SYSTEM ANALYSIS FOR FUTURE LONG-RANGE OPERATION CONCEPTS

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Abstract

A systems analysis is conducted to show the potential of intermediate stop operations (ISO) in terms of fuel efficiency increase and cost-effectiveness. It can be shown that both with existing and re-designed aircraft, the fuel saving potential is in the order of 7 to 15.5 % on a single mission, depending mainly on aircraft design range and the geographic location of the refueling point with regards to origin and destination.

Based on the findings for single mission, a global analysis of all Airbus A330 and Boeing 777 flights served in 2007 is performed, defining fuel-optimum intermediate airports wherever possible. An A330-200 type of aircraft with a design range reduced to 3000 nm would yield highest global fuel benefits of 10.4 % considering both ISO flights and flights served in conventional ways, whereas a 4400 nm design would be able to serve the most number of flights in ISO mode. An airport load analysis shows, that due to the concentrated location of route-streams, the top ten selected airports for intermediate stops would serve 30-44 % of all ISO flights for the fleets under consideration. The most frequented airports would then experience additional traffic of roughly 130 flights per day.

It is further shown that a cost-benefit analysis is necessary to reveal the true economic benefit of this concept for an airline, going beyond plain fuel cost to a trade-off between opposing cost elements, revenues, maintenance, and utilization.

1 Introduction

The air transportation system (ATS) is facing major challenges in the near and even more in the distant future in the areas of environment, cost effectiveness, efficiency, capacity, safety, and security. For theses aspects, targets for the near to medium term future have been set e.g. by ACARE. Technological innovation is key to the achievement of many of these goals. While recent developments tend to show marginal efficiency improvements, more radical changes and improvements are necessary to achieve the acquired goals that are the basis for a sustainable development of global air transportation.

Aircraft operations contribute to about 3 % of man-made carbon dioxide emissions. This share is created by general aviation and scheduled flights. Airbus internal scenarios for the year 2022 show that long-range (LR) flights serving routes over 4000 nm account for around 3 % of the total scheduled flights, and around 5 % of the available seats are offered on these flight distances. However, around 25 % of the yearly commercial aviation fuel consumption is generated by LR operations of this distance [1].

From this fact, LR aircraft and their way of operation are understood to provide a big lever for effectively introducing innovation into the air transportation system.

1.1 Approach

A Systems Engineering (SE) oriented approach provides fundamental ideas to this study. The ATS is considered to be a complex system, as described in, [2–5]. The following SE principles find their application. A trigger / problem definition leads to a short requirements and functional analysis. In a synthesis phase, possible designs are generated and then evaluated in the analysis phase. This phase also includes a life-cycle oriented cost-benefit analysis.

1.2 Innovative concepts for LR operations

A variety of innovative aircraft and operational concepts exist to make LR operations more efficient. For the purpose of this study, it is distinguished between marginal innovations as opposed to radical innovations. While the latter group includes concepts such as natural and hybrid laminar flow concepts, blended wing body configurations, and

Tab. 1. Concepts for LR operations with a marginal rate of innovation.

CONCEPT	EFFICIENCY POTENTIAL	SAFETY / AUTOMATION REQUIREMENTS / PAX COMFORT
Flying slower	0(+)	0 / 0 / 0
Formation flight	+	– / – – / –
Civil aerial refueling	++	– –/ – – / 0
Intermediate stops operations	++	0 /0 / –

++ significant positive impact
+ positive impact
0 minimum impact
– negative impact
– – significant negative impact

radical engine configurations, marginal innovations are considered to be achievable with less technological and entrepreneurial effort. From a manufacturer point of view, their development poses a lower financial risk to the company as the innovation lies not only in the system but in the way of its operation. It is assumed that such innovations can be realized within a shorter period of time as development efforts are lower compared to radical innovations. A list of such marginal innovations is given in Tab. 1.

Flying slower makes use of the fact that drag increases quadratic with speed. However, leaving the ‘cruise bucket’ would lead to inefficiencies, as long as the aircraft is not specifically designed for such lower speeds. The full potential of flying slower could be achieved with new engine concepts like e.g. open rotors, which are out of our scope of marginal innovation.

Formation flight borrows from the way migrating birds travel, its drag reduction potential was shown for military applications [6]. For civil aviation, a fuel saving potential of up to 12 % is simulated [7]. Also aerial refueling is a common way of extending ranges in military aviation. Its adaption to civil aviation also shows great fuel saving potential even if the tanker-aircraft fuel is considered [8]. Both concepts however are critically subject to issues regarding safety, technical requirements for automation, and passenger comfort.

Similar to aerial refueling, intermediate stop operations (ISO) benefits from a reduction in take-off weight and all subsequent snowballing effects. By reducing the length of the served flight legs the amount of excess fuel carried from the beginning can be reduced. For ISO, refueling takes place at one (or more) intermediate landing(s) equally distributed between origin and destination. This may cause passenger discomfort due to an extended flight time and through additional landing and take-off.

Concluding from this brief and qualitative analysis, ISO seems to be a candidate concept worth more thorough investigation.

For all four example concepts, significant parts of innovation are due to new ways of aircraft operations. Therefore, new ways of interacting with the surrounding ATS elements are necessary. In order to analyze such complex system interactions, an approach capturing all relevant effects is necessary.

1.3 Related Studies

A number of previous studies devoted their work to the analysis of ISO concepts with one or more intermediate stop-over. Some are briefly discussed in the following.

Greener by Design [9; 10] analyses the influence of design range on fuel economy. By applying an empirical weight equation, they compute blockfuels for a 15000 km mission in direct flight operations and with two intermediate stops for refueling. Their results promise, for the same payload, fuel savings of 29% - 49%, depending on the payload transported. The reduction in operating empty weight (OEW) is in the same order of magnitude and will, according to the authors, also have a strong impact on the aircraft list price. It is concluded that beyond a distance of about 7400 km, intermediate refueling stops might be favorable in terms of fuel efficiency. While using simple weight models to highlight the question addressed, the authors recommend using models that also incorporate more realistic design constraints and effects; also the related concept of air-to-air refueling should be considered, bearing fuel saving potential in a similar order of magnitude.

Creemers [11] compares on a mission of 7200 nm a typical LR aircraft to a medium range aircraft operated with one intermediate stop with regards to fuel efficiency, DOC saving potential and environmental impact. A B747-400 serves as basis and is compared to a generic B747-400MR with a 50 % reduced design range of 3600 nm; both aircraft are identical in terms of technology level and passenger capacity. Creemers concludes that this design range reduction could result in fuel savings of 21 %, DOC reduction of 9 % while overall block time would increase by 7.5 % due to the intermediate landing and take-off for refueling. Furthermore, the environmental impact of a mission is assessed to be 13 % below the reference direct flight in terms of global warming potential (GWP).

Tab. 2. Overview of previous studies on intermediate stop operations and their findings.

STUDY	NO. OF STOPS	MISSION LENGTH [KM]	SINGLE LEG LENGTH [KM]	BLOCKFUEL SAVINGS AGAINST DIRECT FLIGHT	AIRCRAFT TYPE	AIRCRAFT SIZE [SEATS]
Greener by Design [9]	2	15000	5000	29 % - 49 %	–	–
Creemers [11]	1	13334	6667	21.5 %	747-400	420
Hahn [12]	2	15000	5000	22.5 %	777-200HG	305
Kenway et al. [14] + own study	3	11112	2778	~58 %	A330-200	293

Hahn [12] uses an aircraft design synthesis code FLOPS (Flight Optimization System) for his studies. A Boeing 777-200 serves as reference and is optimized for direct flight and multi-step operations. A design range reduction from 15000 km to 5000 km for triple-step operations would result in an operation weight empty reduction of around 29 %[1] and a blockfuel reduction of around 22.5 %[2]. Hahn also concludes, that these observed effects are stemming to equal extent from the reduction in range on the one side and from a redesign to a shorter design range on the other.

Tyagi et al. [13] conduct a study on multi-stage operations and expand the scope further to operational aspects like route and network analysis from an airline point of view.

Kenway et al. [14] use low to medium level design tools for multidisciplinary redesign of an A330-200 sized aircraft with reduced range. By reducing the A330's design range to 1500 nm compared to the actual 6400 nm, fuel savings of 13.4 % can be achieved for the new design compared to a standard A330-200 design on a 1500 nm mission. Investigations of intermediate stop operations on a long-haul distance are out of the scope of this study. The values in Tab. 2 for theoretic 4-step operations are indirectly derived from Kenway's findings.

An overview over the results of previous studies is given in Tab. 2.

2 Requirements and Functional Analysis for ISO

Like any other system, the ATS has to fulfill an array of main functions that are amongst others to serve the demand for air transportation, to ensure safe operations, to ensure the economic viability, to ensure productivity and reliability, and to consider environmental aspects.

The ATS consists of an array of further system elements, for example commercial aviation, military aviation, general aviation, airlines, airports, air navigation service providers (ANSP), meteorological service providers, manufacturers, political instances and more.

The system of interest in this study covers the ATS sub-systems aircraft, airline, airports, and routes.

The A330-200 was selected as a representative aircraft for LR operations.

All routes which are served by either Airbus A330-200 or Boeing 777 aircraft according to 2007 OAG data are considered. The system to develop and analyze is required to serve exactly the same origin-destination pairs, either as ISO or in direct operations.

To ensure the present transport volume (in terms of ASK), the aircraft system is required to accommodate an equal amount of passengers to its reference aircraft.

The main function of candidate airports for intermediate stops is to enable safe landing and take-off. They must have at least one runway of 2500 m in length or more. For safe operations, navigation aids must be in place including ILS or at least DMEs.

The overall system is required to provide a transportation system benefit.

3 System Synthesis

The NASA Flight Optimization Program (FLOPS) is used for the synthesis task of an A330-200 type of aircraft. The aircraft design and performance is validated against published data. The calculated values for mission fuel are compared; the results are listed in Tab. 3.

[1] This is computed from the OEW increase of 41 % from the 5000 km to the 15000 km design, given in the paper.
[2] This value is computed from the blockfuel increase of 29 % from the 5000 km to the 15000 km design, given in the paper.

Tab. 3. Comparison of mission fuel calculated values to published references for a A330-200 type of aircraft

MISSION LENGTH [NM]	SOURCE	MISSION FUEL [LB]		REL. DIFF.
		VALIDATION BASIS	CALCULATION	
2100	[15]	51676	52415	+ 1.43 %
2420	[15]	60162	60190	+ 0.05 %
4850	[15]	124206	123856	- 0.28 %
5160	[15]	133994	132671	- 0.99 %
6400	[14]	171221	169466	- 1.03 %

For all calculated values given in Tab. 3 the relative error is 2.2 % or below. This is assumed to be accurate enough for this study, as mainly comparative analysis is performed.

This design serves as the reference for further studies. An array of additional aircraft configurations with the same requirements but reduced design ranges between 3200 nm and 6400 nm is populated. Those are also optimized for fuel burn, with wing area and thrust level as the free parameters, and later used for ISO operations. For both the original layout and the reduced-design-range layout, off-design mission performance calculations are conducted. For the ease of handling, a meta-model of the off-design fuel burn for all design ranges is composed using polynomial regression.

A database of all worldwide airports fulfilling the postulated requirements is set up.

4 System Analysis

The results of a mission analysis for a variation of theoretic ISO mission profiles are shown first. Then, the real-world routes and frequencies are analyzed and results are presented. Finally, an economic evaluation is conducted using a cost-benefit analysis method.

4.1 Theoretic Mission Analysis

The effects of operating with intermediate stops compared to direct flight operations are analyzed first for a single generic mission with varying location of the intermediate airport. Fig. 1 describes the experimental set-up where *M* serves as the intermediate airport for a trip from *A* to *B*. The parameters in Eqs. (1) and (2) describe the relative location of *M* to *A* and *B*. f_{detour} is the route extensions due to *M* located off the great-circle between *A* and *B*. f_{offset} describes the excentricity of *M* to the geographic midpoint between *A* and *B*. All calculations are based on great-circle approximations, since this is perceived to be accurate enough within this study.

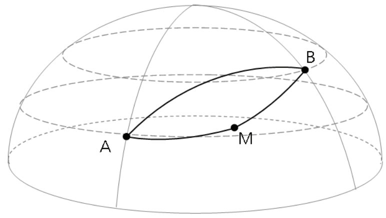

Fig. 1. Sketch of intermediate stop operations concept

$$f_{detour} = \frac{\overline{AM} + \overline{MB}}{\overline{AB}} \qquad (1)$$

$$f_{offset} = \frac{\max\left(\overline{AM}, \overline{MB}\right)}{\overline{AM} + \overline{MB}} \qquad (2)$$

The influence of ISO and f_{offset} on fuel burn is shown in Fig. 2. All missions are calculated with a standard 6400 nm layout, no reduced design range. Blockfuel changes are relative to the direct flight with that aircraft. It can be seen that only for missions longer than approximately 3400 nm, ISO show fuel saving potential for a midpoint location of *M* (f_{offset} = 0.5). For longer missions, also more excentric points for an intermediate landing yield potential for fuel saving. A saving of around 7 % can be achieved for the 6400 nm mission, which at the

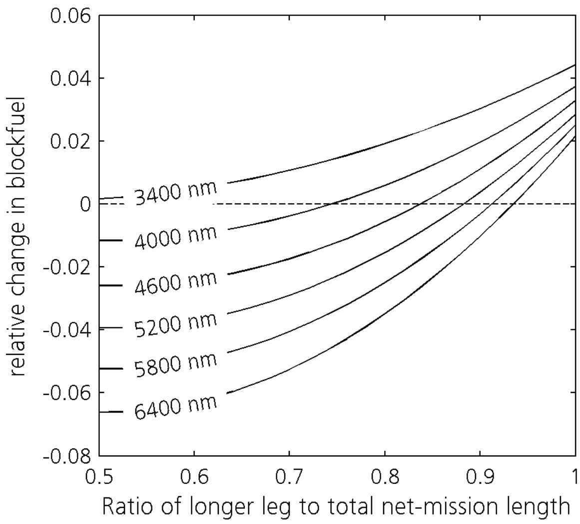

Fig. 2. Change of blockfuel for a A330-200 type of aircraft for different mission lengths and different midpoint positions f_{offset}.

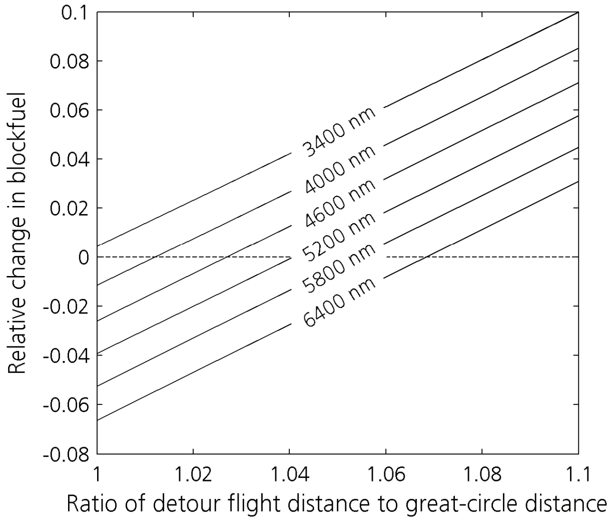

Fig. 3. Change of blockfuel for a A330-200 type of aircraft over an increasing detour factor f_{detour} due to an off-route position of the refueling-point. Refueling point is at 50% of net-route length.

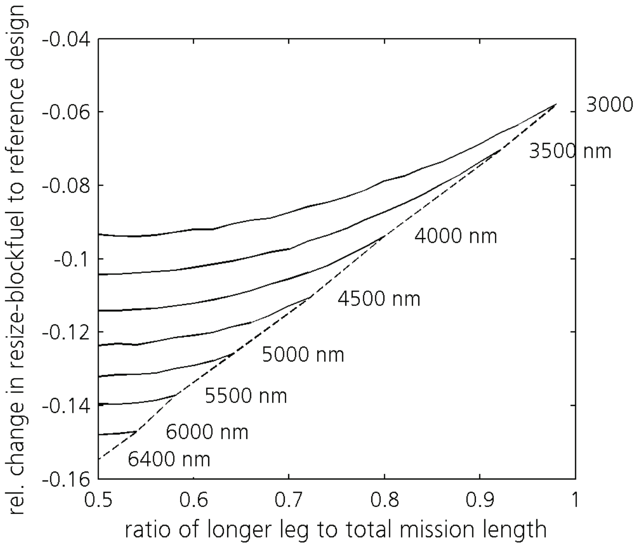

Fig. 4. Blockfuel comparison of a A330-200 type of aircraft optimized for 3200 nm in intermediate stop operation to a 6400 nm standard design flying direct. Off-design calculations for different mission lengths between 3000 and 6400 nm.

same time is the range limit for the direct reference flight.

By using the same experimental set-up as before, Fig. 3 shows the impact of a detour between 0 and 10 % on fuel burn improvement due to ISO. For a 6400 nm mission, ISO is more fuel efficient than a direct flight.

When real city pairs are connected with ISO, the effects shown in Fig. 2 and Fig. 3 are superposed in the majority of all cases, due to the not-perfect geographic location of potential intermediate airports.

While the previous analysis did not consider aircraft that are resized for shorter mission, this is done in Fig. 4. An aircraft optimized for 3200 nm and operated in ISO mode is compared to a 6400 nm aircraft in direct flight operations. A maximum fuel saving is possible on a 6400 nm mission, ranging around 15.5 %.

4.2 Global Route Analysis

To allow for a holistic assessment of the viability of the ISO concept on a global level it is necessary to analyze the concept's impact under realistic air network conditions. This is with respect to typical flight routes, geographic location of airports as well as capacity constraints from an ANSP's and airport perspective. The potential fuel savings or airline revenues due to the structure of the network can only be determined more accurately by accounting for the underlying geographic distribution of suitable airports and a realistic air traffic demand.

For this purpose, a selection of LR connections for which ISO seem to be applicable is made based on OAG data. All scheduled flights served by Airbus A330 and Boeing 777 in 2007 are chosen and their respective frequency is determined. For each of these routes all airports suitable for an intermediate stop are identified by different criteria. One possible criterion for that would be the detour factor f_{detour} introduced above, but a small f_{detour} itself does not ensure that the corresponding intermediate airport is located ideally as close to the midpoint of the direct route (theoretical optimum for intermediate landing) as possible. Therefore, an additional criterion based on the offset factor f_{offset} is used, allowing for finding the airport which lies closest to the midpoint. Further criteria dependent on the specific aircraft redesign include minimum overall trip fuel and minimum overall trip time as well as the maximum net present value (NPV) which can be achieved by choosing a specific intermediate airport. For the following analysis, the fuel ratio criterion[3] is chosen since this implicitly includes both geometric relations of the

[3] Overall fuel consumption for both legs with redesigned aircraft in ISO mode divided by original fuel consumption of direct flight with original aircraft

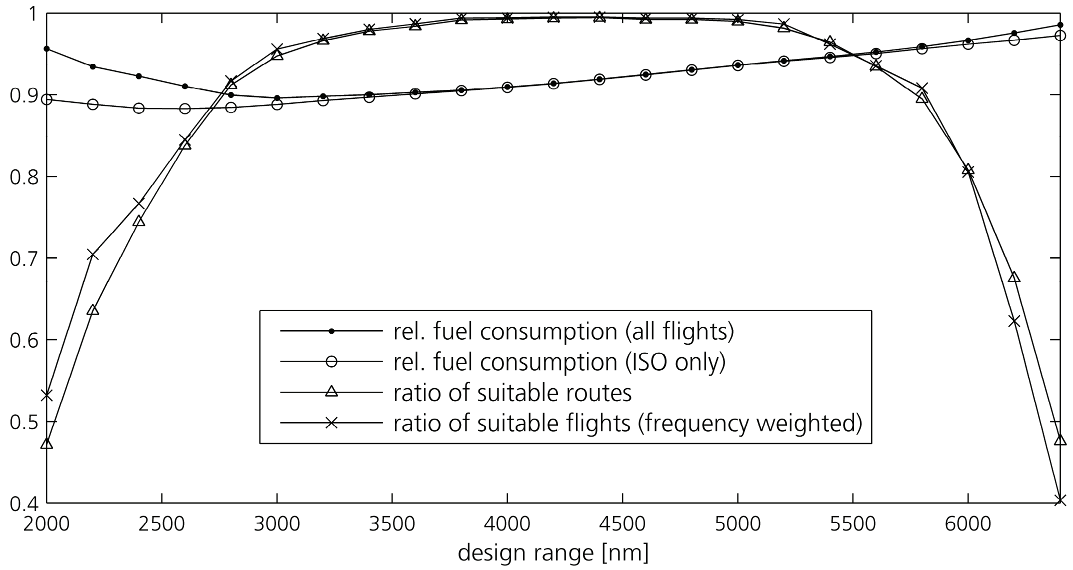

Fig. 5. Change of relative fuel consumption and ratio of suitable ISO routes as well as flights with respect to the ISO-aircraft's design range

route legs and cost aspects for the airline as well as environmental aspects.

Based on the minimum fuel ratio for each of the considered routes, the most suitable airport for an intermediate landing is determined and its rate of occurrence is summed up. This global route analysis is repeated for different aircraft design ranges from 2000 nm to 6400 nm; the overall route and fuel consumption results are shown in Fig. 5. It can be found that the design range resulting in the maximum fuel saving potential for all considered flights due to the global route structure is at around 3000 nm. This calculation is based on the assumption that routes which can not be served by ISO (either due to the limited range of the aircraft or the non-existence of any suitable intermediate airport) would still be operated directly.

Thus 10.4 % fuel can be saved compared to the original direct operations mode, which corresponds to approximately 3.15 million tons of kerosene per year resulting in around 10 million tons CO_2 reduction.

The maximum fuel saving potential with respect to only ISO routes is reached at even shorter design ranges of about 2600 nm. In contrary to that, it is obvious that the number of routes and the number of flights which can be served by ISO have their maxima at around 4400 nm. Although there are more routes operated in ISO mode, the fuel savings on these routes are smaller due to the fact that those shorter routes are served less efficiently by larger aircraft having a higher MTOW and therefore (due to snowball effects) requiring more fuel for the same ISO mission.

There is also a small amount of routes that can not be served with ISO at all, e.g. the connection

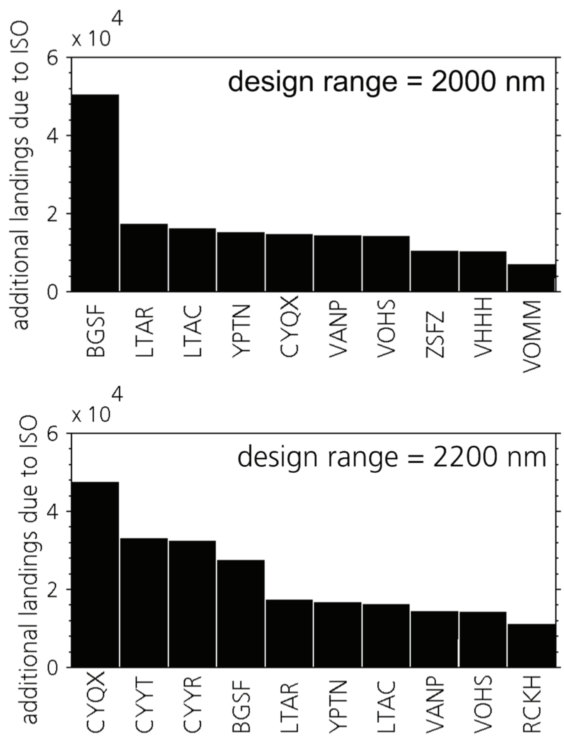

Fig. 6. Ten most used airports for intermediate stops for aircraft with a design range of 2000 nm and 2200 nm, respectively

HNL-NRT. This flight from Honolulu, Hawaii to Tokyo (Narita), Japan only crosses the Pacific Ocean with no opportunity for landing en-route.

It can be observed that aircraft designed for 6400 nm only show a fuel saving potential of 2.8 %. Compared to the theoretical mission result of approx. 7 % savings with the original aircraft operating in two steps, this leads to the conclusion that there are additional penalties due to the non-ideally distributed airports with respect to the global route structure considered in this study.

The top of Fig. 6 depicts the numbers of additional landings at the 10 most frequently used airports worldwide for intermediate landings for a design range of 2000 nm.

Those 10 airports will serve as refueling base for 172302 flights corresponding to 44.3 % of all flights for which ISO are applicable with aircraft redesigned for 2000 nm.

In this case Kangerlussuaq Airport (BGSF), Greenland would be the most used airport for intermediate stops with a 2000 nm designed aircraft, since this aircraft is not able to cross the North Atlantic when flying from Europe to North America or vice-versa without stopping in between. Designing the aircraft for 2200 nm would result in a complete different picture (Fig. 6, bottom). In this case the three most frequented airports in ISO mode would be located in Newfoundland, Canada, because the aircraft is capable of crossing the Atlantic Ocean completely before stopping to refuel.

This directly raises questions concerning the local airport and airspace capacity. Besides the fact that most of the year Kangerlussuaq is facing severe winter weather conditions, 50646 additional landings and take-offs per year (corresponds to approx. 139 additional movements per day, which represents a multiple of today's throughput) could of course not be processed sufficiently by this relatively small airport which does not have the required infrastructure available. Also, at Gander International Airport (CYQX), Newfoundland, some additional 47691 movements per year (130 movements per day) caused by intermediate stops would nearly double its present throughput and therefore most likely exceed the airport's design capacity. In addition to the required airport infrastructure regarding gates and equipment there are ground staff and air traffic control resources necessary to handle the amount of passengers and air traffic safely and efficiently. This demonstrates that capacity aspects should definitely be considered in further detail within a holistic study of the ISO concept. An additional criterion for the selection of suitable airports based on the available airport capacity could be incorporated in the analysis to do so.

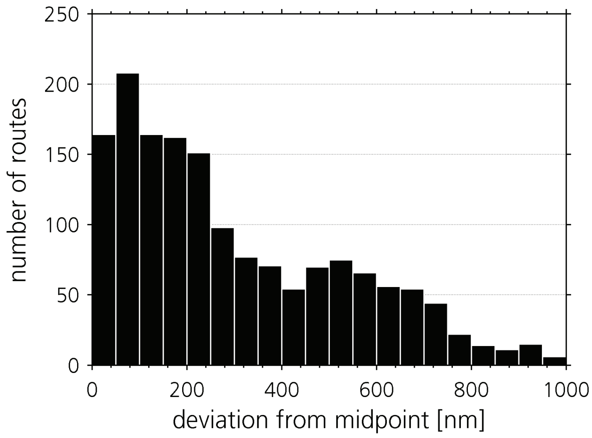

Fig. 7. Amount of routes dependent on their deviation from the theoretical optimum refueling location for a design range of 3000 nm

As mentioned before, a design range of 3000 nm was identified to be most fuel efficient in ISO mode when the global route structure and the geographic distribution of airports are taken into account. Fig. 7 and 8 show corresponding bar charts for this specific case.

In Fig. 7 for different deviations from the theoretical optimum the corresponding number of routes is presented. It can be seen that even for a small amount of routes a deviation of 1000 nm (or even longer; not shown in figure) is accepted when flying in ISO mode. One of these routes is e.g. the connection from Puerto Plata, Dominican Republic to Manchester, UK, for which the best suitable intermediate airport is located in Bermuda. This flight saves approximately 9 % of fuel compared to

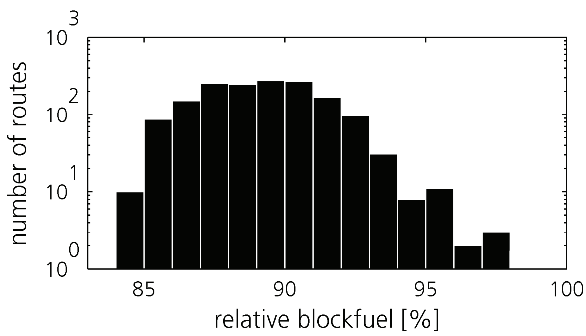

Fig. 8. Amount of routes dependent on the relative blockfuel consumed in ISO mode relative to direct operation

the original direct flight although the stop already takes place 819 nm after departure before crossing the rest of the Atlantic Ocean and therefore results in a huge offset from the optimum midpoint of the route.

Fig. 8 depicts the number of routes for different values of relative blockfuel. It can be observed that most of the routes for which ISO make sense (94.71 % of all considered routes for a design range of 3000 nm) save between 9 and 13 % fuel when using the optimum intermediate airport for refueling.

The geographic distribution of all best suitable airports for ISO with aircraft redesigned for 3000 nm is displayed in Fig. 9. The airports are represented by symbols according to the amount of additional movements they are facing due to intermediate landings. Besides the three airports in Canada, the airport of Sivas, Turkey (LTAR) as well as Shemya, Alaska, USA (PASY) would in this configuration be the five most frequently used refueling airports in the world.

4.3 Economic Analysis

The assessment of the economic viability of a new concept is essential from a customer (in this case: airline) point of view. Especially the improvement rate in cost-effectiveness compared to a preceding system in operation or an alternative concept is of interest. Direct operating cost (DOC) is an established metric to perform economic valuation of existing aircraft or future aircraft concepts [16; 17].

In this study, the scope of the economic analysis is extended to a life-cycle cost-benefit analysis in order to reflect the impact of a new concept on its economic performance more accurately. Standard DOC methods account for crew expenses (cabin and cockpit), landing and navigation fees, maintenance, fuel, depreciation, insurance, and interest. DOC formulae use global technical, operational, and economic parameters to come up with an average DOC value on a flight-cycle or flight-hour basis.

The applied method goes beyond DOC and models relevant cost and benefit parameters along the system life-cycle, which comprises phases for design, production, usage and support and disposal [2] of the system. The actual time of occurrence of the cost and revenue elements is captured to account for the time value of money.

The airframe development costs are assessed using formulae given in [18]. The airframe production cost take into account the conceptual aircraft design specifications including weight breakdown on ATA chapter level, key geometric variables and further economic descriptors [19]. The engine development and production costs are based on the statistic analysis of historic jet-engine programs [20]. The development costs are broken down on each manufactured aircraft. Profit margins, as well as factors for spare-part costs are applied to come up with a theoretic aircraft price that accounts for the initial investment in the airline cash flow on a single-aircraft basis.

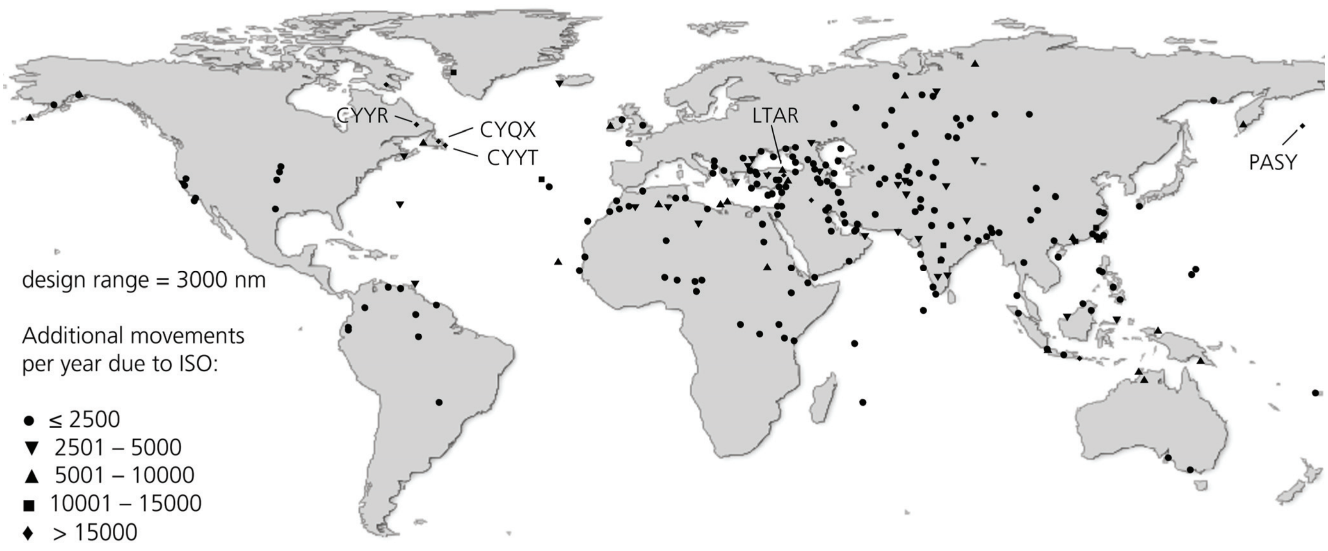

Fig. 9. Distribution of ISO optimum intermediate airports for a design range of 3000 nm; the five most busy airports are marked

The utilization of the aircraft in the operational phase of the life-cycle is modeled based on the aircraft cycle time including flight time, taxi and runway operation times, turnaround time and additional refueling time for ISO. The latter is a function of the estimated fuel burn for the second leg and required reserves.

Maintenance is based on discrete, rule-based events. They are triggered by elapsed flight hours, flight cycles, time, or a combination of these parameters. Each maintenance event has a specific duration, during which the aircraft's utilization is set to zero while creating costs to the airline for labor and material. Additionally, the loss in revenue potential is considered. Cost, time of occurrence, and check mean downtime are based on ordinary least squares (OLS) regressions from data available in maintenance, repair and overhaul related databases [15; 21]. Therefore the maintenance costs scale with aircraft sizes and weights.

Revenues are modeled using statistics with flight's great circle distance and seating class as independent variables.

All values are escalated over the aircraft life-cycle to account for inflation.

All mentioned aspects form the airline's cash flow over the aircraft life, which can be summarized as net present value (NPV). The NPV is a common metric to quantify a project's net-contribution to wealth [22] for a certain period of time while accounting for the time value of money and the opportunity cost of capital. It can be calculated as given in Eq. 3 where C_o is the initial investment (i.e. aircraft price) and C_i is the cash-flow in the i-th year. The discount rate r represents the rate of return that could be achieved with a similar risky investment.

$$NPV = C_0 + \sum_i \frac{C_i}{(1+r)^i} \tag{3}$$

In this study, the NPV is calculated for operations between city pairs *A* and *B* (see Fig. 1) for both direct operations and flights with one intermediate stop at the midpoint *M*.

In Fig. 10, the results for NPV calculations after 20 years for a 5000 nm mission are compared between direct and ISO. Similar to the fuel saving potential curves of Fig. 4, an increasing f_{detour} and f_{offset} reduce the economic advantage of ISO over flying direct routes. Improvements of around 8 % are achieved for this mission length. As for a 5000 nm, the fuel saving potential is around 13 % (see Fig. 4), further aspects which are pointed out in the following lead to an overall reduced improvement.

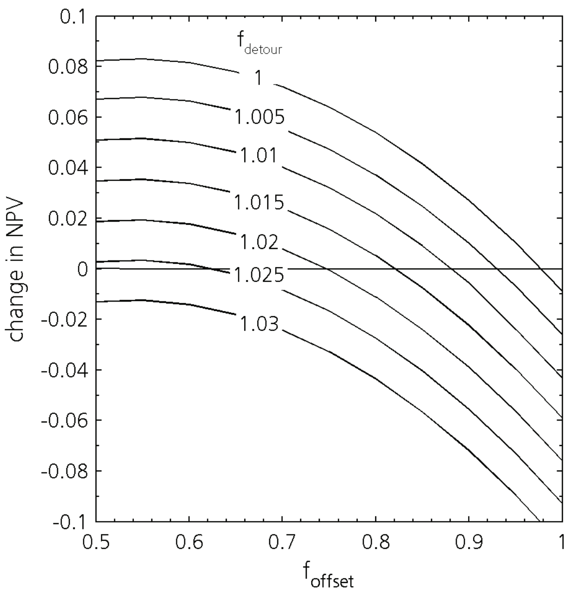

Fig. 10. Relative change in NPV for ISO compared to direct flight on a 5000 nm mission. For the direct flight, an aircraft optimized for 6400 nm is used, for the ISO case the aircraft is designed for 3200 nm.

For the ISO case, the ticket price is assumed to be the same as for the direct flight. Expenses for navigation and crew are scaled with the actual flight time or distance and therefore are a function of Eq. 1 and Eq. 2.

The ratio of flight cycles to flight hours will almost[4] double due to the extra landing. This has a strong negative impact on all cycle-dependent maintenance events such as:

- pre-flight checks
- components overhaul (brakes, tyres (remould and replace), wheel inspection, thrust reverser, APU)
- the engine shop visits (No. 1-3)

The cycle time of ISO will increase due to additional flight segments for descent, climb and taxi to and from the intermediate airport; the refueling phase at the intermediate airport which is a function of the 2nd leg length, and the parameters f_{detour} and f_{offset} in Eqs. 1 and 2.

The aircraft price is strongly depending on the development and production cost of the aircraft in this model. For ISO, the aircraft is fuel-optimized for shorter design ranges by varying the wing area and engine thrust. A reduction in aircraft size has a

[4] As the flight time will increase for ISO while the cycles double, the ratio of flight cycles to flight hours will not exactly double.

Tab. 4. ISO parameters for CDG-DTW route

#	A	B	M	f_{detour}	f_{offset}	FUEL RATIO
1			(direct)	1.000	–	1
2	CDG	DTW	BGSF	1.092	0.512	0.946
3			CYQX	1.008	0.634	0.881

generally positive impact on the aircraft production cost as well as on its maintenance cost in operations.

A more specific cost analysis is conducted for the Paris (CDG) - Detroit (DTW) route. The direct flight is operated with an aircraft optimized for 6400 nm while two alternative ISO routes are operated with an aircraft optimized for 2200 nm. The airport M for the two ISO is given in Tab. 4.

The development of costs, revenues, and NPV over the aircraft life is given in Fig. 11. When taking the NPV at the end of the aircraft life as a measure for economic effectiveness, the ISO (#3) case via CYQX ranks first, followed by the direct flight and the ISO (#2) via BGSF.

ISO #2 shows better fuel performance than #1; this is depleted by the significant detour, resulting in longer travel time and lower utilization. Lower utilization is leading to fewer revenues. While in direct operations there are 728 flights possible, it is 676 and 624 for cases #2 and #3, respectively; these values are unimpeded of maintenance events.

It can be seen, that both ISO cases show more frequent oscillation, caused by the increased cycle-dependent maintenance. Both ISO-cost curves are below the #1-cost curve due to lower utilization and due to the fact that smaller sized aircraft and engine require less maintenance effort. Of course, reduced fuel consumption has a major share in the cost reduction.

Also, the difference in the revenue curve is attributed to the differences in yearly utilization as ticket prices are assumed to be fixed for all three cases. The lower start of the NPV curve shows the impact on the economic performance of the initial investment cost which are lower for the ISO aircraft optimized for 2200 nm only. Due to the exponential nature of the NPV, cost elements in the early life have a great lever on the overall NPV after e.g. 20 years in the present case.

5 Conclusion and Outlook

The presented results highlight the significant potential in fuel saving of the ISO approach both for single mission and its adaptation to real-world routes and airports. Only few airports are necessary to serve as intermediate stops for a significant share of all ISO flights on the routes analyzed here. As a consequence these airports would face a tremendous increase in take-offs and landing cycles. Actual airport capacity limitations might reduce the potential of ISO.

Further studies should take a closer look at passenger acceptance of such a concept. Additional travel time and landings would probably only be accepted along with a reduced ticket price.

Real-world airline requirements are more complex than the ones assumed here; also they are

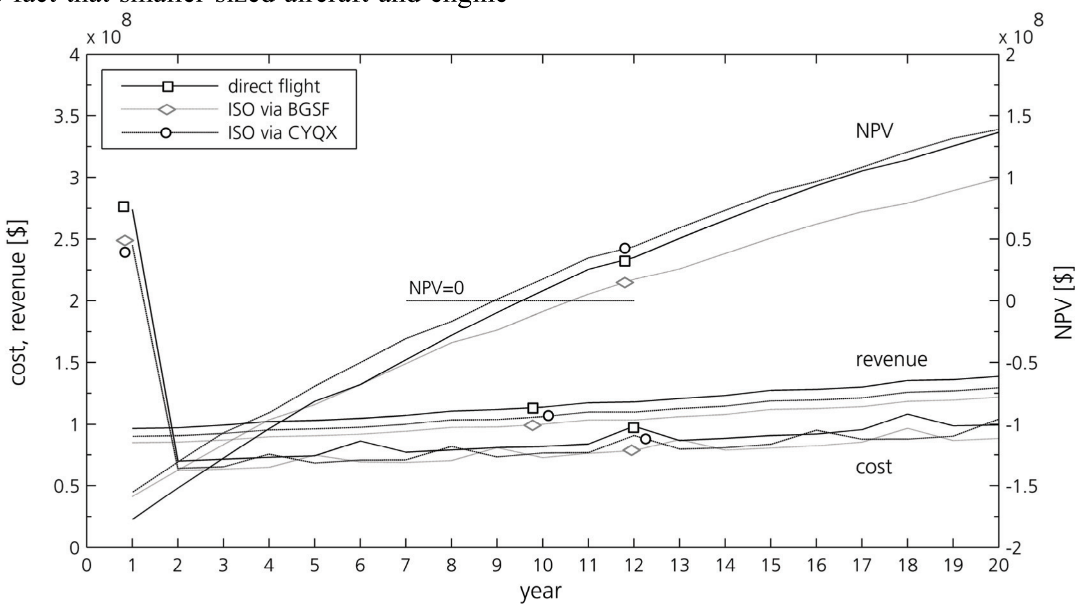

Fig. 11. Cost, revenue, and NPV for a flight from Paris (CDG) to Detroit (DTW); the direct flight is compared to 2 cases of ISO via Kangerlussuaq (BGSF), Greenland and Gander Intl', (CYQX), Newfoundland

more individual for different airlines. Even with the ISO concept being established in the future, it is likely that some airlines want to continue serving certain routes in direct operations mode. It is therefore critical for ISO-range optimized aircraft to be capable of serving neuralgic routes such as between the two US-coasts or the Europe to US East coast routes. Aircraft need to have a design range of at least 3500 nm to serve these routes. According to Fig. 5, the ISO potential in fuel saving would be around 9 % on a global fleet level for such a design range.

While in this study, historic flights from 2007 serve as the basis for analysis, future projections considering traffic growth-rate scenarios should be considered to show the future benefit of the ISO concept. These results could then be included in global carbon dioxide emission inventories to assess the contribution of ISO to aviation's global ACARE targets.

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