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Wind Optimal Flight Trajectories to Minimise Fuel Consumption within a 3 Dimensional Flight Network

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Abstract—**This paper assesses the potential fuel savings benefits that can be gained from wind optimal flight trajectories. This question is posed on a 3 dimensional fixed flight network consisting of discrete waypoints which is representative of the size of Europe. The optimisation implements Dijkstra's shortest path algorithm to compute the minimum fuel burn route through a network and compares this to the fuel burn for the shortest distance route. Particular effort is applied to testing the repeatability and robustness of the results. This is achieved through a sensitive analysis based on a number of identified model parameters relating to the setup of the flight network. The results of this study show fuel savings between 1.0% – 10.3%, and suggest that the benefits of wind optimal flight trajectories are significant.**

Keywords—Air Traffic Control, Optimal Trajectory, Graph Theory, Environment, Networks

I. INTRODUCTION

With the continuing expected growth of air traffic and current concerns regarding climate change, it is vital that the aviation industry finds ways to reduce the environmental impact of flying. The main contributor to the greenhouse effect is carbon dioxide and of the total anthropogenic CO_2 emissions worldwide, 2% is due to aviation; international aviation produces around 60% of these emissions [1]. The Advisory Council for Aeronautical Research in Europe (ACARE) set a CO_2 reduction target of 50% by 2050 compared to 2005 levels [2]. ACARE envisaged that 5-10% of this reduction would be a result of improvements to Air Traffic Management (ATM) [3].

Wind optimal flight trajectories are an area of extensive research and greater emphasis has been applied to this area in recent years. Currently its implementation can be seen within the current flight system over the North Atlantic, where tracks are updated twice-daily to take advantage of favourable winds [4]. Although Atlantic tracks start and end at 5/6 designated entry points either side of the ocean [5], there are otherwise very limited restrictions on flight routing enabling flight path optimisation to be implemented with relative ease. Most previously conducted research into wind-optimal flight trajectories has considered 'free flight', similar to the infrastructure over the oceans, where limited flight routing constraints exist. In [6], it is highlighted that there is enormous potential for time and resource savings for flight with less ATM restrictions. Flight routes today, however, are restricted by ground-based navaids [7], and jet routes specified by ATM are restricted to passing over such navaids for tracking purposes. This system allows for safe and efficient operations with

manageable air traffic controller work load in increasingly busy skies. The Next Generation Air Transportation System (NextGen) are aiming to implement the successor to radar tracking, Automatic Dependent Surveillance-Broadcast (ADS-B), in the USA by 2020 [4]. ADS-B will alleviate the need for ground based navaids and result in increased ATM flexibility. Despite this, it is still unlikely that improved ATM operations will enable aircraft to operate in 'free flight' conditions, especially considering the expected growth of air traffic and the logistics of collision avoidance.

Due to the nature of this problem, the most common methodology employed in previous research is optimal control theory. In these instances the objective is to minimise the total travelling time from one point to another through selection of an initial heading angle with prescribed airspeed. In [8, 9, 10] the optimisation is carried out on a horizontal plane at a singular flight level of constant altitude. This method originates from research carried out by Zermelo in the early 1930's that proposed a way of determining the minimum time path for boats travelling through strong currents [10]. Optimal control theory optimisation in this context has disadvantages associated with convergence to local minima, an ongoing area of research, and is also only suitable for application to 'free flight' rather than discrete networks. In [8], it is mentioned that due to advancements in computational power, shortest path algorithms can be utilised to compute optimal trajectories that minimise the total cost from origin to destination through a pre-defined network. Although within ATM these methods are generally applied to problems involving constrained airspace, such as obstacle avoidance, and neglect the effect of wind, these methods always guarantee global optima and are suitable for investigation on current flight networks. The most commonly used and documented algorithm for this purposes is Dijkstra's shortest path algorithm [11], which works by computing the lowest cost path from a specified start vertex to all other vertices in the network.

This article presents a study addressing the goal to reduce aircraft fuel consumption through utilising favourable winds to optimise flight trajectories. Due to current ATM flight route restrictions, this research focuses on a fixed flight network, representative of the current flight path infrastructure, and uses a 3 dimensional domain to enable both horizontal and vertical wind optimisation. The optimisation relies on Dijkstra's algorithm as the most wide-spread method used for this purpose. It should be noted that this paper does not however discuss the advantages and disadvantages of the chosen algorithm in terms of its running time, computational complexity or stability.

The layout of this article is as follows: section II presents the problem definition, main optimisation parameters and methodology; section 3 discusses the results focusing on the effects of modifying identified model parameters; and section IV presents the conclusions and suggestions for future work.

II. METHODOLOGY

A. Problem Definition

The domain is defined as the research space and consists of the wind field and waypoints' position, density and connectivity. The investigation herein is conducted over Europe. Real wind data for this region between [10-30] degrees longitude and [35-75] degrees latitude is sourced for specified altitudes from the National Oceanic and Atmospheric Administration (NOAA). This data is used to create the 3D wind vector maps. The flight network is based on the current infrastructure consisting of discrete ground based navaids and flight levels of 1000ft separation. In order to test altitude effects, 5 flight levels (FL200, FL250, FL300, FL350 and FL400) are included in the model. The specified levels are at 5000ft increments rather than 1000ft as specified by ATM due to wind data availability from NOAA. In the model, vertical movement between levels is constrained such that an aircraft can only climb or descend between adjacent flight levels at any one time.

The trajectory optimisation in this case is only applied to the cruise phase of flight. Although a typical aircraft trajectory consists of initial climb, a steady-state cruise and final descent, the potential savings during the initial climb and final decent stages are generally small compared to those in cruise. This is due to the additional air traffic control constraints involved [8]. The initial cruise altitude is specified at the central flight level for this network setup (FL350) and all start and destination points are located at this altitude. This enables the wind optimal route to explore favourable wind both at higher and lower altitudes relative to the start point.

The aircraft model is based on an A320 since it is common in the fleet of European airlines. The fuel burn data and airspeeds for this aircraft are extracted from the Base of Aircraft Data (BADA) [12] and are implemented within the simulation, as explained in section II.D. It is assumed that the

aircraft weight remains constant for the duration of the cruise phase. This assumption is necessary to conservatively reduce complexity of the model and to allow for a focused assessment into the effects of wind optimisation.

At this stage it is important to note the optimisation only considers a single aircraft present in the network at any one time. For a multi-aircraft optimisation, separation standards and the effects of collision avoidance would have to be incorporated therefore adding restrictions to the chosen optimised trajectory.

B. Model Parameters

Preliminary investigations within a 2 dimensional domain were conducted, representative of flight at a constant altitude, on a scale representative of Europe. Although the domain was fictional and implemented both a fictional wind map and flight network, these studies found fuel savings in the order of 10%. This preliminary investigation served to identify the main model parameters detailed in Table I. To ensure the repeatability and robustness of the results for the subsequent 3D study, sensitive analyses were conducted into the effects of each of these parameters.

C. Graph Search Optimisation

To implement the optimisation framework within the MATLAB simulation model, graph theory is used where the vertices represent waypoints connected by a set of edges representing flight paths. The placement of these edges is defined in an adjacency matrix. Dijkstra's shortest path algorithm is implemented within the model to compute the minimum fuel burn path through the flight network. For comparison the fuel burn associated with the shortest distance route through the network is also calculated within the model using Dijkstra's algorithm. Dijkstra's algorithm is a form of dynamic programming, where the initial complex problem is broken down into simpler subproblems. In this case, the shortest cost (i.e. fuel or distance) path to a specified end vertex is computed using previously calculated shortest paths to the other, intermediate vertices. It should be noted that vertices are never revisited.

TABLE II. MODEL PARAMETERS TO BE INVESTIGATED TO DETERMINE THEIR IMPACT ON FUEL BURN SAVINGS WHEN MODIFIED.

Model Parameter	Effect on Results	Consideration in this research
Wind Map	A particular wind map could present favourable winds and produce unrepresentative savings.	Test multiple wind maps from different instances in time ensuring a variety of wind conditions.
Waypoint Density	Increasing number of waypoints could increase opportunity to utilise favourable winds.	Vary number of waypoints present in network for a number of test cases.
Network Connectivity	As above, increasing connectivity could increase opportunity to utilise favourable winds.	Vary the connectivity between waypoints for a number of test cases.
Sector Length/Scale of Network	As above, increasing the sector length could increase opportunity to utilise favourable winds. This is reinforced in a paper by Hok [8] where wind optimal savings for domestic flights were found to be 3% compared to 10% for trans-oceanic flights.	Due to project time constraints, the network scale will be fixed at the size of Europe. The 2D preliminary investigation supported that this was a suitable scale for wind optimal routing to obtain fuel saving benefits.
Fuel Model	Possibility that the different fuel burn rates for cruise at different altitudes, or during climb or descent between flight levels, would determine the optimal fuel burn route rather than the exploitation of favourable winds.	A simulation model has been developed which assumes the same fuel burn for all stages of flight. This model optimises the flight trajectory based on the exploitation of favourable winds alone. This is run in parallel to the main fuel burn simulation model for comparison.

To specify the fuel cost associated with each edge, the time to travel along each edge is calculated. To achieve this, the wind velocity and aircraft velocity are combined using the vector laws of cosines (Eqns. 1-3). First the model discretises each edge into smaller segments of known length for which the corresponding wind vector is found. The contribution from the wind velocity (w) in the direction of travel (V_{wind}) is added to the aircraft velocity (V) to obtain the resultant velocity at each edge segment, fig. 1. The time contribution of each segment is totaled to give the final time cost of the edge.
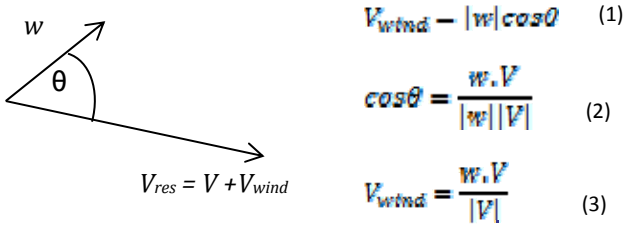
$$V_{wind} = |w|\cos\theta \tag{1}$$

$$\cos\theta = \frac{w.V}{|w||V|} \tag{2}$$

$$V_{res} = V + V_{wind}$$

$$V_{wind} = \frac{w.V}{|V|} \tag{3}$$

Fig. 1. Calculation of the resultant aircraft velocity (V_{res}) using vector law of cosines. The magnitude of the aircraft velocity V is constant along each edge.

D. Fuel Burn Model

The fuel burn data is acquired from BADA [12] and applied to each edge once the flight stage (i.e. cruise, climb or descent) of each has been determined. In BADA, fuel burn rate (kg/min) is specified for cruise at a given flight level and airspeed. These airspeeds are the aircraft velocities incorporated in the simulation model at each flight level, assuming a constant throttle setting (i.e. constant V). For climb and descent, fuel burn rate is given for a specified rate of climb or descent in ft/min. This is the fuel burn required for a steep climb or descent to a specified flight level i.e. in initial take-off and landing. These values are too severe for the cases in this optimisation where the climb and descent rates are shallow due to the relatively small changes in altitude between the flight levels. Fig. 2 depicts the shape of a climb path modelled within this simulation. The climb path has been modelled in this way to determine a more realistic value for fuel burn rate than those taken directly from BADA and applied for the whole duration of the climb.
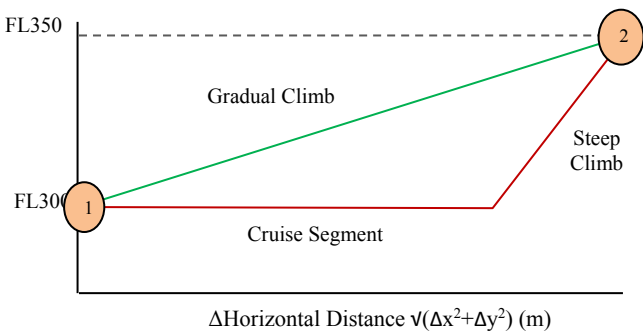
Fig. 2. Graphical depiction of fuel burn approximation in climb.

Points 1 and 2 in fig. 2 represent waypoints, the green line (Gradual Climb) represents ideal gradual climb between waypoints, and the red line (Cruise Segment + Steep Climb) represents the approximate climb path modelled to obtain a realistic approximation of fuel burn. The fuel burn rate for climb obtained from BADA is only utilised for the 'steep climb segment' of the approximate climb path. The cruise segment makes up the remainder of the approximate climb path and this occurs at the lower of the altitude levels. This is where drag is highest which ensures the approximation does not under predict the fuel required. The same approach is applied for the fuel burn rate of descent and again to avoid over optimistic predictions, the fuel burn rate for the lower flight level is applied to the cruise segment.

III. RESULTS & DISCUSSIONS

A. Wind Field

Five wind maps are sourced from NOAA over a 6 day period, to represent a cross-section of wind conditions; detailed in table II. Examples of two of these wind field vector maps are graphically depicted in figs. 3 and 4 at FL350. Simulations for four routes between start and destination points located at the 4 outer corners of the network are conducted on each map. For the example network depicted in figs. 3 and 4, the four tested journeys are between nodes 39-57, 40-57, 39-56, and 40-56.

TABLE II. DETAILS OF WIND BEHAVIOUR IN THE 5 WIND MAPS.

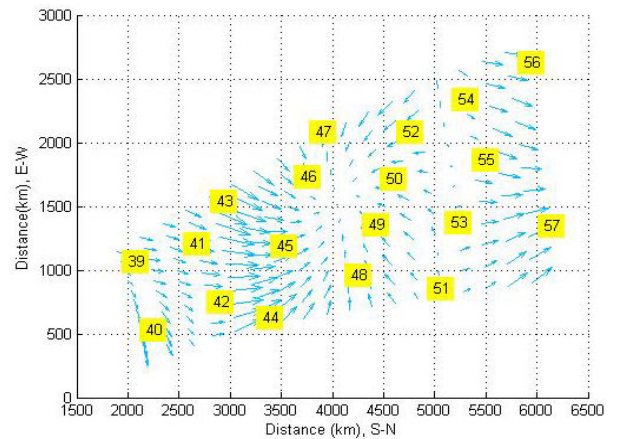| Wind Map	Source Date	Description
1	24/03/2015 00:00	Predominantly light, south westerly
2	25/03/2015 12:00	Moderate, predominantly south westerly
3	29/03/2015 00:00	Moderate, many directions
4	29/03/2015 12:00	Strong stormy, regions of same direction
5	30/03/2015 00:00	Light, regions of same direction

Fig. 3. Example wind map. This example shows Wind Map 1 and also details positions of waypoints.
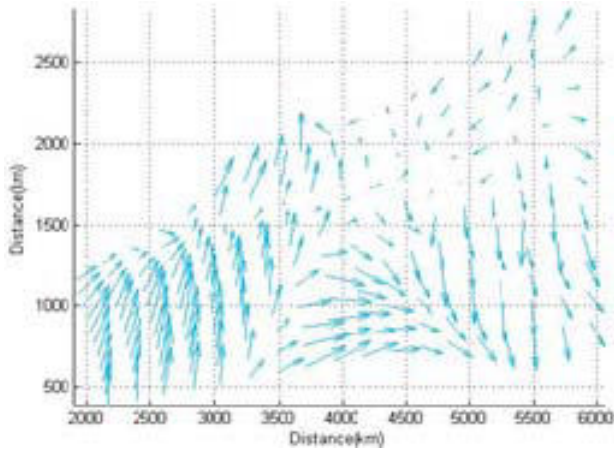
Fig. 4. Example wind map. This example shows Wind Map 4.

Fig. 5 shows the results in both the outbound and return journey directions. The outbound journey here is described as spanning from South to North and/or East to West and, for example, if the outbound journey is the route between Waypoints 39 and 57, its corresponding return journey is from Waypoints 57 to 39.
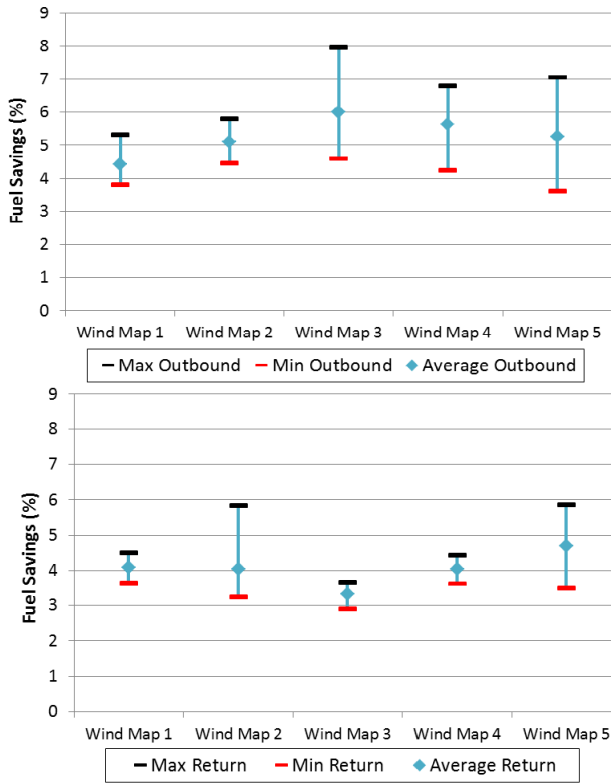

Fig. 5. Fuel savings between wind optimal and shortest distance routes for each wind map.

Fig. 5 shows significant fuel savings for all wind maps in both journey directions. It is, however, the outbound journeys that show the greatest potential for large fuel savings. The outbound journeys here benefited from high velocity tailwinds from the Atlantic, in particular due to the jetstream.

An observation of particular interest is related to the variations in the routes flown by the aircraft for the different wind maps. For wind maps 3 and 5, it is observed that the wind optimal trajectories vary both horizontally and vertically compared to the shortest route; an example of the horizontal track variation is shown in fig. 6. However, for wind maps 1, 2 and 4 only vertical track variations occur, and although fuel savings are still found, it is possible that these gains are predominantly due to the aircraft seeking favourable fuel burn rates at higher altitudes as a result of less drag; discussed in section III.D. It is observed that wind maps 3 and 5 contain wind vectors varying in both magnitude and direction. Wind maps 1, 2 and 4 however contain wind vectors in predominantly the same direction, so despite the presence of high velocity winds there is no benefit to flying a path that horizontally deviates from the shortest path. The wind behavior in Wind maps 1, 2 and 4 can be explained by the selected investigation region of Europe, where winds from the Atlantic Ocean and jetstream typically cause tailwinds in the same south westerly direction over the European airspace.
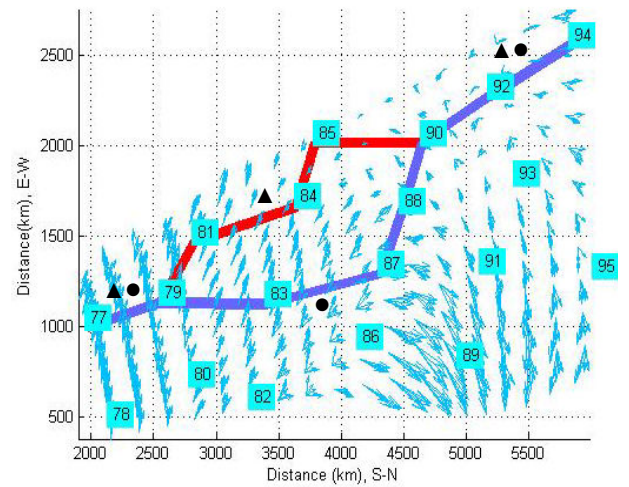

Fig. 6. Plan view of the wind optimal (blue ●) and shortest distance (red ▲) routes through wind map 5 between Waypoints 77 and 94 (as shown on the figure). Percentage fuel saving is 7.1% and distance difference is 1.5%. (Note-lines representing the connectivity between waypoints have been omitted for clarity and that wind vectors at all five flight levels are displayed.)

B. Network Connectivity

Connectivity defines the number of neighbouring waypoints to which each waypoint is connected. A sensitivity analysis was conducted to assess whether increasing the number of paths between waypoints would increase fuel savings. Fig. 7 shows the results based on a network of 30 waypoints using wind map 4. Connectivity is defined as the number of next closest waypoints in the direction of flight through the network.

Little variation in fuel burn savings resulted from increasing network connectivity. It was predicted that as the connectivity increased, fuel savings would also increase. However, with increased connectivity the aircraft had the ability to fly a more direct path between start and destination. Since this benefits the fuel consumption of the baseline shortest distance route as well as the wind optimal route, this explains

why the modification of this parameter does not significantly affect overall fuel burn savings.
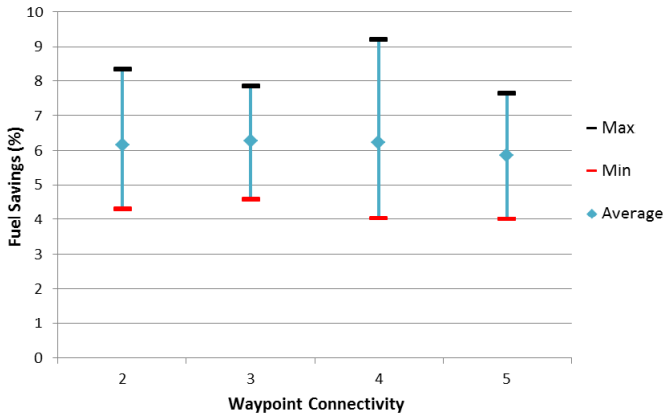

Fig. 7. Relationship between percentage fuel saving and network connectivity. 4 journeys are tested for each case.

C. Waypoint Density

Similarly to network connectivity it was predicted that increasing the waypoint density would increase the opportunity for wind optimal routes to exploit favourable winds. To investigate this, the number of waypoints is varied from 5 through to 50. The test cases are 5, 8, 10, 15, 20, 25, 30, 40 and 50 waypoints.
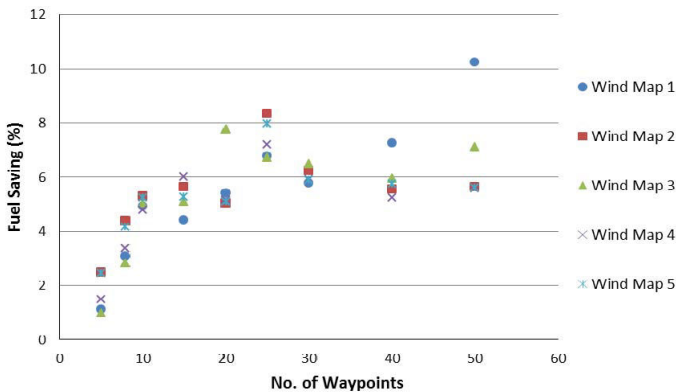

Fig. 8. Relationship between percentage fuel saving and waypoint density.

The results presented in fig. 8 indicate that a flight network of sparse waypoint density can have a detrimental effect on the benefits of wind optimal routing. However, in general, it can be seen that once the density reached 25 waypoints there is little advantage gained from increasing waypoint density further to exploit fuel savings. Similarly to the conclusions presented on network connectivity, it is probable that this is due to the effect that increasing this parameter also has on the shortest distance route, therefore eliminating the potential to increase fuel savings.

D. Fuel Burn Model

Results presented in section III.A reinforce that the different fuel burn rates of an aircraft at different flight levels can influence the path of the optimal route. The observation from section III.A is that in the majority of cases only the

vertical track of the wind optimal route varies from the shortest distance route. Generally, aircraft climb to higher altitude levels suggesting that the effects of less drag at altitude are more predominant than the influence of favourable winds. This highlighted the need for an investigation into these effects. For direct comparison, a model which used the same fuel burn rate for all stages of flight has been developed. This model optimises the route based on favourable winds alone.

It is unsurprising that the majority of wind optimal routes are at high altitudes since in general favourable wind exists at higher altitudes [8]. This is beneficial for fuel savings since, due to the combination of savings from both the wind and reduced drag, large fuel savings can occur. This is demonstrated in fig. 9 where the fuel savings from wind optimal routing alone, i.e. in the case of the constant fuel model, reaches a maximum of 4.05% compared to a maximum of 8.25% in the varying fuel model case. Although the reduced drag at higher altitudes contributes further to fuel savings found from the inclusion of vertical optimisation, it is important to realise the significance of up to 4% fuels savings from the utilisation of favourable winds alone.
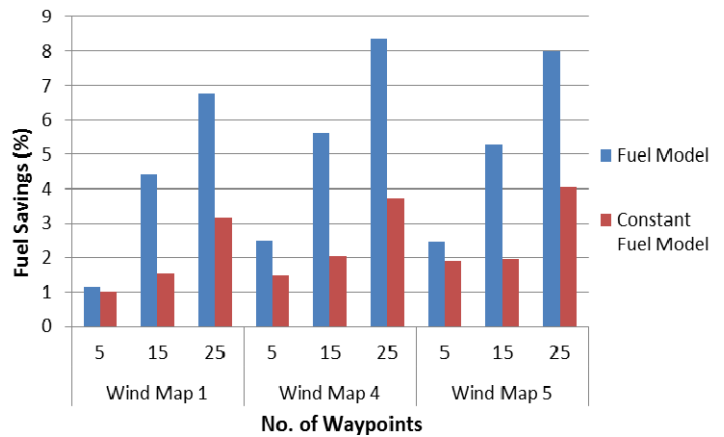

Fig. 9. Fuel savings comparison between the varying and constant fuel burn models.

Fig. 10 shows both fuel model routes utilising higher flight levels. However, despite favourable winds existing at the highest flight level, where drag penalties are lowest, the varying fuel burn model optimised route does not utilise these winds. This is due to the increased fuel required for climb, and that neither the difference in drag between these two levels nor the magnitude of the favourable winds is significant enough to overcome this. Fig. 11 shows an instance where the wind optimal route for the varying fuel model does climb to the highest flight level despite the fuel penalties. In this case the magnitude of the wind at this level is significant enough to overcome the additional fuel used to climb. The differences between these examples emphasises that even when the horizontal track does not vary from the shortest distance route favourable winds do still affect the path of the optimised route. From the points presented within the discussion so far, it can be concluded that wind vector magnitude variation between flight levels predominantly influences the vertical track of the optimised route and the wind vector direction variation influences the horizontal track.
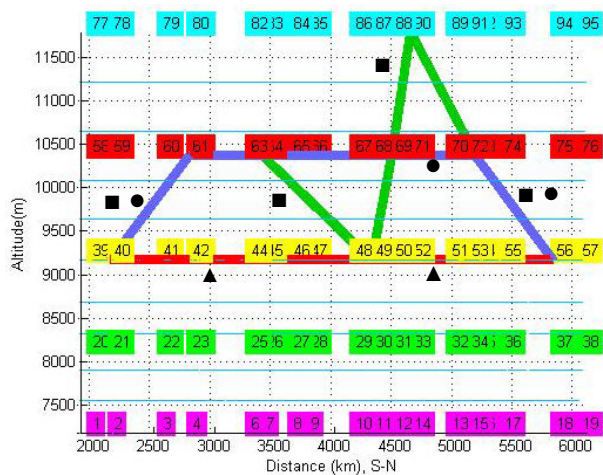
Fig. 10. Vertical track variation through wind map 1 for wind optimal (blue ●), constant fuel burn wind optimal (green ■) and shortest distance (red ▲) routes between Waypoints 40 and 56. Fuel savings are 4.31% for varying fuel burn model and 2.29% for constant fuel burn model.
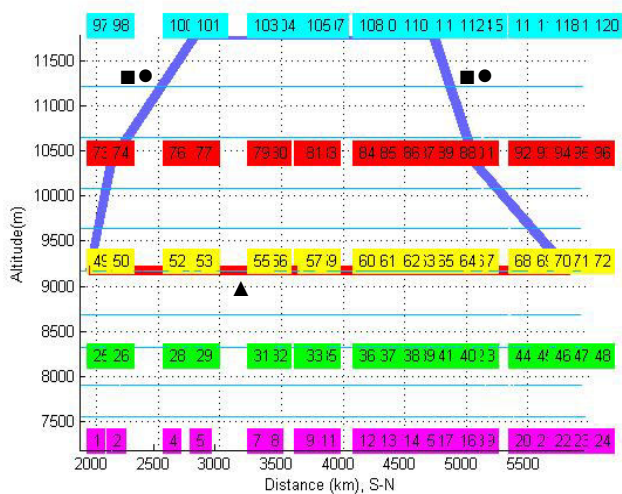

Fig. 11. Vertical track variation through wind map 5 between Waypoints 49 and 71. Fuel savings are 5.86% for varying fuel burn model and 1.67% for constant fuel burn model.

IV. CONCLUSIONS & FUTURE WORK

This article has shown that significant fuel savings can be gained from wind optimised flight trajectories for a single aircraft through a 3 dimensional restricted flight network. The optimisation was conducted through a fixed flight network consisting of discrete waypoints and flight levels based on the size of Europe. Although waypoint and flight level positioning was not extracted from real data, effort was made to apply realistic constraints to replicate the current flight infrastructure as closely as possible. Extensive effort was applied to investigate the potential effects of varying the flight network setup and a number of identified model parameters. In all cases fuel savings greater than 1% where found and this extended up to a potential saving of 10.3% for an outbound journey through wind map 1 consisting of 50 waypoints. This suggests that the benefits of wind optimal flight trajectories are significant particularly when considering the relative low effort and cost for airlines to implement.

Vertical wind optimisation of flight trajectories poses concern with regard to passenger comfort and pilot workload, especially if an optimal wind route varies flight levels frequently. This issue is highlighted in [13] where vertical optimisation is conducted in 'free flight' and it was found that unacceptable 'spikes and stutters' in the flight path were common. In this research however, it was found that the fuel burn penalties resulting from climb between flight levels eliminated these frequent changes in altitude. However, due to lack of available data the distance between flight levels in this research was 5000ft instead of the 1000ft as it is in reality. In future work the correct flight levels would need to be modelled to ensure this issue would still not impact the results.

A final comment on the proposed optimisation is that due to the application of a static wind field, forecasting and routing would have to be carried out offline in advance of the scheduled departure time. For the optimisation to be performed in real time with the capability to adapt to react to changing weather conditions, further research and consideration into the chosen shortest path algorithm would be necessary. A disadvantage specific to Dijkstra's algorithm utilised herein is its computational speed. One particular paper [14] looks into computing optimal flight paths within 10s of seconds, a necessity for on-board flight planning, and proposes alternative algorithms to Dijkstra's. This extends beyond the scope of this project but would be a necessary consideration in the future.

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