29th Congress of the International Council
of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

MODELING AN OPERATIONS CONCEPT FOR COMMERCIAL AIR-TO-AIR REFUELING BASED ON A VEHICLE ROUTING PROBLEM FORMULATION

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Abstract

The paper present a study pertaining to the development of an operational concept for air-to-air refueling of commercial aircraft. This study has been carried out the in the framework of a European project, called RECREATE (REsearch on a CRuiser Enabled Air Transport Environment), where air-to-air refueling has been proposed as a new paradigm to help reduce the environmental impact and improve the fuel efficiency of long-haul air transport operations. In this study, the air-to-air refueling network design problem is formulated and solved as a vehicle routing problem with time windows. Resolving the formulated vehicle routing problem allows to optimize the required tanker fleet size, its composition in terms of tanker aircraft types, and the assignment of tankers to cruisers. The initial numerical results clearly demonstrate the viability of the proposed approach.

1 Introduction

The air transportation industry is responsible for approximately 2% of global man-made carbon dioxide CO_2 emissions [1] and is subject to objectives to reduce environmental impacts. Research has shown that air transportation has detrimental effects due the environment due to the emissions of (CO_2), nitrogen oxides (NO_x) and noise. In response, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) goals for 2020 call for a 50% reduction of CO2 emissions, 80% reduction of NOx emissions and 50% reduction in perceived aircraft noise in comparison to the year 2000 [1]. In the context of these European objectives to reduce the impact of the air transportation industry, the REsearch on a CRuiser Enabled Air Transport Environment (RECREATE) project proposes a new air transport paradigm in which cruiser-feeder operations are utilized [2]. These operations entail that, 1) large aircraft (cruisers) fly fixed routes and rendezvous with smaller aircraft (feeders) that transfer passengers, fuel and other goods, or 2) long-haul passenger cruisers are refueled by tanker aircraft in-flight. The research effort presented herein is targeted at the latter cruiser-feeder concept, i.e., Air-to-Air (AAR) refueling.

Nangia [3] investigated the effect of in-flight refueling on the fuel consumption of conceptual aircraft designed for ranges of 3,000 NM, 6,000 NM and 9,000 NM. In the case of a 6,000 NM flight, Nangia predicted that an aircraft designed to fly 3,000 NM with one refueling operation requires 43% less fuel than a direct flight conducted using a 6,000 NM range aircraft. Fuel savings increase to 47% in the case of 9,000 NM flight in which the short-range aircraft is refueled twice and a direct flight is flown by an aircraft with a design range of 9,000 NM.

At present no operational concept is available that describes how air-to-air refueling can be implemented in the air transportation industry. Additionally, it remains unclear how many tanker aircraft are required to serve a stream of cruisers and where they should optimally be stationed. Due to this uncertainty, it is difficult to accurately estimate the costs of implementing commercial air-to-air refueling and whether these costs are outweighed by the benefits.

The research effort presented herein contributes to the discussion concerning air-to-air refueling of commercial aircraft by developing and optimizing an operations concept for serving commercial air traffic on the North Atlantic Organized Track System (NATOTS) and to optimize the tanker fleet size, its composition in terms of tanker aircraft types, the assignment of tankers to cruisers. To this end, the air-to-air refueling network design problem is formulated and solved as a vehicle routing problem with time windows. The proposed operations concept is described shortly in Section 2, after which the vehicle routing problem formulation, an appropriate solution technique, and optimization results are discussed in Section 3.

2 Operational Concept and Baseline Scenario

2.1 RECREATE Cruiser Traffic Scenario

In the context of RECREATE, an operations concept for the air-to-air refuelling of commercial aircraft is developed. The concept is applied to a baseline scenario, involving a North-Atlantic air-to-air refuelling network. An air-to-air refuelling network enables airlines to perform direct flights between airports that are currently incapable of handling conventional long-haul aircraft, due to their size. The number of hub-to-hub flights is therefore expected to decline whereas traffic on other routes will increase. To construct the North-Atlantic air-to-air refuelling network, it is first necessary to estimate the flow of passenger aircraft that are to be served by tankers.

To estimate traffic demand, use has been made of the 2010 Official airline Guide (OAG) [4]. The 2010 OAG schedule database contains all scheduled passenger and cargo flights of that year and is used to identify flights from Europe to the United States. To investigate the effect of replacing conventional long-haul aircraft with RECREATE cruisers, the total number of eligible flights in a year is calculated by assuming that all or a fraction of the conventional fleet is being replaced. This assessment is made by assuming that all aircraft on flights longer than 5500 NM are substituted by a RECREATE cruiser, followed by all flights longer than 5000 NM, 4500 NM, 4000 NM and 3500 NM, respectively. The number of air-to-air refueling flights that result when conventional aircraft are replaced by RECREATE cruisers can be seen in Figure 1.

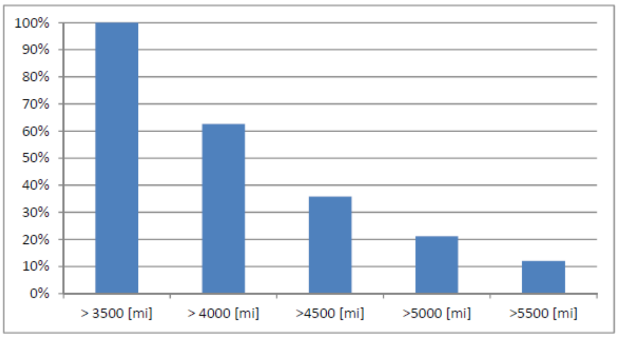

Fig. 1. Percentage of trans-Atlantic flights performed by RECREATE cruisers that utilize AAR operations.

It is assumed in this study that all aircraft traveling at least 4500 NM are replaced by RECREATE tankers, which corresponds to 36% of the air traffic.

Due to time zone differences and optimal local departure and arrival times, air traffic over the North Atlantic is condensed into waves. These waves typically last for five hours and have an average density of 52 aircraft per hour [5]. Thus, the problem size for which the operations concept is optimized consists of a five-hour window in which 5x52x0.36 ≈ 95 cruisers are to be scheduled. This value is consistent with data found in the OAG database.

2.2 Tanker Base Locations

Previous studies have identified several airports that might be suitable for air-to-air refueling operations in the North Atlantic region. Linke et al. [6] determined where airports should ideally be located such that aircraft can make intermediate refueling stops. Figure 2 marks these ideal regions for aircraft that feature a design range of 2,000 NM. Recalling that the RECREATE cruiser has a design range of 2500 NM, it is clear that ideal locations for refueling flights between Europe and the United States, - whether in the air or on the ground - are in the oceanic area south of Greenland and east of Canada. In this study, Gander International Airport (Newfoundland, Canada) has been selected as the prospective tanker base for the westbound traffic flow, primarily due the favorable (midway) refueling location and its proximity to the NATOTS tracks (see Figure 3). The runways of Gander airport can, at present, already accommodate the world's largest and heaviest aircraft. In this study, it has been assumed that the alternate airport for Gander is St Johns (located at a distance of about 150 Nm from Gander), which is also an international airport

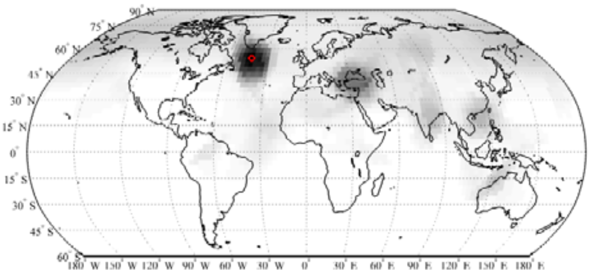

Fig. 2. Color-shaded areas represent regions of the world that are ideal for locating airports at which aircraft could make intermediate stops for refueling purposes [6].

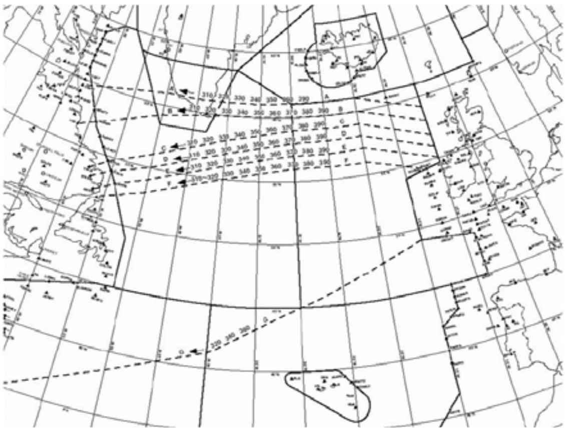

Fig. 3. Examples of westbound tracks in the North Atlantic Organized Track System (NATOTS) [5].

The NOTATS was developed in order to offer sufficient capacity over the North Atlantic, as well as to ensure lateral, longitudinal and vertical separation between aircraft crossing the ocean. In this study it is assumed that cruisers will typically cruise along a NOTATS track, while refueling takes place on a parallel track offset 15 NM from the NATOTS track.

2.3 Air-to-air refueling procedures

The air-to-air refueling procedure adopted in the proposed operational concept has been based on existing military air-to-air refueling procedures. Notably, the NATO air-to-air refueling procedures for fixed wing aircraft are used as a starting point for the development of commercial air-to-air refueling operations. NATO describes several rendezvous (RV) procedures for such aircraft [7]. In [8], the suitability of military air-to-air refueling procedures have been evaluated in relation to potential use for commercial passenger aircraft operations. In this study it was concluded that the so-called "RV Golf" NATO procedure meets the requirements related to commercial air-to air refueling operations to the highest degree.

In military aviation, aerial refueling is performed according to a standard approach, where the tanker flies ahead and above the receiver aircraft. However, in case of aerial refueling for passenger aircraft, safety, cost and comfort criteria suggest a different operational configuration, where the cruiser is flying above and ahead of the tanker [9]. This unconventional configuration requires the development of a new aerial refueling boom system [10]. Although it is, as yet, uncertain whether a forward-swept boom is technically feasible, the preliminary analyses conducted within RECREATE are promising. There are several advantages that result from the fact that the tanker approaches the cruiser from behind and is responsible for all maneuvering during the rendezvous and refueling process. These advantages include the fact that little additional training is required for pilots of passenger aircraft to utilize air-to-air refueling. Furthermore, the additional workload of these pilots is kept at a minimum. Moreover, the comfort of passengers is preserved to the highest degree, as the passenger aircraft remains in steady-state cruise, whilst the tanker is maneuvering to be in position to refuel the receiving aircraft. Finally, to be able to approach aircraft from behind in bad weather conditions, the approaching aircraft must be equipped with an airborne intercept radar [7]. It is far more cost-efficient to equip the smaller tanker fleet with such expensive equipment rather than the large passenger aircraft fleet.

Air-to-air refueling operations associated with aircraft traveling on the NATOTS tracks must also comply with lateral, longitudinal and vertical separation requirements between aircraft. Lateral separation is ensured due to the 60 NM distance between neighboring NATOTS tracks. Aircraft on the same track are separated vertically by 1,000 ft. Also, flights on the same track are separated longitudinally by using the so-called Mach Number Technique [5]. This technique calls for the strict adherence to cleared true Mach numbers that are issued to take minimum longitudinal separation distances and differences in airspeeds into account.

In the adopted scenario, air-to-air refueling operations are assumed to be executed on a track offset 15 NM to the right of the original NATOTS track (see Figure 4). This distance guarantees adequate lateral separation and is also used during emergency procedures [11]. Once the air to-air refueling operation is completed, the RECREATE cruiser returns to its original NATOTS track.

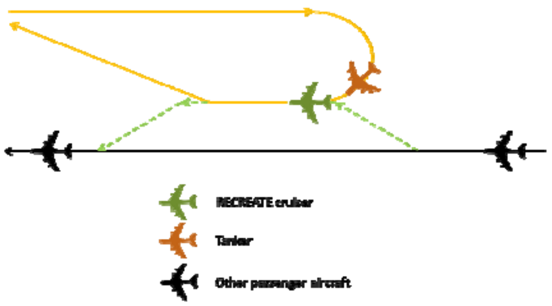

Fig. 4 : An illustration of the refueling track configuration in which a RECREATE cruiser is refueled on a track offset 15 NM from the assigned NATOTS track [8].

In the scenario assumed in this study, all cruisers are flying at the same speed on a given track, and the (constant) separation between two consecutive aircraft on the track is at least ten minutes. The refueling takes place at an altitude, which is well below cruise altitude (typically, around 8,000 m). Refueling takes also place at a Mach number that is slightly below the cruise Mach number, viz., Mach 0.77 - 0.78. The lower refueling altitude helps to ensure that no loss in ground speed is sustained during refueling operations when flying at a lower Mach number. Opting for a relatively low refueling altitude offers operational advantages. Notably, it helps to ensure that the tanker aircraft has ample excess thrust and operating speed range.

In line with the RV Golf procedure [7], a common (offset) track length equivalent to 15 minutes flying time is taken into account to allow for the tanker to descend to rendezvous altitude, visual acquisition and timing corrections. The "wet contact" is assumed to take five minutes.

2.4 Tanker fleet and Optimal Refueling Location

As is the case with passenger aircraft that are to be refueled mid-air, as yet, no tanker aircraft have been designed specifically to be a part of a commercial air-to-air refueling network. The design of these tankers is one of the objectives within the RECREATE project. Although issues such as the placement of the (forward-swept) refueling boom have been addressed, the size and range (endurance) of the tanker aircraft have not yet been determined.

When looking at the military market, the largest military tanker aircraft currently available is the KC-10 Extender, which is capable of refueling up to three RECREATE cruisers in a single tour. However, it is technically feasible that even larger aircraft such as the B747-800 or A380 are converted to tanker aircraft. Thus, the largest conceptual tanker should in theory be able to refuel six to seven RECREATE cruisers during a single mission.

The size of the tanker employed has a significant impact on the location of the optimal refueling point. Clearly, the most ideal track in terms of fuel consumption from the perspective of the cruiser is not necessarily located overhead the tanker base. Similarly, if this ideal track is located at a large offset distance from the tanker base, this would impose a detour and hence a high fuel consumption for the tanker. The selection of the most appropriate refueling point, given the tanker base location, in terms of the lowest possible fuel consumption for cruisers and tankers combined, has been determined for a range of tanker designs of different size.

It is assumed that all tanker designs share the same performance characteristics, but differ in the number of fuel offloads that they can provide per mission tour. Tanker sizes ranging from very small (capable of refueling only a single cruiser) up to very large tankers (capable of seven offloads in a single mission) have been considered.

Figure 5 schematically shows the problem of selecting the most appropriate refueling location (offset distance) for a given tanker base location relative to the baseline NATOTS track. Optimal refueling locations are those for which the sum of the fuel consumption of the tanker aircraft and additional fuel consumption of cruisers due to a longer flight path with respect to the original route is minimum. In each scenario, a single tanker is dispatched to refuel a number of cruisers. In the scenarios used to determine the optimal refueling locations, the number of cruisers to be refueled varies from one to seven. During each refueling operation, the tanker is assumed to travel 300 km (about 20 minutes flight time). From Fig. 5, it can be inferred that the total distance flown by the cruisers as a function of the offset distance (d) is given by:

$$R_{cruiser} = 2.\sqrt{d^2 + \left(\frac{NAT}{2}\right)^2} + 2.3000 \quad [km] \qquad (1)$$

The distance travelled by a tanker providing n offloads is given by:

$$R_{cruiser} = 2.(500 - d) + n.300 \quad [km] \qquad (2)$$

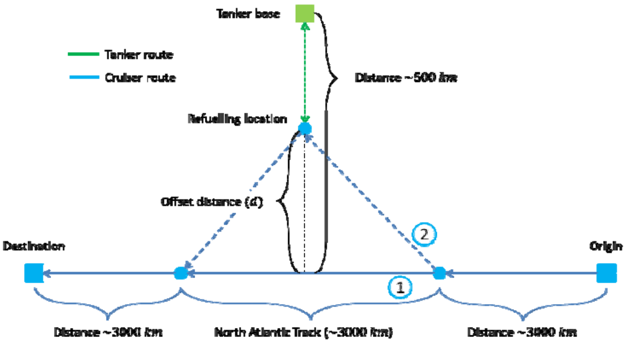

Fig. 5 : The refueling point is located at an offset distance (d) from the reference (NAT) flight track of the cruisers.

For each of these seven scenarios, the position of the refueling points varied from an offset position of zero with respect to the original cruiser flight track up to an offset of 500 km. At each offset position, the aggregated fuel consumed of the tanker and one or more cruisers is calculated using the Breguet-range cruise equation [3]:

$$R = X \ln\left(\frac{W_1}{W_2}\right) \quad , \qquad (3)$$

with:

$$X = V.\frac{L}{D}.\frac{1}{SFC} \quad , \qquad (4)$$

where in Eq.(3) R is the range of an aircraft, whilst W_1 and W_2 correspond to the aircraft weight at the start and end of a cruise, respectively. The X-factor relates the cruise speed and aircraft technology levels and is further detailed in Eq.(4). In this equation, V is the cruise speed, L/D is the lift-to-drag ratio and SFC is the specific fuel consumption.

In this study, the lift-over-drag ratio assumed for both cruiser and tanker is 16, whilst the specific fuel consumption corresponds to that of the GE CF6-80E1A2 engine, as employed on an Airbus A330-300 aircraft [8]. The adopted cruise speed is 243 m/s, for both tanker and cruiser.

It is noted that in the Breguet-range equation evaluations, the cruiser weight at the refueling point and at the end of the flight) is given by:

$$W_2 = OEW + WFR + WP \ , \qquad (5)$$

where OEW is the operational empty weight, WFR is the weight of the reserve fuel and WP is the payload weight.

Figure 6 shows some results for three scenarios, viz., the refueling of a single, four and seven cruisers using a single tanker of corresponding size. It can be seen that the refueling of an increasing number of cruisers shifts the optimal refueling point closer to the original flight track of the cruisers. For tanker designs featuring up to three offloads, the optimal refueling point is essentially above the tanker base (i.e., optimal offset distance d is 500 km). It is readily clear that when a fleet is available comprising tankers of various sizes, a compromise needs to be made in establishing the most appropriate refueling location.

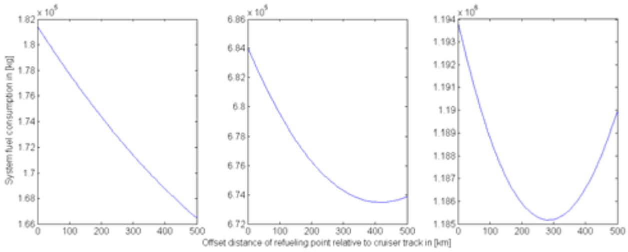

Fig. 6 : The total fuel consumption corresponding to varying locations of the refueling point for scenarios in which one (left), four (center) and seven (right) cruisers are refueled by a single tanker.

3 Modeling the Air-to-Air Refueling Network Design as a Vehicle Routing Problem

3.1 Model Formulation

In this study, the design of the air-to-air refueling network for a given traffic flow is formulated as a so-called Vehicle Routing Problem with Time Windows (VRPTW). The VRPTW formulation is an extension of the classic vehicle routing problem (VRP) and is defined as follows: given a set of depots, a homogeneous fleet of vehicles and a set of known demand locations, find a set of closed routes (tours), originating and ending at the depots, that service all demands and minimize the travel cost; in addition, the service at each demand must start within an assigned time window.

It is readily clear how the air-to-air refueling network design problem can be identified as a VRPTW. The tankers are the vehicles that service the cruisers (depots) through in-flight refueling at a given location and within a given time window. The VRPTW formulation in this research actually applies two sets of time windows: one determining the timing of refueling operations as required by RECREATE cruisers and the other reflecting the endurance of tanker aircraft. In addition to time windows, the vehicle routing problem is further extended here such that the tanker fleet size and the mix of tanker designs are not fixed. As a result, the optimization of the problem also gives the optimum fleet composition. This formulation is commonly called a fleet mix and size vehicle routing problem with time windows. Assigning individual tanker aircraft to cruisers, results in integer (binary) variables, whereas the refueling time of a RECREATE cruiser is a continuous variable.

There is one major complication in the air-to-air refueling network problem that necessitates a modification in the basic VRPPTW formulation. Whilst in the basic VRPTW formulation the customers (demand locations) are stationary, in the air-to-air refueling network problem, the customers (i.e., the cruisers) are moving. During the refueling procedure, the tanker is paired with the receiving cruiser and thus moving along the same track as the cruiser. An extension to the basic formulation is needed to allow for the non-stationary nature of the customers and tankers during fuel delivery. To make the problem more tractable, it is assumed here that tankers and cruisers all fly at exactly the same speed throughout the entire operation.

In this study, a fleet mix and size vehicle routing problem with time windows, based on the formulation of Bräysy et al. [12], is used as a baseline. This formulation is then modified to allow for the non-stationary nature of the customers. The following notation is utilized in this mixed integer linear programming model:

n	number of cruisers to be refueled
K	number of tanker types
L_k	number of tanker aircraft of tanker type k
Q_k	capacity of a tanker of type k ($Q_1 < Q_2 \ldots < Q_K$)
E_k	endurance of a tanker of type k ($E_1 < E_2 \ldots < E_K$)
f_k	fixed acquisition cost for a tanker of type k ($f_1 < f_2 \ldots < f_K$)
d_i	fuel demand of a cruiser $i = 1, \ldots, n$
e_i	start time of refueling time window cruiser $i = 1, \ldots, n$
l_i	end time of refueling time window of cruiser $i = 1, \ldots, n$
s	service (refueling) time of a cruiser
t_{ij}	the travel time of a tanker between cruisers (or base) i and j

An arc flow representation is used, in which a graph G = (N;A) is defined with N = {0,… ,n + 1}. Nodes {0} and {n + 1} represent the cruiser base at the start and finish of a tour, respectively. Additionally, C = {1,… ,n } defines the set of cruisers and V = {1,… ,K } is the set of all tanker types. W_k = {0,… ,L_k }, in turn, is the set of all tankers per type k. Finally, A ⊆ N × N represents all travel opportunities between nodes, where (i,i), (i, 0) and (n +1,i) are excluded.

The decision variables are as follows:

x_{ij}^{kl}	expresses whether tanker l of type k travels directly from cruiser i to j.
y_i^{kl}	the time that refueling of cruiser i is started by tanker l of type k in minutes after $t = 0$.

Note that x_{ij}^{kl} is a binary variable, whereas y_i^{kl} is a real variable. The possible outcomes of the decision variables are:

$$x_{ij}^{kl} = \begin{cases} 1 \\ 0 \end{cases} \quad \forall k \in V, \forall l \in W, \forall (i,j) \in A \tag{6}$$

$$y_i^{kl} \geq 0, \quad \forall k \in V, \forall l \in W, \forall i \in N \tag{7}$$

The objective function minimizes the sum of the total acquisition cost and mission flight time of the tankers and is given by:

$$min\left[\sum_{k\in V}\sum_{l\in W}\sum_{j\in C} f_k x_{0j}^{kl} + \sum_{k\in V}\sum_{l\in W}(y_{n+1}^{kl} - y_0^{kl})\right] \tag{8}$$

The number of tankers of type k deployed from the base is represented in the first term of Eq.(8). Thus, the first term evaluates the total fixed cost of the tanker fleet. The second term of the objective function determines the total flight time (from take-off to landing at the tanker base) aggregated over the set of deployed tankers. It is noted that, since the tankers fly at a given constant speed, minimizing flight time also implies minimizing fuel consumption.

The model comprises the following set of equality and inequality constraints:

$$\sum_{k\in V}\sum_{l\in W}\sum_{i\in N} x_{ij}^{kl} = 1 \quad ,\forall j \in C \tag{9}$$

$$e_i \sum_{j\in N} x_{ij}^{kl} \leq y_i^{kl} \quad and \quad y_i^{kl} \leq l_i \sum_{j\in N} x_{ij}^{kl}, \\ \forall i \in C, \forall k \in V, \forall l \in W \tag{10}$$

$$\sum_{i\in N}\sum_{j\in C} d_j x_{ij}^{kl} \leq Q_k \quad ,\forall k \in V, \forall l \in W \tag{11}$$

$$y_{n+1}^{kl} - M(1 - x_{0j}^{kl}) \leq y_j^{kl} + E^k - t_{0j}, \\ \forall j \in C, \forall k \in V, \forall l \in W \tag{12}$$

$$y_i^{kl} + s + t_{ij} - y_j^{kl} \leq M(1 - x_{ij}^{kl}), \\ \forall (i,j) \in C, \forall k \in V, \forall l \in W \tag{13}$$

$$y_0^{kl} + t_{dep}^k - y_j^{kl} \leq M(1 - x_{0j}^{kl}), \\ \forall j \in C, \forall k \in V, \forall l \in W \tag{14}$$

$$y_i^{kl} + (t_{i,j=n+1}^{kl} + s + t_{arr}^k) - y_{j=n+1}^{kl} \leq \\ M(1 - x_{i,j=n+1}^{kl}), \ \forall i \in C, \forall k \in V, \forall l \in W \tag{15}$$

$$\sum_{j\in N} x_{0j}^{kl} = 1 \; and \; \sum_{i\in N} x_{i\,n+1}^{kl} = 1, \quad \forall k \in V, l \in W \tag{16}$$

$$\sum_{i \in N} x_{ih}^{kl} - \sum_{j \in N} x_{hj}^{kl} = 0, \quad \forall h \in C, \forall k \in V, l \in W \tag{17}$$

$$x_{i0}^{kl} = 0, \quad x_{ii}^{kl} = 0, \quad x_{n+1i}^{kl} = 0, \quad \forall i \in C, \forall k \in V, \forall l \in W \tag{18}$$

$$t_{ij=n+1}^{kl} = \sum_{i \in C} \sum_{j \in C} \left((x_{ij}^{kl} .s + w_{ij}^{kl}) - x_{ij} t_{ij}^{kl} \right) + s \tag{19}$$

$$w_{ij}^{kl} = (y_j - y_i) x_{ij}^{kl} - (t_{ij}^{kl} + s) x_{ij}^{kl}, \quad \forall (i,j) \in C, \forall k \in V, \forall l \in W \tag{20}$$

Since the decision variables x_{ij}^{kl} are binary, Eq.(9) enforces that only one tanker can be assigned to each cruiser. The constraints expressed by Eq.(10) ensure that the assigned service time remains within the available refueling time window $[e_i, l_i]$ for each cruiser *i*. The maximum available fuel capacity of tankers during a single tour is enforced for each tanker of a given type through Eq.(11). Constraints (12) ensure that tanker mission tours are compatible with the endurance of the tanker. Note that M is an arbitrary large number that renders the inequality constraint (12) inactive when $x_{0j}^{kl} =$ 0 (so-called "big M" trick). The constraints expressed by Eq.(13) guarantee that the arrival times of a tanker at two consecutive cruisers allow for both traveling time and refueling time. Constraints (14) and (15) define departure and arrival time constraints, taking into account a given time-to-climb from the base to cruise altitude t_{dep}^{k}, and a given time-to-descent to descent from refueling altitude to the tanker base t_{arr}^{k}. Constraints (14) and (15), which relate to the stationary (tanker base) nodes, are separate from the constraints (13) relating to the non-stationary cruiser nodes. The travel time from the last refueling in the tour to the refueling point above the base, $t_{i,j=n+1}^{kl}$ in Eq. (15**)**, is defined in Eq.(19). Constraints (16) state that each tanker mission tour originates and terminates at the tanker base. Constraints (17) ensure that, when a tanker arrives at a customer cruiser, it also departs from that customer (balance equation). The constraint Eqs. (18) preclude that tankers are routed back to node {0}, loop back to the same cruiser, or depart from node {*n+1*}. Finally, Eqs. (20) define the waiting time of tanker *l* of type *k* for refueling cruiser *j* when travelling from cruiser *i*. The waiting time is essentially the difference between the time that the refueling starts and the time that the tanker arrives at the cruiser. Note that Eqs.(20) contain quadratic terms. However, due to their particular form, the quadratic terms can be readily linearized.

3.3 Solution Technique

The mathematical formulation of the vehicle routing problem given in Section 3.2 is a mixed integer linear program and can be solved using commercial standard software. During this research, the MATLAB toolbox of ILOG CPLEX version 12.2 was used on a Windows 7 system with 24GB RAM and MATLAB version R2011b [8]. Also, the CPLEX Class API for MATLAB was utilized to generate the model.

Using the standard branch-and-cut search of CPLEX to solve the mixed integer programming model, a large amount of memory is required to store the tree containing all sub-problems. The largest problem size that could be handled using CPLEX consisted of 17 cruisers, which is significantly less than the required wave of 95 cruisers. Nevertheless, exact methods are available for vehicle routing problems with time windows, that have a demonstrated capability of solving 100-customer problems [13]. These methods are typically based on column generation or Lagrangian decomposition. Application of these techniques to the AAR problem is a topic of future research. In addition to exact methods, a variety of heuristic and meta-heuristic methods for dealing with the VRPTW have been explored as well [14]. Also the development and application of these methods will be explored in future research.

3.4 Numerical Example

To illustrate the VRPTW formulation for the AAR, a simple example is presented, involving a stream of 11 cruisers to be refueled by a fleet of 5 tankers, all of the same type. Furthermore, it is assumed that the selected tanker is capable of conducting three fuel offloads to cruisers in a single tour. In line with the observations made in Section 2.4, the refueling point is located exactly above the tanker base. The climb-out from the base to the refueling altitude takes 20 minutes. The same flight time is adopted for the descent from the refueling point to the tanker base. The endurance of the tanker is four hours. The service (refueling) time is taken as 25 minutes, and the time window for the start of the refueling operation is 10 minutes. The refueling window starts when the cruiser directly flies overhead the tanker base.

The cruisers tankers are assumed to fly at the same speed. This implies that when cruiser and tanker are flying in the same direction, the relative (closing) speed is zero, whilst the closing speed is twice the cruise speed when cruiser and tanker are flying in opposite directions.

To further simplify the problem, the performance index is specified as the accrued flight time for the mission tours of the tanker aircraft. In other words, the fixed cost component in the performance index in Eq. (8) has been ignored. The travel times t_{ij} are input parameters that can be directly extracted from the assumed cruiser schedule. The schedule of arrival times at the refueling location that has been adopted in this numerical example is summarized in Table 1. The start time of the refueling time window of each cruiser coincides with the arrival time at the refueling location.

Table 1. Example schedule of arrival times at the refueling location for a problem size of eleven cruisers.

Cruiser no.	*Arrival time at refueling location after t = 0*
1	*t = 49 minutes*
2	*t = 60 minutes*
3	*t = 91 minutes*
4	*t = 113 minutes*
5	*t = 137 minutes*
6	*t = 166 minutes*
7	*t = 200 minutes*
8	*t = 220 minutes*
9	*t = 254 minutes*
10	*t = 273 minutes*
11	*t = 304 minutes*

The results in terms of the tanker assignment to cruisers and the resulting tanker refueling start times are shown in Figure 7.

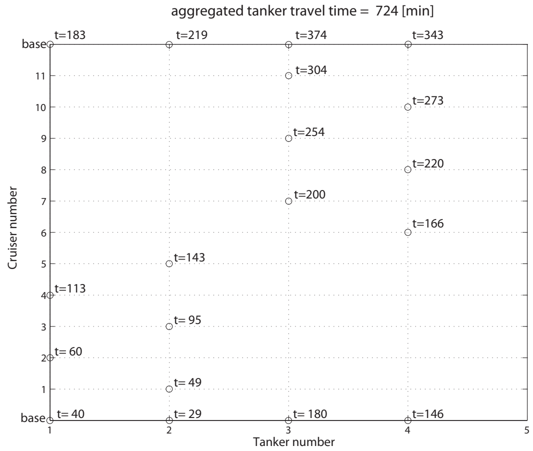

Fig. 7. Time-cost optimal solution to the example VRPTW problem..

In Figure 7, the assignment of tankers (horizontal axis) to cruisers is indicated, along with the time instance at which the refueling is initiated for each tanker-cruiser pair. It can be seen that only 4 tankers are needed to refuel the 11 cruisers. The total accrued tanker travel time for the solution presented in Figure 7 is 724 minutes.

4 Conclusions

In this paper an operational concept for air-to-air refueling of commercial aircraft was presented. More specifically, the air-to-air refueling network design problem for long-haul transoceanic flights was formulated and solved as a vehicle routing problem with time windows. For small-scale problems the formulated vehicle routing problem could be readily solved, but when dealing with large-scale problems, significant computational complications were encountered.

A separate study was conducted to establish the best location of refueling points. It was found that for tankers of moderate size (up to three fuel offloads) the best location is directly overhead the tanker base.

Future research will focus on improved techniques for dealing with large-scale network problems, including the use of problem decomposition methods and the development of fast heuristic approaches. In addition, the network formulation will be refined and extended, to include variable fuel-offloads, the use of multiple simultaneous cruiser tracks/altitudes, and the use of multiple tanker bases.

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Acknowledgment

The results presented in this paper are part of the RECREATE research project, funded from the European Union Seventh Framework Programme, grant agreement no. 284741. This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.

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