	5	18,153	4,133	22,286	24,201
3	0.8	0.76	88	3	10	56,634	20,719	77,353	82,144
4	0.82	0.77	93	6	4	37,367	34,018	71,385	74,579
1	0.82	0.78	95	6	5	39,566	8,084	47,650	52,747
2	0.84	0.79	100	6	1	37,367	8,084	45,451	50,552
7	0.78	0.74	103	1	11	27,310	13,423	40,733	43,435
3	0.8	0.76	107	2	2	33,777	13,906	47,683	51,118
8	0.8	0.75	108	2	3	33,777	18,495	52,272	56,281
6	0.84	0.79	110	7	2	17,145	7,146	24,291	25,947

1	0.82	0.78	112	5	12	70,243	57,276	127,519	131,083
4	0.82	0.77	112	4	2	37,987	14,525	52,512	57,491
5	0.84	0.80	114	7	1	17,145	4,133	21,278	23,194
2	0.84	0.79	117	5	5	65,839	14,119	79,958	87,775
3	0.8	0.76	119	3	2	50,133	20,719	70,852	75,872
1	0.82	0.78	135	5	8	65,839	57,276	123,115	128,366
6	0.84	0.79	138	7	9	19,368	4,133	23,501	25,415
7	0.78	0.74	138	1	1	24,175	5,889	30,064	32,705
8	0.8	0.75	138	3	10	56,634	20,719	77,353	82,144
4	0.82	0.77	140	5	2	62,180	25,048	87,228	94,105
5	0.84	0.80	140	7	7	18,153	9,476	27,629	29,467
2	0.84	0.79	145	5	9	70,243	14,119	84,362	92,174
3	0.8	0.76	145	3	5	53,083	11,907	64,990	70,769
6	0.84	0.79	154	7	3	17,145	9,476	26,621	28,568
8	0.8	0.75	160	2	2	33,777	13,906	47,683	51,118
2	0.84	0.79	166	5	11	70,243	33,496	103,739	111,719
1	0.82	0.78	168	6	3	37,367	19,729	57,096	62,263
5	0.84	0.80	168	7	4	17,145	16,032	33,177	34,218
3	0.8	0.76	169	3	5	53,083	11,907	64,990	70,769
4	0.82	0.77	169	4	2	37,987	14,525	52,512	57,491
7	0.78	0.74	170	1	5	25,598	5,889	31,487	34,126
2	0.84	0.79	180	4	1	37,987	7,848	45,835	51,392
8	0.8	0.75	181	3	6	53,083	20,719	73,802	79,084
3	0.8	0.76	188	2	1	33,777	7,969	41,746	45,695
6	0.84	0.79	188	7	10	19,368	7,146	26,514	28,092
5	0.84	0.80	190	7	1	17,145	4,133	21,278	23,194
7	0.78	0.74	194	1	5	25,598	5,889	31,487	34,126
4	0.82	0.77	196	5	11	70,243	33,496	103,739	111,719
8	0.8	0.75	196	2	1	33,777	7,969	41,746	45,695
1	0.82	0.78	201	5	10	70,243	25,048	95,291	101,884
3	0.8	0.76	203	3	7	53,083	27,530	80,613	86,165
2	0.84	0.79	204	5	5	65,839	14,119	79,958	87,775
8	0.8	0.75	210	3	6	53,083	20,719	73,802	79,084
1	0.82	0.78	214	5	10	70,243	25,048	95,291	101,884
5	0.84	0.80	215	7	5	18,153	4,133	22,286	24,201
6	0.84	0.79	219	7	1	17,145	4,133	21,278	23,194
8	0.8	0.75	221	3	11	56,634	27,530	84,164	90,074
3	0.8	0.76	223	3	2	50,133	20,719	70,852	75,872
4	0.82	0.77	223	6	1	37,367	8,084	45,451	50,552
5	0.84	0.80	226	7	9	19,368	4,133	23,501	25,415
1	0.82	0.78	229	5	1	62,180	14,119	76,299	84,121
2	0.84	0.79	234	5	12	70,243	57,276	127,519	131,083
5	0.84	0.80	237	7	8	18,153	16,032	34,185	35,394
1	0.82	0.78	240	5	3	62,180	33,496	95,676	103,609
4	0.82	0.77	242	5	1	62,180	14,119	76,299	84,121

3	0.8	0.76	245	3	12	56,634	46,703	103,337	105,686
6	0.84	0.79	247	7	1	17,145	4,133	21,278	23,194
2	0.84	0.79	251	6	2	37,367	14,652	52,019	56,552
5	0.84	0.80	252	7	12	19,368	16,032	35,400	36,143
8	0.8	0.75	254	3	6	53,083	20,719	73,802	79,084
1	0.82	0.78	261	6	7	39,566	19,729	59,295	64,223
3	0.8	0.76	262	3	3	50,133	27,530	77,663	83,536
5	0.84	0.80	265	7	9	19,368	4,133	23,501	25,415
2	0.84	0.79	266	4	9	42,913	7,848	50,761	56,311
4	0.82	0.77	269	6	1	37,367	8,084	45,451	50,552
6	0.84	0.79	269	7	2	17,145	7,146	24,291	25,947
1	0.82	0.78	271	6	9	42,212	8,084	50,296	55,392
5	0.84	0.80	277	7	4	17,145	16,032	33,177	34,218
3	0.8	0.76	279	2	1	33,777	7,969	41,746	45,695
8	0.8	0.75	280	3	1	50,133	11,907	62,040	67,823
2	0.84	0.79	286	4	4	37,987	34,213	72,200	75,817
4	0.82	0.77	287	5	5	65,839	14,119	79,958	87,775
5	0.84	0.80	290	7	1	17,145	4,133	21,278	23,194
1	0.82	0.78	292	4	1	37,987	7,848	45,835	51,392
8	0.8	0.75	293	2	10	38,156	13,906	52,062	55,344
3	0.8	0.76	300	3	3	50,133	27,530	77,663	83,536
6	0.84	0.79	300	7	9	19,368	4,133	23,501	25,415
4	0.82	0.77	311	6	3	37,367	19,729	57,096	62,263
8	0.8	0.75	313	3	6	53,083	20,719	73,802	79,084
5	0.84	0.80	314	7	9	19,368	4,133	23,501	25,415
1	0.82	0.78	318	5	1	62,180	14,119	76,299	84,121
2	0.84	0.79	320	5	2	62,180	25,048	87,228	94,105
8	0.8	0.75	324	3	9	56,634	11,907	68,541	74,316
5	0.84	0.80	328	7	10	19,368	7,146	26,514	28,092
4	0.82	0.77	329	5	10	70,243	25,048	95,291	101,884
6	0.84	0.79	329	7	7	18,153	9,476	27,629	29,467
3	0.8	0.76	332	3	1	50,133	11,907	62,040	67,823
1	0.82	0.78	335	4	9	42,913	7,848	50,761	56,311
8	0.8	0.75	339	3	9	56,634	11,907	68,541	74,316
4	0.82	0.77	350	4	1	37,987	7,848	45,835	51,392
2	0.84	0.79	355	5	1	62,180	14,119	76,299	84,121
6	0.84	0.79	356	7	10	19,368	7,146	26,514	28,092
3	0.8	0.76	357	2	1	33,777	7,969	41,746	45,695
4	0.82	0.77	361	6	2	37,367	14,652	52,019	56,552
1	0.82	0.78	362	6	6	39,566	14,652	54,218	58,946
8	0.8	0.75	367	3	6	53,083	20,719	73,802	79,084
3	0.8	0.76	374	2	2	33,777	13,906	47,683	51,118
2	0.84	0.79	382	5	6	65,839	25,048	90,887	98,088
1	0.82	0.78	387	5	2	62,180	25,048	87,228	94,105
6	0.84	0.79	389	7	2	17,145	7,146	24,291	25,947

3	0.8	0.76	391	3	2	50,133	20,719	70,852	75,872
8	0.8	0.75	393	3	3	50,133	27,530	77,663	83,536
3	0.8	0.76	412	3	5	53,083	11,907	64,990	70,769
6	0.84	0.79	415	7	6	18,153	7,146	25,299	27,045
8	0.8	0.75	415	2	3	33,777	18,495	52,272	56,281
3	0.8	0.76	427	3	4	50,133	46,703	96,836	100,059
8	0.8	0.75	432	2	1	33,777	7,969	41,746	45,695
6	0.84	0.79	434	7	5	18,153	4,133	22,286	24,201
6	0.84	0.79	458	7	9	19,368	4,133	23,501	25,415
6	0.84	0.79	473	7	2	17,145	7,146	24,291	25,947

Table legend					
AC type #	**Related AC type**	**OD-pair #**	**Related OD-pair**	**OD-pair #**	**Related OD-pair**
1	B737-800	1	JFK-LHR	7	MIA-CDG
2	B757-200	2	ORD-LHR	8	LAX-CDG
3	B767-300ER	3	MIA-LHR	9	JFK-FRA
4	B787-8	4	LAX-LHR	10	ORD-FRA
5	B777-200ER	5	JFK-CDG	11	MIA-FRA
6	B747-400	6	ORD-CDG	12	LAX-FRA
7	A330-300				

Case study cruiser flight schedule including 125 cruisers in eastbound direction

Track #	Cruise speed [Mach]	Refuelling speed [Mach]	Arrival time at T_w [min]	Cruiser type	OD pair	1st stage cruiser fuel [kg]	2nd stage cruiser fuel [kg]	Total concept cruiser fuel [kg]	Total cruiser fuel direct ops [kg]
4	0.82	0.77	36	5	2	48718	37910	86628	94105
5	0.84	0.80	37	7	4	22733	10693	33426	34218
2	0.84	0.79	40	6	1	22403	22382	44785	50552
7	0.78	0.74	45	1	1	14494	15139	29633	32705
8	0.8	0.75	52	3	6	39279	33908	73187	79084
3	0.8	0.76	57	2	11	31267	25077	56344	60687
4	0.82	0.77	59	5	3	57560	37910	95470	103609
6	0.84	0.79	59	7	7	15871	11656	27527	29467
2	0.84	0.79	64	5	4	82448	37910	120358	124103
1	0.82	0.78	67	5	2	48718	37910	86628	94105
4	0.82	0.77	71	5	9	37279	45614	82893	92174
5	0.84	0.80	72	7	4	22733	10693	33426	34218
7	0.78	0.74	73	1	1	14494	15139	29633	32705
8	0.8	0.75	74	2	10	26464	25077	51541	55344
2	0.84	0.79	80	5	3	57560	37910	95470	103609
6	0.84	0.79	86	7	8	22733	11656	34389	35394
5	0.84	0.80	87	7	5	10279	11656	21935	24201
3	0.8	0.76	88	3	10	39279	37301	76580	82144
4	0.82	0.77	93	6	4	49546	22382	71928	74579

1	0.82	0.78	95	6	5	22403	24483	46886	52747
2	0.84	0.79	100	6	1	22403	22382	44785	50552
7	0.78	0.74	103	1	11	22379	18134	40513	43435
3	0.8	0.76	107	2	2	26464	20893	47357	51118
8	0.8	0.75	108	2	3	31267	20893	52160	56281
6	0.84	0.79	110	7	2	13433	10693	24126	25947
1	0.82	0.78	112	5	12	82448	45614	128062	131083
4	0.82	0.77	112	4	2	29763	22383	52146	57491
5	0.84	0.80	114	7	1	10279	10693	20972	23194
2	0.84	0.79	117	5	5	37279	41406	78685	87775
3	0.8	0.76	119	3	2	39279	31090	70369	75872
1	0.82	0.78	135	5	8	82448	41406	123854	128366
6	0.84	0.79	138	7	9	10279	12817	23096	25415
7	0.78	0.74	138	1	1	14494	15139	29633	32705
8	0.8	0.75	138	3	10	39279	37301	76580	82144
4	0.82	0.77	140	5	2	48718	37910	86628	94105
5	0.84	0.80	140	7	7	15871	11656	27527	29467
2	0.84	0.79	145	5	9	37279	45614	82893	92174
3	0.8	0.76	145	3	5	30056	33908	63964	70769
6	0.84	0.79	154	7	3	15871	10693	26564	28568
8	0.8	0.75	160	2	2	26464	20893	47357	51118
2	0.84	0.79	166	5	11	57560	45614	103174	111719
1	0.82	0.78	168	6	3	34590	22382	56972	62263
5	0.84	0.80	168	7	4	22733	10693	33426	34218
3	0.8	0.76	169	3	5	30056	33908	63964	70769
4	0.82	0.77	169	4	2	29763	22383	52146	57491
7	0.78	0.74	170	1	5	14494	16499	30993	34126
2	0.84	0.79	180	4	1	22775	22383	45158	51392
8	0.8	0.75	181	3	6	39279	33908	73187	79084
3	0.8	0.76	188	2	1	20250	20893	41143	45695
6	0.84	0.79	188	7	10	13433	12817	26250	28092
5	0.84	0.80	190	7	1	10279	10693	20972	23194
7	0.78	0.74	194	1	5	14494	16499	30993	34126
4	0.82	0.77	196	5	11	57560	45614	103174	111719
8	0.8	0.75	196	2	1	20250	20893	41143	45695
1	0.82	0.78	201	5	10	48718	45614	94332	101884
3	0.8	0.76	203	3	7	46408	33908	80316	86165
2	0.84	0.79	204	5	5	37279	41406	78685	87775
8	0.8	0.75	210	3	6	39279	33908	73187	79084
1	0.82	0.78	214	5	10	48718	45614	94332	101884
5	0.84	0.80	215	7	5	10279	11656	21935	24201
6	0.84	0.79	219	7	1	10279	10693	20972	23194
8	0.8	0.75	221	3	11	46408	37301	83709	90074
3	0.8	0.76	223	3	2	39279	31090	70369	75872
4	0.82	0.77	223	6	1	22403	22382	44785	50552

5	0.84	0.80	226	7	9	10279	12817	23096	25415
1	0.82	0.78	229	5	1	37279	37910	75189	84121
2	0.84	0.79	234	5	12	82448	45614	128062	131083
5	0.84	0.80	237	7	8	22733	11656	34389	35394
1	0.82	0.78	240	5	3	57560	37910	95470	103609
4	0.82	0.77	242	5	1	37279	37910	75189	84121
3	0.8	0.76	245	3	12	66474	37301	103775	105686
6	0.84	0.79	247	7	1	10279	10693	20972	23194
2	0.84	0.79	251	6	2	29277	22382	51659	56552
5	0.84	0.80	252	7	12	22733	12817	35550	36143
8	0.8	0.75	254	3	6	39279	33908	73187	79084
1	0.82	0.78	261	6	7	34590	24483	59073	64223
3	0.8	0.76	262	3	3	46408	31090	77498	83536
5	0.84	0.80	265	7	9	10279	12817	23096	25415
2	0.84	0.79	266	4	9	22775	27089	49864	56311
4	0.82	0.77	269	6	1	22403	22382	44785	50552
6	0.84	0.79	269	7	2	13433	10693	24126	25947
1	0.82	0.78	271	6	9	22403	27011	49414	55392
5	0.84	0.80	277	7	4	22733	10693	33426	34218
3	0.8	0.76	279	2	1	20250	20893	41143	45695
8	0.8	0.75	280	3	1	30056	31090	61146	67823
2	0.84	0.79	286	4	4	50369	22383	72752	75817
4	0.82	0.77	287	5	5	37279	41406	78685	87775
5	0.84	0.80	290	7	1	10279	10693	20972	23194
1	0.82	0.78	292	4	1	22775	22383	45158	51392
8	0.8	0.75	293	2	10	26464	25077	51541	55344
3	0.8	0.76	300	3	3	46408	31090	77498	83536
6	0.84	0.79	300	7	9	10279	12817	23096	25415
4	0.82	0.77	311	6	3	34590	22382	56972	62263
8	0.8	0.75	313	3	6	39279	33908	73187	79084
5	0.84	0.80	314	7	9	10279	12817	23096	25415
1	0.82	0.78	318	5	1	37279	37910	75189	84121
2	0.84	0.79	320	5	2	48718	37910	86628	94105
8	0.8	0.75	324	3	9	30056	37301	67357	74316
5	0.84	0.80	328	7	10	13433	12817	26250	28092
4	0.82	0.77	329	5	10	48718	45614	94332	101884
6	0.84	0.79	329	7	7	15871	11656	27527	29467
3	0.8	0.76	332	3	1	30056	31090	61146	67823
1	0.82	0.78	335	4	9	22775	27089	49864	56311
8	0.8	0.75	339	3	9	30056	37301	67357	74316
4	0.82	0.77	350	4	1	22775	22383	45158	51392
2	0.84	0.79	355	5	1	37279	37910	75189	84121
6	0.84	0.79	356	7	10	13433	12817	26250	28092
3	0.8	0.76	357	2	1	20250	20893	41143	45695
4	0.82	0.77	361	6	2	29277	22382	51659	56552

1	0.82	0.78	362	6	6	29277	24483	53760	58946
8	0.8	0.75	367	3	6	39279	33908	73187	79084
3	0.8	0.76	374	2	2	26464	20893	47357	51118
2	0.84	0.79	382	5	6	48718	41406	90124	98088
1	0.82	0.78	387	5	2	48718	37910	86628	94105
6	0.84	0.79	389	7	2	13433	10693	24126	25947
3	0.8	0.76	391	3	2	39279	31090	70369	75872
8	0.8	0.75	393	3	3	46408	31090	77498	83536
3	0.8	0.76	412	3	5	30056	33908	63964	70769
6	0.84	0.79	415	7	6	13433	11656	25089	27045
8	0.8	0.75	415	2	3	31267	20893	52160	56281
3	0.8	0.76	427	3	4	66474	31090	97564	100059
8	0.8	0.75	432	2	1	20250	20893	41143	45695
6	0.84	0.79	434	7	5	10279	11656	21935	24201
6	0.84	0.79	458	7	9	10279	12817	23096	25415
6	0.84	0.79	473	7	2	13433	10693	24126	25947

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