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Evaluation of intermediate stop operations in long-haul flights

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Abstract

Recent crises - both economic and geopolitical - and the rise of new competitors in the form of low-cost carriers and Middle East carriers have put a heavy strain on the profitability of traditional legacy airlines worldwide. Many airlines are struggling to survive and are looking for ways to cut their operational costs.

Continuously increasing fuel prices further contribute to the financial difficulties, and although airlines (and aircraft manufacturers alike) have put a significant effort on reducing the operational fuel consumption, fuel still accounts for approximately 35% of airlines' operating expenses. Therefore many airlines seek new ways to further reduce the operational costs through improved fuel efficiency.

One of the less self-evident methods to potentially significantly reduce the total operational fuel consumption is the introduction of intermediate refueling stops. Previous studies have already shown that operating existing aircraft on a long-haul flight with one or two intermediate stops can lead to potential fuel savings varying from 5% to 25% by reducing the additional fuel burn on long-haul flights referred to as transport loss. On the other hand, the concept of intermediate stop operations will also affect the operational costs through higher landing fees, an increased required maintenance effort, a longer total flight time and different crew costs. As previous studies have not addressed the additional costs or benefits of intermediate stop operations, this study aims to identify the total potential of the concept.

For this purpose, a software tool was developed to analyze individual long-haul origin-destination pairs to identify the optimal operation: either direct or including an intermediate stop. Within the tool crew cost, maintenance cost and local fuel prices are determined for simulated flights according to typical operating procedures. A Dijkstra's algorithm then selects the most suitable and cost-efficient airport from a large database if an intermediate stop proves a viable option for the city-pair.

A number of case studies has shown that although in all cases intermediate stops proved beneficial to reduce the total fuel burn, reducing the total operating cost depended highly on city-pair specific conditions, mainly the local fuel prices, changed crew-composition and wind direction. Still, the case studies do indicate that the concept of intermediate stop operations may offer significant cost reductions for many typical long-haul flights across the world, and could prove a viable concept to gain a competitive advantage for specific airlines and routes.

Keywords: Airline operations; intermediate stop operations; fuel efficiency

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1. Introduction

The economic and geopolitical crises of the last decades in combination with growing competition from Middle-East carriers and low-cost carriers on the domestic and (since recently) long-haul markets have put a heavy strain on the profitability of traditional legacy airlines. This is further exacerbated by the increasing jet fuel prices. Although in recent months the jet fuel price showed a temporary but significant decrease, in general the fuel prices have nearly quadrupled in the last two decades, and fuel accounts for up to 35% of airlines' Direct Operating Cost (DOC). Consequently, airlines are looking into new strategies to reduce their total expenses, amongst others by reducing the total fuel burn.

One of the more straightforward ways to reduce the total fuel burn is by renewing the fleet, and hence to obtain more fuel efficient aircraft. However, clearly fleet planning is a long term strategic process and requires large capital investments, essentially prohibiting frequent fleet renewal. Also in the process of flight planning efficiency gains can be achieved. By accurately planning flight routes on the day of operations using accurate take-off weight and en-route weather predictions the optimal flight route and altitude profile may be selected to further reduce the fuel burn. However, although efficiency gains can be significant in this area, most legacy airlines have already optimized their flight planning process leaving little room for further improvement.

This paper focuses on a third strategy that has been shown to potentially lead to significant fuel savings. Planning one or multiple intermediate refueling stops on long-haul flights significantly reduces the fuel weight to be carried, and as such reduces the cost of transportation, i.e. the additional cost of transporting fuel that is required at a later stage. Langhans (2010) states that although flights longer than 4,000 nautical miles only account for 3% of the total number of scheduled flights, these flights account for around 25% of the yearly total fuel consumption in commercial aviation.

Previous research into *Intermediate Stop Operations* (ISO) has already shown significant potential fuel savings when refueling stops are included in long-haul flights. Creemers and Slingerland (2007) show that the design range of an aircraft plays an essential role in the effectiveness of ISO. The work shows that the total fuel consumption of a 7,200 NM flight can be reduced by up to 15% by making an intermediate stop half way, while using conventional existing long-haul aircraft. When the aircraft is specifically designed for medium-range operations (such as e.g. the Airbus A300), the total fuel savings could increase to 27%. Although the potential fuel savings differ significantly, the work of Green (2002), Hahn (2007) and Kenway et al. (2010) all confirm that ISO can lead to 15-29% fuel savings using one or multiple stops and existing long-haul aircraft.

Although previous research has shown the potential to save fuel through intermediate stop operations, in the work mentioned above only the effect on fuel burn is taken into account, or only part of the Direct Operating Cost. In reality, though, ISO also significantly impacts other flight-related costs such as flight and cabin crew cost, maintenance cost, landing fees, etc. Furthermore, the efficiency improvement resulting from ISO depends heavily on the local fuel prices at the departure and intermediate stop airports. Therefore this study aims to analyze the total potential reduction of the Direct Operating Cost of an Origin-Destination (OD) pair, taking into account all time- and cycle-related costs and local fuel prices. It should be noted, though, that the effect of ISO on demand is not modeled in this study, and that the number of passengers traveling is assumed equal to that of direct flights. To analyze the effect of ISO, a database of relevant airports has been created which includes the local fuel prices and the geographic location of the airports. These airports, including the airport of origin and destination for a selected long-haul flight, then serve as the nodes in a network for which all viable connections are simulated using an aircraft model. This yields the total cost of operating each of the flight legs in the network, and allows to identify the optimal combination of flight legs between the airport of origin and destination in terms of total operating cost using a modified Dijkstra's algorithm.

The structure of this paper is as follows. In Section 2 the method to simulate the individual flight legs will be explained in more detail, followed by an elaboration on the cost modeling for each of the flight legs in Section 3. Section 4 describes in more detail the definition of the network of relevant airports and the algorithm used to identify the optimal combination of flight legs. Then, Section 5 will introduce some relevant case studies, followed by the conclusions and recommendations in Section 6.

Nomenclature

D	drag force (*N*)
L	lift force (*N*)
m	aircraft mass (*kg*)
t	time (*s*)
T	thrust force (*N*)
V	true airspeed (*m/s*)
W	aircraft weight (*N*)
γ	flight path angle (*deg*)

2. Flight simulation

To provide a realistic estimate of the efficiency gains obtainable through ISO, it is important to model all possible flight legs with sufficient accuracy to be able to assess and compare the total operating costs of each leg. The basic motion of the aircraft is modeled in two dimensions using a point-mass model under the assumption that the thrust vector lies parallel to the speed vector. Flight is simulated in the International Standard Atmosphere (ISA) using an average representative wind component parallel to the speed vector, and the two-dimensional flight profile is projected onto the great circle arc between the two cities defining the flight leg. The equations of motion can then be expressed as:

$$\begin{aligned} m\dot{V} &= T - D - W\sin\gamma \\ mV\dot{\gamma} &= L - W\cos\gamma \end{aligned} \tag{1}$$

where L, T, and D represent the aircraft's lift, thrust and drag force, respectively, V is the true airspeed and γ is the flight path angle. Finally, m and W are the aircraft's mass and weight. The equations of motion are then integrated over time to simulate the flight over the great circle arc between two airports. The aircraft model simulates the take-off roll, the climb to cruise altitude, descent and landing, and for each phase selects representative values for the airspeed and rate of climb based on current airline standard operating procedures.

The optimal cruise altitude depends heavily on the weight of the aircraft and, consequently, changes as the aircraft burns fuel and becomes lighter. It is therefore common practice on long-haul flights to execute so-called step climbs. Rather than continuously climbing as the aircraft becomes lighter, the aircraft ascends at 2,000 feet increments to account for the weight reduction. In the aircraft model integrated in this study these step climbs are taken into account and executed when specific weight thresholds are reached.

The simulation of the flight legs described above determines the fuel required for a specific take-off weight. However, it should be noted that the take-off weight includes the initial fuel mass, and as such the required take-off weight cannot be determined directly. Since carrying the least amount of fuel minimizes the cost of transportation, an iterative process is used to determine the minimum take-off weight of the aircraft which ensures that sufficient trip fuel is available to safely complete the flight leg. The initial fuel mass also includes fuel for taxiing and the regulatory contingency and reserve fuel amounts. The simulation then yields the fuel burn and the flight time for an individual flight leg, which is used to determine the Direct Operating Cost of the flight.

Table 1. Available aircraft types.

Aircraft type	ICAO code	First flight	Capacity (passengers)	Max. take-off weight (MTOW) (*kg*)	Maximum range (*NM*)
Boeing 747-400	B744	1988	408	397,000	7,300
Airbus A330-300	A333	1992	290	242,000	6,100
Boeing 737-800	B738	1997	180	79,000	3,100

To be able to assess the feasibility of the ISO concept this study includes three different aircraft types. Some general characteristics of the aircraft are depicted in Table 1. The older generation Boeing 747-400 is expected to benefit most from the ISO concept due to its four engines, especially compared to the more recent and more efficient Airbus A330-300. The Boeing 737-800 may prove particularly suitable for the ISO concept. The significantly smaller design range, may, based on the conclusions of Creemers and Slingerland (2007), improve the fuel efficiency, albeit due to the smaller capacity more flights are required to serve the same demand.

3. Cost modeling

The Direct Operating Cost (DOC) is modeled according to the methodology described by Liebeck et al. (1995). Apart from the largest cost contributor – the total fuel burn discussed in the previous section, the method includes three additional cost types. Within the crew cost – the largest contributor to the DOC apart from fuel, both the flight and cabin crew costs are modeled separately. Although in reality most airline crews receive yearly salaries, an estimate of the crew cost can be made per flight hour, relating the crew cost directly to the flight time. Furthermore, the composition of the flight crew and the cabin crew depend on the duration of the flight (following the Federal Aviation Authorities (FAA) guidelines) and the aircraft capacity, respectively. In addition, crew members are assigned resting days based on the duration of their flight. Finally, $1000,- US is added per crew member per day at an outstation for expenses and allowances. It is noted that the number of days at an outstation is also dependent on the duration of the flight. Although the ISO concept may lead to longer total flight durations between an OD-pair, the relatively short flights to and from the intermediate stop location may allow for smaller flight crews and shorter stays at the outstation, hence potentially reducing the total crew cost.

Secondly, maintenance cost is taken into account, which consists of both engine and airframe maintenance. Maintenance cost can be further divided into a time- and a cycle-related component. It is readily clear that the ISO concept will increase both the time- and cycle-related components of the maintenance cost.

Finally, for every flight navigation and landing fees have to be paid. Navigation fees are paid to the countries that are overflown to support the air traffic control services, and depend on the weight of the aircraft. Landing fees – also based on the aircraft weight – are paid for airport services. Clearly, the total cost of both types of fees will increase in ISO.

It is finally noted that both the crew cost and the maintenance cost contain elements that are dependent on time. The ISO concept – requiring an additional landing and take-off (LTO) cycle and a deviation from the shortest flight path to reach a stopover airport – leads to a longer trip time, which is directly reflected in the DOC. However, a stopover also requires taxi time to the refueling station, time to refuel the aircraft and time to taxi out to the runway again. This additional stopover time is also taken into account in the model, and is dependent on the size of the airport used for the stopover and the aircraft type use in the flight.

4. Network modeling

The model described above allows to simulate flights on any flight leg within the range of the aircraft, and allows to identify the total fuel weight required and part of the DOC (still excluding fuel cost) of that flight leg. To now identify the optimal route or sequence of routes connecting a long-haul city-pair requires a three step process. First a worldwide database of airports is established. Although in total almost 42,000 airports are located around the world, to reduce the size of the database in this study only medium to large airports are considered. This ensures that the largest aircraft types considered in this study are able to safely operate from these airports. This is further enforced by selecting only airports with a Category II or Category III Instrument Landing System (ILS CAT II / III) available, which means aircraft can safely land on the selected airport even in heavy weather conditions. This reduces the database used in this study to around 400 relevant airports worldwide. In addition to the geographic location of the airports in the database, also the local fuel prices are stored, based on recent data available from a large legacy airline. Together with the total fuel burn this then yields the fuel cost, hence completing the DOC.

To evaluate all possible flight legs between the airports in the database would still be prohibitively computationally inefficient, and would require to evaluate a significant number of unreasonable flight legs. Therefore three additional selection procedures are added, which depend on the OD-pair to be evaluated. Firstly, only airports that lie relatively

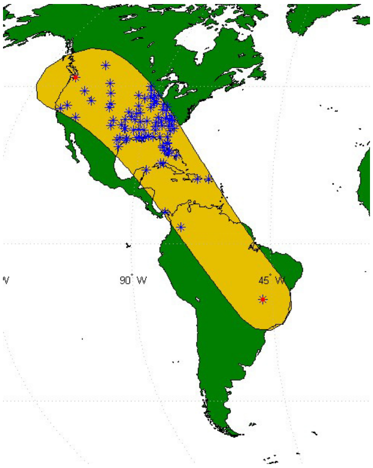

Fig. 1. Airport selection for the Seattle-Brasilia OD-pair.

close to the original, direct flight route are considered. This essentially means that only airports within a 1,000 km range on both sides of the great circle arc between the OD-pair are taken into account. Furthermore, although all airports in this buffer zone are considered as potential stopover locations, only flight legs that are in the general direction of the direct flight are evaluated. As an example consider the OD-pair Amsterdam-Barcelona with potential stopovers in Paris and Marseille. Although theoretically the aircraft could fly the combination Amsterdam-Marseille-Paris-Barcelona, this route would not be considered as the leg between Marseille and Paris is in the opposite direction of the OD-pair. Finally, flight legs shorter than 500 km are not considered. Figure 4 shows the resulting airport database used for the OD-pair Seattle-Brasilia, where the 1,000 km buffer zone is indicated in yellow, the origin and destination airports in red and the potential stopover locations in blue asterisks.

After gathering all the data required from each of the flight legs, what remains is the selection of the optimal combination of flight legs in terms of cost to operate the OD-pair. For this purpose a modified Dijkstra's algorithm is used. Apart from the cost matrix used to define the cost between any city-pair, the method also uses a so-called adjacency matrix consisting of binary values for each of the city-pairs. This is used to indicate viable flight legs by assigning a 1 to legs that comply with the selection criteria discussed above, and a 0 to all other legs. Although flight legs that should not be considered could also be penalized in the cost matrix, using the adjacency matrix ensures that none of these legs is evaluated, reducing the computational effort required.

5. Results

As an example of the methodology and to analyze the feasibility of the Intermediate Stop Operations concept, a number of case studies has been done for long-haul routes distributed around the world, of which three are presented herein.

5.1. Bangkok–Sydney

The first example is the flight between Bangkok and Sydney, which is operated five times per day currently by different types of long-haul aircraft, including the Boeing 747-400. The great circle distance between the two cities is just over 4,000 NM and due to the general southward direction no significant wind vector is assumed. As can be seen in Fig. 5.1, only seven airports are considered as potential refueling airports. It should also be noted that, given the maximum range of the Boeing 737-800, an intermediate stop is always required to operate the OD-pair.

Figure 3 and Table 2 show the results for this OD-pair, where the fuel price ratio is the ratio of the fuel price at the stopover airport and the departure airport. It can be seen that all three aircraft types make a stopover in Makassar. Especially for the Boeing 747-400 the cost reduction is significant, in total up to 2.4% per seat. This is mainly caused

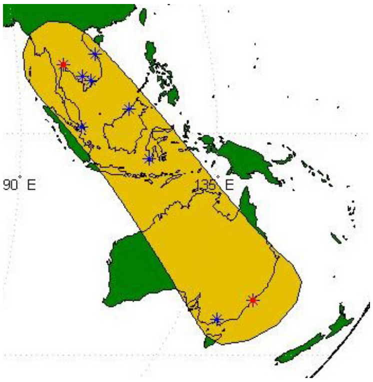

Fig. 2. Airport selection for the Bangkok–Sydney OD-pair.

Table 2. Bangkok–Sydney results.

	B738 ISO	A333 direct	A333 ISO	B744 direct	B744 ISO
Stopover airport	Makassar	-	Makassar	-	Makassar
Route time (*hr:min*)	10:00	8:36	9:48	8:40	10:06
Flight crew	2	3	2	3	2
Fuel price ratio	0.95	-	0.95	-	0.95
Fuel cost (kUSD)	20.8	36.3	36.5	64.9	60.2
Crew cost (kUSD)	20.3	23.3	18.3	27.3	24.2
Maintenance cost (kUSD)	4.75	6.07	7.36	15.4	18.9
Route fees (kUSD)	1.12	1.18	2.36	1.68	3.36
Total route cost (kUSD)	42.0	66.9	65.8	109.2	106.6
Cost per seat (USD)	233	230	225	269	261

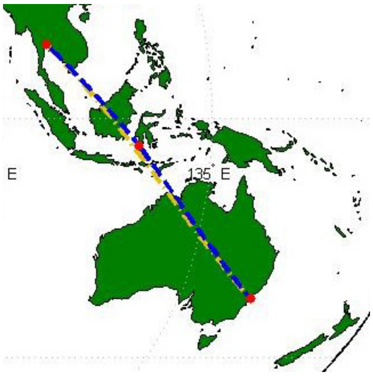

Fig. 3. Optimal route for Bangkok–Sydney with intermediate stop in Makassar.

by 5.9% fuel savings (or 7.2% in terms of cost) and reduced crew cost. Due to the intermediate stop the Second Officer is no longer required, and the total number of resting days is reduced from six to four. For the Airbus it is remarkable to note that even though the additional LTO-cycle increases the total fuel burn by 2.1%, the relatively low fuel prices at Makassar and the reduced crew cost still lead to a small reduction of the total cost of 1.5%. This example shows that even though ISO proves beneficial for the fuel efficiency, the effect on fuel burn is not always reflected in the total cost of operating the flight.

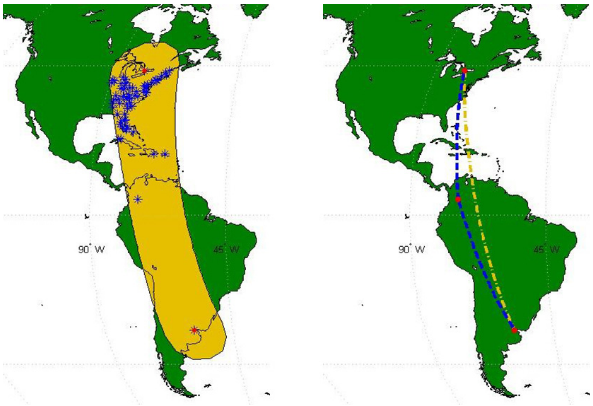

Fig. 4. (a) Problem setup YYZ–EZE; (b) Optimal route YYZ–EZE.

5.2. Toronto–Buenos Aires

The second example shows a route between Toronto (YYZ) and Buenos Aires (EZE), which is currently not operated as a direct flight. The total great circle distance is 4,850 NM, and due the southward direction again no significant wind vector is assumed to be present. The available intermediate stop airports are shown in Fig. 5.2(a). Although the high density of airports in the United States leads to a high number of available intermediate stop airports, these airports are all located quite close to the origin and are therefore not considered as refueling stations. As can be seen in Fig. 5.2(b), an intermediate stop is made in Bogota, in a region where only a very small number of airports are available for refueling.

The numerical results shown in Table 3 show that both the Boeing 747 and the Airbus A330 can achieve an approximate 3% decrease in the total cost for the flight as compared to the direct flight. Even though the fuel is slightly more expensive at Bogota the reduced fuel burn for both aircraft types reduces the fuel cost, which, together with the reduced crew cost again leads to an overall cost reduction. Another surprising conclusion for these results is that the Boeing 737-800 is the cheapest aircraft to operate this route per seat. Bogota is located almost exactly in the middle between Toronto and Buenos Aires, and as such the route is split up into two segments of almost equal distance. The two segments of approximately 2,500 NM are close to the optimal range for the Boeing 737-800.

Table 3. Toronto–Buenos Aires results.

	B738 ISO	A333 direct	A333 ISO	B744 direct	B744 ISO
Stopover airport	Bogota	-	Bogota	-	Bogota
Route time (*hr:min*)	11:37	10:03	11:18	10:07	11:37
Flight crew	2	3	2	3	2
Fuel price ratio	1.02	-	1.02	-	1.02
Fuel cost (kUSD)	22.4	46.9	45.1	84.8	77.9
Crew cost (kUSD)	19.6	26.8	22.2	31.5	28.9
Maintenance cost (kUSD)	4.60	7.01	8.78	17.8	21.4
Route fees (kUSD)	1.12	1.18	2.36	1.68	3.36
Total route cost (kUSD)	47.7	81.9	79.4	135.8	131.5
Cost per seat (USD)	265	280	272	334	322

5.3. New York City–Doha

The final route presented in this paper is the route between New York City and Doha in Qatar, which is a distance of over 5,700 NM. Due to the general eastward direction of this route the effect of wind can no longer be neglected,

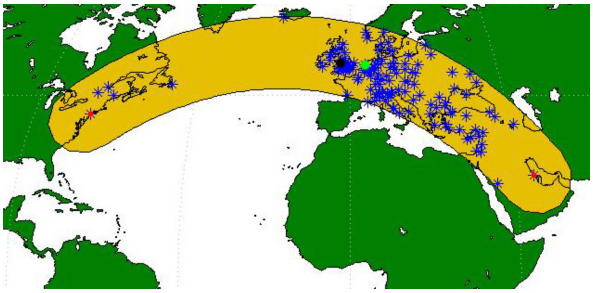

Fig. 5. Problem setup New York City–Doha.

and therefore a constant representative tailwind is modeled. Figure 5.3 shows the problem setup and the intermediate stop locations. The numerical results for this route are presented in Table 4.

Table 4. New York City–Doha results.

	B738 ISO	A333 direct	B744 direct	B744 ISO
Stopover airport	Manchester	-	-	Amsterdam
Route time (*hr:min*)	12:28	11:47	11:53	13:31
Flight crew	2	3	3	2
Fuel price ratio	1.05	-	-	1.01
Fuel cost (kUSD)	25.1	45.4	91.5	82.8
Crew cost (kUSD)	20.9	31.1	36.4	33.2
Maintenance cost (kUSD)	4.90	8.14	20.7	24.5
Route fees (kUSD)	1.12	1.18	1.68	3.36
Total route cost (kUSD)	51.9	85.8	150.2	143.9
Cost per seat (USD)	289	294	370	353

For this route, the Boeing 737-800 makes an intermediate stop at Manchester, indicated in black in Fig. 5.3. Although the fuel is significantly more expensive than at other airports in Europe, in this case the range of the aircraft at the given payload prohibits flying further into Europe. Still, the 737 performs best in terms of cost per seat. The 747-400 makes a refueling stop in Amsterdam, due to the relatively low fuel cost. The total savings in terms of fuel cost are over 9.5%, and together with a reduction in crew cost the total operational cost for the 747 is 4.2% lower than in the direct route. A surprising result is obtained for the Airbus A330. Although the total flight distance is long, the combination of tailwind (essentially reducing the air distance flown), relatively high fuel prices in Europe and the general efficiency of the aircraft make the direct flight slightly cheaper to operate.

6. Conclusions and recommendations

A study is presented on the viability of Intermediate Stop Operations in long-haul flight operations of legacy airlines. In this study not only fuel burn but the total Direct Operating Cost of an OD-pair was evaluated, which includes the effects on crew cost, maintenance and landing and en-route fees.

It was found that for the older generation Boeing 747-400 for most routes a 5-10% reduction of the total cost was achieved with a single intermediate refueling stop. For the more modern Airbus A330-300 with a significantly better fuel efficiency the results showed a reduction of 2-6% in total cost. In both cases, but for the latter even more so, the cost reduction was mainly contributed to by the reduction of crew cost in terms of both the number of flight crew required and the regulatory resting days.

Although not capable of flying long-ranges, the Boeing 737-800 has also been evaluated as the distances flown in ISO are relatively close to its design range. It was found that for most routes the 737 indeed proved to have the lowest cost per seat. The combination of fuel efficiency and relatively low crew cost generally lead to costs per seat that are similar to but lower than that of the contemporary Airbus A330-300.

In general, however, the cost reduction found is small and depends heavily on the available refueling airports and, more importantly, the local fuel prices.

In this study only the effect on cost was assessed. For a legacy carrier focusing on a high service standard and short connection times, introducing the ISO concept may also have a significant effect on the demand for air travel. When the relatively small cost reductions are considered, it is unlikely that the ISO concept will be a good alternative to direct flights.

On the other hand, it should also be noted that the current success of the Middle-East carriers closely resembles the ISO concept, especially on routes between Europe and Asia. Furthermore, recently two low-cost carriers started operating between Europe and North-America using 737 class aircraft, with stopovers in Newfoundland and Iceland. This shows that the concept may prove viable for non-legacy carriers to address new markets.

Although the findings of the study show some potential for the ISO concept, some limitations in this work need to be addressed in further research.

Firstly, the effects on the demand of airlines should be included. Since the ISO concept leads to longer flight times to serve the same OD-pairs, passengers will have longer travel times. These effects may very well counteract the cost reductions found in this work for legacy carriers. Alternatively the ISO concept could be further evaluated focusing on low-cost operations where ticket fare prices weigh heavier than travel time for most passengers.

Furthermore, since the cost reduction depends heavily on the local fuel prices and the type of aircraft used, airline specific data may be required to assess the viability of the concept for specific airlines. Additionally, the flight simulation, and especially the vertical flight profiles, should be improved to better predict the fuel consumption.

Finally, the effect on aircraft utilization should be considered. The ISO concept essentially leads to more ground time per OD-pair served, and consequently reduces the aircraft utilization. This may require additional aircraft to serve the same network. In addition, the increased number of cycles may – apart from the effect on maintenance – require faster fleet replacement, which would increase financing costs.

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