PROJECT FINAL REPORT

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RECREATE - Final publishable summary

Executive Summary

"I'm in the simulated cockpit of an airliner, watching the displays as we close in on the tanker above us. By pushing a series of buttons, I have started the final, automated approach toward the refueling boom, through which 30,000 pounds of fuel will be pumped into the fuel tanks." - These words in an Aerospace America article by Philip Butterworth-Hayes impressively summarize the highlights of 3.5 years of focussed research into the new cruiser-feeder concept of air transport, which has the verified potential to significantly reduce fuel consumption. The results laid out in this summary have been widely presented in papers to the scientific aerospace community and via the media to the general public.

Starting out with the earlier assessments of the benefits of cruiser-feeder operations which had pointed out the aerial refuelling concept as a promising concept, the REsearch on a CRuiser Enabled Air Transport Environment (RECREATE) project has been able to show in a consolidated, congruent manner that civil air-to-air refuelling (AAR) can be implemented in an airworthy and economically and ecologically beneficial way. A number of research methodologies coming from different fields and institutes were employed to cover the basic questions about the feasibility of what could be a complete renewal of the existing air transport system. The research project conducted by nine European research institutes, universities and small business partners successfully concluded in January 2015.

Due to the complexity of analysing a whole transport system and based on the choices and assumptions made for a comparison, only a range for the fuel reduction can be given. The conservative, aircraft-design driven and bottom-up derivation amounts to 11% fuel reduction, including also the fuel used by the tanker aircraft. The statistical, top-down specification shows an upper range of 23% fuel reduction. Implementing AAR on a large scale will enable more long-range point-to-point services and thus lead traffic away from existing hub airports and towards regional airports. This in turn also leads to local economic consequences.

Besides fuel reductions, there are also similar advantages of weight reductions. For a word-wide system, we can think in terms of a series of "optimum" cruisers with different passenger capacities (e.g. 200 to 300) and range capabilities (e.g. 2000 – 3500 nm). With AAR, the benefits increase as the total (refuelled) range increases. This will allow a greater flexibility to cope with "thin" and "thick" routes around the World.

From a design point of view, the conventional military refuelling configuration would be replaced by a forward-swept boom configuration which has been shown to be the most promising option, for safety, economical and passenger comfort reasons. Further the civil tankers need to be fairly small, capable of refuelling 2 or 3 cruisers. The tanker radius is between 500 - 1000 nm (2 - 2.5 hours of flight). So a civil tanker is very different from a military tanker which is usually designed for long endurance and multiple roles.

Future research required for making civil AAR a reality should include the conception of realistic business cases for air transport organisations, aircraft fuel providers and other stakeholders. Regarding airworthiness, a roadmap for civil certification has been developed. Technical research should focus on the design of automated flight control systems and on the airworthiness of the forward swept boom configuration, including ground and flight test demonstrations.

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Project Context and Objectives

Introduction

Current forecasts estimate a growth above 4% in worldwide air traffic per year for years to come. It is widely agreed that an equivalent rise of fuel consumption and CO_2 emissions in aviation will not be acceptable. Current aircraft and propulsion technology developments as well as major step-change contributions to fuel burn reduction are required for the second half of this century. A major step may come from breakthrough technology development or a radical change in operations. One radical change in operations to alleviate the rise in fuel consumption and CO_2 emissions are cruiser-feeder operations.

The definition of the cruiser-feeder concept states that the payload - passengers and/or cargo - is transported for the largest part of the way by one transport aircraft, called the cruiser. During flight, a mid-air contact with another aircraft is initiated. This second aircraft, the feeder, either joins the cruiser physically for a large part of the journey, or couples for a limited time to exchange passenger, cargo and/or fuel. Such a contact can take place one or several times during one journey. An obvious special case of cruiser-feeder operations, air-to-air refuelling (AAR), has been studied in the past. Estimations of the attainable reduction in fuel burn was shown in research preceding this project. These estimations suggested further in-depth research to underpin the data with refined analysis.

The European Union 7th Framework Programme funded project *REsearch on a CRuiser Enabled Air Transport Environment* (RECREATE) has been conducted by the following nine European research institutes, universities and small business partners:

- Nationaal Lucht- en Ruimtevaartlaboratorium NLR (The Netherlands, RECREATE coordinator),
- Deutsches Zentrum für Luft - und Raumfahrt DLR (Germany),
- Totalförsvarets Forskningsinstitut FOI (Sweden),
- Technische Universität München TUM (Germany),
- Delft University of Technology DUT (The Netherlands),
- The Queen's University of Belfast QUB (United Kingdom),
- Zurich University of Applied Sciences ZHAW (Switzerland),
- Dr Rajendar Kumar Nangia (United Kingdom),
- Nuclear Research and Consultancy Group NRG (The Netherlands).

From 01 August 2011 until 31 January 2015, the feasibility of cruiser-feeder operation concepts has been studied, aiming at assessing the implications of a recreation of air transport operations.

Top level objective

The top level objective of the RECREATE research is to demonstrate on a preliminary design level that the cruiser-feeder concept can comply with airworthiness requirements for civil aircraft. For convenience of the reader, a generic and non-process orientated definition of airworthiness is: the ability of an aircraft or other airborne equipment or system to operate without significant hazard to aircrew, ground crew, passengers (where relevant) or to the general public over which such airborne systems are flown. A clear perspective of compliance with airworthiness requirements is a *conditio sine qua non* for further research and development of this out-of-the-box concept. The subsequent Scientific and Technological (S&T) objectives are:

1. to substantiate on a conceptual and preliminary design level that viable and acceptable concepts exist for cruiser-feeder operations;

2. to identify and qualify the necessary procedures and steps and required facilities to assure airworthiness of cruiser-feeder operations;

3. to confirm that the reported benefits of cruiser-feeder operations are consistent with the refined analysis and high fidelity simulation.

To achieve the S&T objectives, a collaborative research effort has been conducted with respect to:

- preliminary aircraft design dedicated to cruiser-feeder aircraft,
- the means of compliance to satisfy airworthiness requirements enabling cruiser-feeder aircraft,
- automatic flight control and flight simulation dedicated to cruiser-feeder aircraft.

Scientific and technological methodology

The scientific and technological methodology chosen for the RECREATE research consists of three integrating and three disciplinary research activities. The three integrated research activities and the three disciplinary work packages supporting the integrated work packages are listed below. An evolutionary delivery approach has been adopted, with two iterates (initial and final) for the disciplinary activities and three iterates (initial, updated and final) for the integrating activities.

Objectives of WP1: Concept for cruiser-feeder operations

First, a baseline concept of operations is established, the baseline being a conventional air transport without cruiser-feeder operations. Starting from this baseline, a cruiser-feeder concept of operations is defined, analysed and used to generate system requirements and other requirements, for instance the Top Level Aircraft Requirements.

Objectives of WP2: Airworthiness of cruiser-feeder operations

Civil aircraft adapted for use in military air-to-air refuelling operations are airworthy, providing a starting point for research on airworthiness of future cruiser-feeder operations. Applicable regulations and user requirements are studied and derived, and all potentially necessary means of compliance are being identified. A high level Functional Hazard and System Safety Assessment for cruiser-feeder operations is being made, finally leading to safety and airworthiness validation means of compliance with airworthiness requirements that are applicable to cruiser-feeder operations.

Objectives of WP3: Benefits of cruiser-feeder operations

Starting with the analysis of the chosen baseline and based on data generated in the other RECREATE work packages, environmental, dispatch reliability and economic delta analyses are conducted. The investigation of these potential benefits is essential for any future consideration of this operations concept.

Objectives of WP4: Conceptual and preliminary design

The requirements needed for a viable and acceptable airworthy concept will likely lead to new aircraft designs. For this reason, conceptual aircraft design is required for both the feeder, cruiser and *aerial transfer boom system*. This conceptual design is refined in a subsequent preliminary aircraft design phase. For the preliminary aircraft designs, an aerodynamic database on sizing, performance and stability & control will be created on the preliminary design level.

Objectives of WP5: Automatic flight control

Cruiser-feeder operations need to be highly automated if they are to function globally. The design of an *automatic flight control system* is important as well as understanding requirements and limitations of the system. In cruiser-feeder operations three bodies are involved, feeder aircraft, transfer boom and cruiser aircraft, which are to be controlled as one connected system. This is a challenge especially in all weather conditions. To understand the requirements of the distributed control system, models accounting for turbulence and elasticity are needed. A conceptual and preliminary design is made of a multi body *automatic flight control system* and a *human-machine interface* for the pilots of the cruiser and the feeder aircraft.

Objectives of WP6: Flight simulation

In order to develop a multi body cooperative *automatic flight control system*, flight simulation models are implemented to identify critical interactions, such as for instance due to atmospheric gust or wake-vortex interaction of the leading aircraft. Finally, flight simulation models are used for the identification of human factors. This is important in order to verify that the proposed manoeuvres are acceptable regarding safety and pilot workload.

Main Scientific and Technological Results

"I'm in the simulated cockpit of an airliner, watching the displays as we close in on the tanker above us. By pushing a series of buttons, I have started the final, automated approach toward the refueling boom, through which 30,000 pounds of fuel will be pumped into the fuel tanks." - These words in an Aerospace America article by Philip Butterworth-Hayes impressively summarize the highlights of 3.5 years of focussed research into this new concept of air transport, which has the verified potential to significantly reduce fuel consumption. The results laid out in this summary have been widely presented in papers to the scientific aerospace community and via the media to the general public (please also refer to the dissemination activities summarized below).

Starting out with the earlier assessments of the benefits of cruiser-feeder operations which had pointed out the aerial refuelling concept as a promising concept, the RECREATE project has been able to show in a consolidated, congruent manner that civil air-to-air refuelling can be implemented in an airworthy and economically and ecologically beneficial way. A number of research methodologies coming from different fields and institutes were employed to cover the basic questions about the feasibility of what could be a complete renewal of the existing air transport system.

Due to the complexity of analysing a whole transport system and based on the choices and assumptions made for a comparison, only a range for the fuel reduction can be given. The conservative, aircraft-design driven and bottom-up derivation amounts to 11% fuel reduction, including also the fuel used by the tanker aircraft. The statistical, top-down specification shows an upper range of 23% fuel reduction. Implementing AAR on a large scale will enable more long-range point-to-point services and thus lead traffic away from existing hub airports and towards regional airports. This in turn also leads to local economic consequences.

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Future research required for making civil AAR a reality should include the conception of realistic business cases for air transport organisations, aircraft fuel providers and other stakeholders. Regarding airworthiness, a roadmap for civil certification has been developed. Technical research should focus on the design of automated flight control systems and on the airworthiness of the forward swept boom configuration, including ground and flight test demonstrations.

In the following part, the research results are presented per work package in more detail. The individual results have also been presented during the final meeting in Amsterdam on 29 January 2015. These presentations have been added in Appendices A through G. All research results have been reported in the corresponding WP reports (24 deliverables).

WP1: Concept for cruiser-feeder operations

The objective of this integrating activity has been to develop, iterate, select and describe two cruiser-feeder concepts, for further study. One chosen concept is realizable in the distant future (at least 50+ years from now), the other concept however is expected to be realizable in the medium-term (within 20+ years from now). This concept requires development and acceptance of new airworthiness regulations, but can be done with today’s technology.

First, a conventional baseline without cruiser-feeder operation has been defined to compare the benefits of future concepts with today’s technology, see Table 1:

Table 1: Baseline concept

Cruiser	
Capacity	250 passengers
Range	5000 nm
Specific fuel consumption	0.525

Given the broad definition of cruiser-feeder operations, iterations conducted at the start of this activity involved a large diverging number of cruiser-feeder concepts. In a subsequent convergence sweep, two concepts were down selected for further investigation. The first final concept is civil air-to-air refuelling, of which the overall characteristics are shown in Table 2:

Table 2: First final concept: Air-to-air refuelling as special case of cruiser-feeder operations

Cruiser		**Feeder**	
Capacity	250 passengers	Fuel offload capacity	35000 lb / 3 contacts
Range	2500-3000 nm	Range / endurance	500 nm / ~4 hours
MTOW	100000 kg	AAR envelope	< 24000 ft, Mach < 0.8
Specific fuel consumption	0.525	AAR procedure	20 min (5 min wet contact)

Concepts with transfer of payload and passengers based on engines burning chemical fuel have been shown not be economically feasible, as the overall weight of the system and thus the total amount of fuel burnt are too high. However, if the cruiser can be propelled by a nuclear power source, the efficiency is very high compared to the reference case, even if the total weight of the system is higher. Although the nuclear cruiser cannot be shown to meet airworthiness requirements with today's technology, this concept has been retained for study because it cannot be excluded that new nuclear physics will be discovered and confirmed in the future. The second final concept (Table 3) concerns a nuclear propelled cruiser where the transfer of passengers and cargo is done via a life supporting container mechanism.

Table 3: Second final concept: cruiser-feeder with nuclear propelled cruiser

Cruiser	
Capacity	1000 passengers
MTOW	900000 kg
Range / endurance	60000 nm / 1 week
Cruise speed	M = 0.8
Docking speed	M = 0.7
Cruise altitude	> 36000 ft
Payload transfer	Single container station concept (100 passengers each)

The two studied concepts address long-distance air travel but with very different techniques. Table 4 shows the level of detail in which both concepts have been studied during the project.

Table 4: Level of aircraft design applied to two concepts

WP	**AAR**	**Orbiting Nuclear Cruiser**
WP 1 Concept	X	X
WP2 Airworthiness	X	(x) To some extent
WP3 Benefits	X	(x) To some extent
WP4 Design	Concept Design and Preliminary Design	Concept Design only
WP5 Control	X (conventional AAR)	-
WP6 Simulation	X (conventional AAR)	-
WP7 Dissemination	X	X

The AAR concept, as outlined in the WP1 reports, is clearly within reach for aviation if the industry and concerned legal bodies decide to go into this direction. As for the orbiting nuclear concept it is not within reach anytime soon but the concept, as such, has great potential.

AAR can play an important role dealing with the sustainability challenge aviation faces. If the final operational cruiser-feeder concept presented in this report is introduced on today´s system as it is, it has the potential of bringing large benefits:

- Reduce fuel burn and direct CO_2 emission by 10-20%, depending on the assumptions made for the analysis.
- Local environment – Noise and local air quality will be better or on the same levels as today.

The number of movements and aircraft will increase; however, the total mass of the system will be significantly lower. Operational constraints on the system with present traffic load, such as scheduling, workload on feeder bases and impact from weather hazards (mainly turbulence), seem manageable. Figure 1 gives a visual impression of the performed traffic simulations of the entire traffic taking place today within 48 hours.

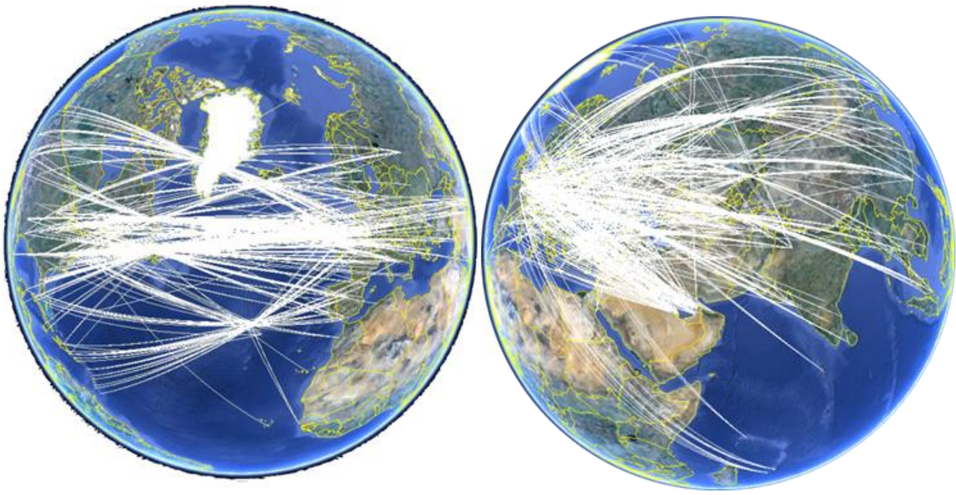

Figure 1: Transatlantic and Europe-China scenario in traffic simulation

It has previously been outlined that aviation faces the dilemma that short flights which are the most common are the cause of the congestions whereas long flights burn most of the fuel and hence have the largest environmental impact. With continued urbanisation and more megacities on earth, the use of air transport should be reserved for long distance travel where no other viable options exist. Following the Intergovernmental Panel on Climate Change (IPCC), high speed rail can substitute short-distance air travel up to 800 km and in some case even up to 1500 km (a good example today is Beijing – Shanghai). This is one clear way of mitigating greenhouse emissions from air travel and also alleviate noise and air pollution problems which many of the world's megacities face already today.

Apart from major fuel and weight savings on long flights, AAR has the potential to reduce the number of short flights since the smaller, more efficient, AAR-cruisers inherently give an opportunity to serve more point to point connections. To set-up a new intercontinental " point-to-point connection" from an airport in a "mid-sized city" that today has no (or few) intercontinental connections, will of course be an easier business case with smaller efficient RECREATE cruisers as compared to the larger baseline cruiser. Every new long distance point to point connection will reduce "hub travel" to some degree. The potential and sensitivities going from a hub – spoke system to more point to point connections has been studied in WP3.

A complete removal of the hub-spoke system in the near term is not realistic, but for the future the system has to be pushed away from the big hub solution. As for technical development of air-to-air refuelling concept, other novel fuel transfer configurations with the tanker behind the cruiser (or non-centreline set-ups) can improve aircraft efficiency, system performance and safety. In WP4 some of these ideas have been exploited. Civil AAR should also not be viewed in isolation. A possible introduction of alternative fuels would also benefit AAR as well as other novel operational concepts like formation flying for civil aircraft which also could be used together with civil AAR.

WP2: Airworthiness of cruiser-feeder operations

The objective of this integrating activity has been to develop a route towards airworthiness of cruiser-feeder operations. Bringing two aircraft in close vicinity of one another in mid-air, either for docking or for refuelling, is potentially dangerous. Today, no civil certification regulations concerning cruiser-feeder operations exist. However, the airworthiness of such a concept must be established along the guidelines of the current regulatory system of the safety of civil aircraft operation and with an equivalent level of safety.

Based on the concepts of operations described, a Functional Hazard and System Safety Analysis of the selected cruiser-feeder concepts has been performed to map all hazards not covered by current airworthiness regulations, for both cruiser-feeder concepts. Using the operational scenarios relevant for collision risk, performance, availability and integrity requirements for the functions of the air-to-air refuelling system have been determined. A schematic for this system modelling is shown in Figure 2.

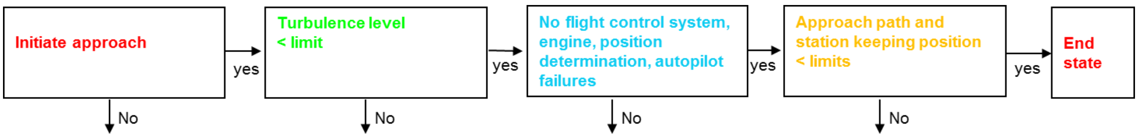

Figure 2: Schematic of safety system model

These were input for the system design which has been performed in other RECREATE Work Packages. Simulations based on physical models of the air-to-air refuelling system have been performed in WP5 for the most critical collision risk scenarios to verify that the air-to-air refuelling system design meets the safety requirements. Non-collision risk related hazards of the receiver-tanker have been identified and safety measures to mitigate these hazards have been proposed.

Collision risk related hazards for the nuclear cruiser-shuttle concept are similar to those for the conventional fuel receiver-tanker concept. Non-collision risk related hazards of the nuclear propelled cruiser have been identified and safety measures to mitigate these hazards have been proposed.

As a second important step, an approach for the certification of airworthiness of civil cruiser-feeder operations has been developed taking into account existing military regulations for aerial refuelling. An evaluation of the existing EASA Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25 Amendment 11) has been made, resulting in an overview of applicable specifications and specifications to be amended for cruiser-feeder operations. Following the evaluation, an approach to certification has been proposed. Because of their similarity of operations this approach has been based on the regulations covering automated landing, the EASA CS-AWO (All Weather Operations). The similarity lies in the objective to achieve an accurate and safe approach to a specific position. The amended regulations and Acceptable Means of Compliance (CS-AWO AMC) cover the required safety level, the considered conditions regarding aircraft, operations and environment, the performance requirements, performance demonstration and failure conditions.

Simulations have been used to get quantified data for these models, for normal operation and for the most critical scenarios:

- For wind shear or turbulence encounter the most critical situation is the station keeping position with the boom almost connected or just disconnected (boom very close to cruiser) and a sudden upward movement of the cruiser.
- For system failures the most critical situation is the station keeping position and a sudden engine failure, with or without the boom almost connected or just disconnected.

It has to be noted that real ground and flight testing to demonstrate the safe operation of nuclear propulsion is not justifiable due to the inherent risk of the release of radioactivity. Here, the development of high fidelity simulation with a very high level of confidence far beyond the current state-of-the-art will be required.

Finally, a tentative future roadmap for certification of air-air refuelling of commercial air transport aircraft has been provided. The roadmap describes the steps that must be taken to formally establish regulations and acceptable means of compliance.

WP3: Benefits of cruiser-feeder operations

The objective of this integrating activity has been to analyse economic benefits, dispatch reliability and environmental effects of cruiser-feeder operations using the defined baseline as reference. The impact on fuel consumption, exhaust emissions, local noise production and shareholder value have been studied.

Benefits analyses of the updated concept indicate a range of fuel and mass savings for the cruiser aircraft for cruiser-feeder concepts in which only fuel is transferred (Fig. 3). Remark that it is a challenge for an optimized conventional configuration cruiser to be as efficient as an aircraft optimized for long range, because of the relatively larger fuselage and fixed weight of some of the equipment, furnishings etc. On the conservative side, fuel savings for the cruiser only - derived bottom-up by aircraft design - amount to around 21% for one refuelling. With two refuellings, this value could be increased, and further investigations on the effect of thrust-to-weight ratio and reserve fuel are ongoing. From this benefit the fuel consumed by the tanker(s) has to be subtracted. If the tanker is very efficient with a fuel ratio - i.e. ratio fuel given / fuel consumed - equal to 8, the tanker reduces the total efficiency of the cruiser-feeder combination by about 5-6%. In case of a more realistic tanker with a fuel ratio of 4, the impact of the tanker is a reduction by about 10-12%. A lower bond of fuel saving is in the order of 11%, which is still a huge fuel saving compared to nowadays standards in the industry. On the optimistic side and based on a top-down, statistical approach, an upper bond of 23% fuel saving for the cruiser-feeder combination has been calculated previously.

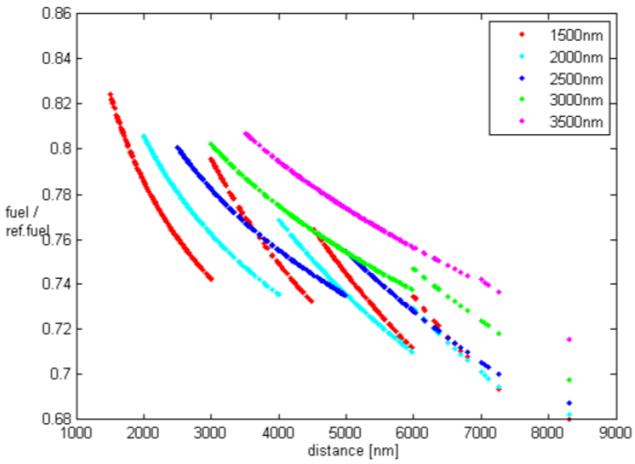

Figure 3: Fuel savings for single cruiser routes and different cruiser design ranges

The environmental impact next to the reduction of fuel burn and thus CO_2 emissions has been studied as well. A consequence of smaller and lighter cruiser aircraft compared to today's long range passenger aircraft is a reduction of noise at the departure/arrival and hub airports, which are mostly located in densely populated areas. A noise reduction in turn leads to economic benefits through reduced noise fees and a rise in property value near existing airports. The noise impact through the additional heavy load near the required tanker bases has not been investigated. The tanker bases are assumed to be located in sparsely populated areas, where noise is not of a great influence.

To examine the insertion of the cruiser-feeder concept into a representative air traffic scenario based on the Star Alliance fleet, route optimization is conducted to account for interactions between cruiser and feeder weights and efficiencies, locations for feeder bases, feeder radius of operation and cruiser route modifications. Feeders with higher efficiency achieve the best results in the traffic simulations at a feeding capacity of 2 or 3 refuelling, with operations conducted close to the feeder base. However, there is significant variability in these findings, with less optimal findings when considering those routes serviced on European-Asia routes in contrast to transatlantic routes. Small disruptions to refuelling operations can largely be absorbed due to inefficient use of feeder aircraft at a number of the feeder bases, but large scale unplanned disruptions can have a significant impact, resulting in multiple failed operations and severe impact on the network stability.

The increased ground traffic at both airport and refuelling bases raises challenges for dispatch reliability with increasing number of flights and the impact on local communities. As highlighted in the traffic simulations, dispatch reliability must now also account for the refuelling operation delay and the impact on ground handling capability of both minor disruptions requiring diversions of aircraft to alternative refuelling positions and accommodating additional aircraft landings in the event of major disruptions resulting in aborted operations.

AAR has been shown to be beneficial in terms of fuel reduction compared to non-AAR, even when considering a network based on more point-to-point connections, less on a hub-and-spoke system. Implementing AAR on a large scale will thus also enable more long-range point-to-point services and thus lead traffic away from existing hub airports and towards regional airports, with the related economic and environmental consequences.

Regarding economic benefits achievable in a cruiser-feeder configuration, evaluation of the configuration to include realistic route and demand analysis confirms that the economic viability of the concept is tied to the correct implementation of the underlying feeder network in order to maximise benefit. Transformation of the network to the cruiser-feeder enabled environment without consideration of *available seat miles* significantly reduces the profitability (and hence viability) of the concept, and in order to match previous revenue generation levels without passing additional costs onto passengers, additional aircraft are required which in turn reduces the environmental and cost benefits achievable over the baseline to approximately 14% and 12% respectively. However, improved scheduling of cruisers to match feeder availability may significantly enhance these cost benefits through enabling better utilisation of feeders capable of multiple refuelling exercises, and in particular, enable the adoption of new concepts such as the point to point network. It has been shown that with the use of AAR, the increased fuel burn associated with the additional routes serviced can be reduced significantly, and a significant increase in *available seat miles* within the network can be achieved without a corresponding proportional increase in operational cost.

WP4: Conceptual and preliminary design

The objective of this activity has been to conduct conceptual and preliminary design iterations of dedicated cruiser and feeder aircraft according to two the chosen concepts:

1. The **aerial refuelling concept**, where passenger aircraft (the cruisers) receive fuel from tanker (the feeders)
2. The **passenger exchange concept**, where one large dimensions aircraft with nuclear propulsion (the cruiser) exchanges passengers in flight, with various shuttle aircraft (feeders), by means of pre-loaded containers.

Families of cruiser and feeder aircraft are generated as well as refuelling boom designs. The generated design data is used in support of the benefits analyses, the airworthiness analyses and the automatic flight control system development.

Cruiser and feeder aircraft specifically designed and optimised for their task have been shown to increase the benefits achievable by air-to-air refuelling. The gain results on the one hand from the fact that a long-range cruiser aircraft designed for a specific range including refuelling will have a reduced Operating Empty Weight (OEW) as it will be designed for a smaller Maximum Fuel Weight (MFW) and thus a smaller Maximum Take-Off Weight (MTOW). Design studies of long-range passenger aircraft able of being refuelled have been performed with conceptual and preliminary design tools. The design work on aircraft and refuelling systems has demonstrated that aerial refuelling for civil aircraft is technically feasible. Indeed, it is standard in military operations. From an engineering point of view no showstopper has been identified. However the developments (refuelling system, tanker, engines) would require huge investments, drastically reducing the economic viability of the concept.

It has been shown that the tanker design has a huge impact on the overall efficiency. Current military tankers, however, are not optimized for the refuelling task but are converted cargo and passenger aircraft. Dedicated tanker design studies have shown the advantages of a joint-wing tanker concept.

The initial conceptual design phase lead to optimistic results compared to the following preliminary design work. This can be attributed mainly to the following factors:

- In the conceptual sizing and design process constant empty mass fractions have been assumed, which are valid for long-range aircraft but not for the short/medium range refuelled aircraft. More realistic values deducted from the preliminary design work should be in the order of 0.5 to 0.6 for the refuelled designs.
- Similarly, we assumed an L/D ratio of 19.9, equivalent to long-range aircraft. This assumption is invalid if the aircraft wing size is properly reduced for the more lightweight refuelled aircraft. This leads to a an increase of the relative importance of the fuselage drag. The preliminary design results indicate that, depending on the number of refuellings, the L/D ratio should be one to two points lower.
- For flight control reasons the refuelling had to be scheduled at a reduced altitude. Each refuelling therefore requires a descent and climb segment which leads to an additional fuel consumption of about 0.5 to 1% per refuelling operation.

Therefore, the results of the more accurate preliminary design work are less optimistic and show lower reductions in fuel consumption for the cruiser aircraft than the initial estimations.

Based on all findings, we estimate the overall fuel savings for the cruiser alone to range between 15 and 20% of the block fuel. The alternate concept of staged flights would lead to fuel savings in the order of 10 to 15% but would need no tanker aircraft.
Adding the fuel consumption of the tanker aircraft reduces the fuel saving s for the aerial refuelling concept by about 5%, leading to overall savings between 10 and 15%.

A trade-off study showed that a non-conventional, inverted receiver-tanker configuration is beneficial and essentially the more viable configuration. Such a configuration increases the safety of the passenger aircraft from possible debris from the tanker or refuelling boom after a collision, removes possible passenger discomfort due to flying in the tanker wake and limits the amount of extra pilot training required to the much smaller number of tanker pilots. Furthermore, the passenger aircraft need a minimum of refurbishment for the new manoeuvres, and thus have a minimum loss of cruise efficiency, while the costly surplus thrust requirements and supporting equipment lay with the smaller number of tankers.

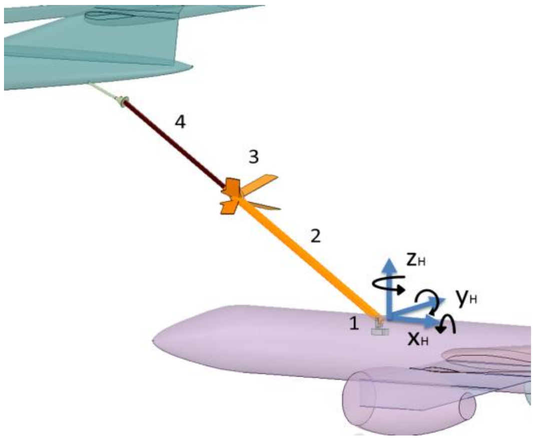

Figure 4: Forward extending boom concept. Receiving passenger aircraft up and left

A number of different concepts for a forward extending boom have been studied. A big challenge lies in the controllability and aeroelastic stability for this concept. Preliminary aeroelastic analysis results show that a design space free from static and dynamic aeroelastic instabilities exists.

Preliminary design with aerodynamic CFD computations for a refuelling boom has been done for the conventional configuration. An aerodynamic database was created containing the results of about 800 computations for a number of relative boom position parameters and the control surfaces' deflection angles. This preliminary aircraft design data has supported the development of an automated flight control system.

Several design studies have investigated the nuclear cruiser concept in cooperation with the Nuclear Research and Consultancy Group NRG. A pressurized container exchange concept was adopted for the in-flight transfer of passengers, crew, cargo and consumables, see Fig. 5.

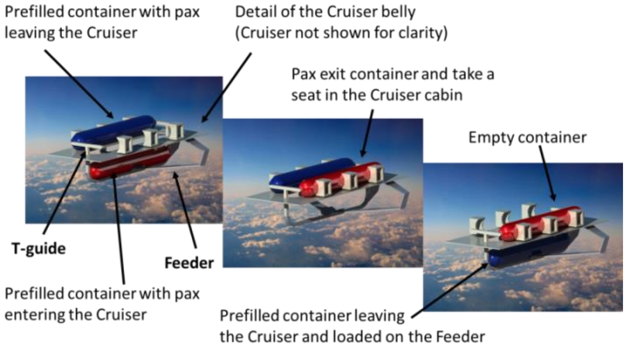

Figure 5: Container exchange concept for passenger and cargo transfer

On a conceptual basis, weight estimations, aerodynamic design and design of a nuclear propulsion system for the cruiser aircraft were performed; see Fig. 6 for a conceptual design sketch. Options for a Brayton cycle and a Rankine cycle propulsion system were studied.

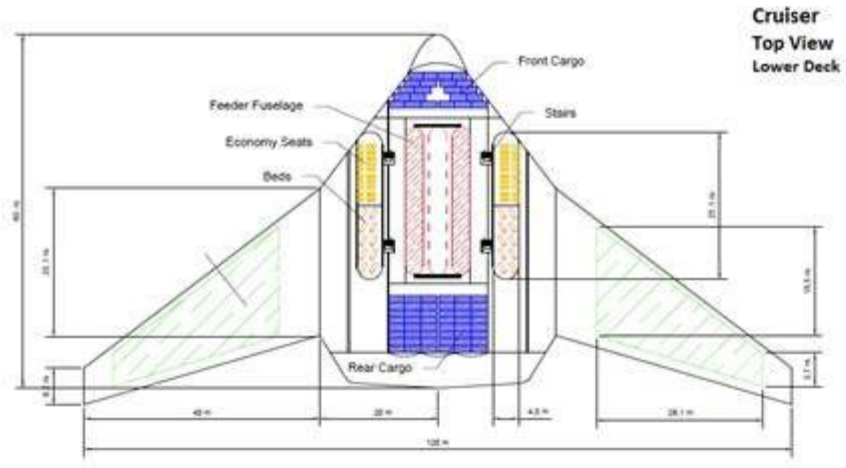

Figure 6: Conceptual design of a nuclear cruiser aircraft

WP5: Automatic flight control

An early assessment showed that successful cruiser-feeder operations will require automatic flight control systems for the cruiser aircraft, the feeder aircraft and the refuelling boom to enable automatic conduction of the manoeuvre to achieve an adequate level of safety and availability. The objective of this activity was to develop this automated in-flight refuelling system, including sensor suites with redundant measurement technologies, actuators and controllers, and to model that system in a realistic simulation environment. The work had to consider, extend and comply with the airworthiness requirements defined in WP2 as well as the operational concepts elaborated in WP1.

It could be demonstrated that aerial refuelling of civil transport aircraft as one possible concept of cruiser-feeder operations is viable and safe. Since manual control is no option with respect to the high levels of safety and availability, an automatic flight control system was developed, comprising the following main components:

- Cruiser-feeder operations and maneuver design: An approach maneuver was designed that accounts for operational and regulatory aspects. The envisaged approach trajectory starts at the minimum separation that is required for independently controlled flight and leads to a very close proximity in range of the fuel transfer boom. Tasks related to the automation system to be performed by the cruiser and feeder pilots were defined, which allowed a realistic evaluation of the automatic flight control system by piloted simulations conducted in the scope of work package 6. Requirements were put on the refuelling boom envelope and system design, which were used as basis for detailed boom design in the scope of WP4.
- Sensor selection and sensor data fusion algorithms: Adequate sensors were selected for relative position estimation between the aircraft as well as between the boom tip and the receptacle. An exhaustive sensor suite was defined comprising inertial measurement units, code phase DGPS receiver, radio frequency ranging transponders and electro-optic sensors. The sensor suite along with the sophisticated sensor data fusion algorithms led to highly accurate measurements required for close formation flight with high availability and integrity, i.e. sensor faults are reliably detected and excluded, leading to high confidence in the estimated variables.
- Guidance and control: Automatic flight control laws for the cruiser, feeder, and the boom were developed. A decoupled approach was chosen. The cruiser controller is based on the standard PID concept and tuned with emphasis on tracking performance. The developed refuelling boom controller is based on exact linearization of the constrained boom system where the boom hinge point motion is forced by the tanker motion. The combination of cruiser control laws for relative position control and boom control laws for engagement of the connection between the aircraft has proven functionality for the considered cruiser-feeder scenario.
- Mode selection and phase transition: A finite state machine was developed and implemented that ensures a safe and predictable behavior of the coupled cruiser-feeder system during all phases relevant for a successful and safe conduction of automated aerial refuelling of civil transport aircraft.
- Supervision: Algorithms were developed that monitor control and navigation performance as well as external disturbances. Based on geometric and stochastic parameters, these algorithms ensure a timely abort in case of system malfunctions or exceedance of admissible external disturbance levels.

All the afore mentioned components were implemented in an exhaustive simulation environment, also considering effects of the correlated wind turbulence field and aircraft elasticity. A screenshot of such a simulation is shown in Figure 7.

Figure 7: Simulation of refuelling manoeuvre

Using this simulation environment it could be demonstrated that aerial refuelling can be automatically conducted. For project RECREATE it had not only to be successfully demonstrated but also safety had to be proven according to the findings of WP2. It could be shown by simulation that a collision between the aircraft, which is the most safety-critical event, is less probable than specified in the safety requirements derived in WP2. For that, a special simulation method was applied (subset simulation) since conventional Monte Carlo simulation is not feasible for calculating the very low probabilities associated to the examined events. In general the sensitivity of the safety simulation results is the higher the lower the probability is. Especially for the case where a probability of 10^{-9} was proven only minor changes in the aircraft models might lead to considerable differences in the resulting thresholds. However, the objective of project RECREATE was to prove that close formation flight could be conducted safely according to civil certification specifications. Although the simulation models did not exactly represent a special type of aircraft, all contributing subsystems were simulated to a reasonable extent. This allows the conclusion that with similar configurations the considered safety requirements could be complied by using the control, navigation, and supervision algorithms developed, implemented, and tested in the scope this work package.

The knowledge gained in the scope of WP5 concerning feasibility, safety, and also the results of the piloted simulations conducted in the scope of WP6 based on the developed automatic flight control system provide a good baseline for possible next steps, especially the demonstration of automatic close formation flight by flight tests. Additionally, the introduced sensor suite, data fusion, and safety simulation algorithms can be directly applied to different aircraft configurations discussed in the scope of WP4.

WP6: Flight simulation

The objective of this activity has been to, firstly, verify the developed models and flight control systems in flight simulator experiments. Secondly, the impact of the human-machine interface and contributing human factors, such as pilot workload, on the safe and reliable execution of the refuelling manoeuvres are assessed by professional airline pilots.

Two research flight simulators have been adapted to conduct these civil air-to-air refuelling manoeuvres. The developed simulation models and the automatic flight control systems were integrated in the real-time simulation environments of the research flight simulators at NLR and DLR, GRACE (Generic Research Aircraft Cockpit Environment) respectively GECO (Generic Experimental Cockpit).

A Human-Machine-Interface (HMI), which consists of the information displays and control mechanisms available to the pilots in the cockpit, has been developed (Figure 8).

Figure 8: Human-Machine Interface for refuelling manoeuvres in the System Display

During the experiments these two flight simulators were run in a coupled mode, the tanker aircraft being modelled in GECO and the cruiser aircraft in GRACE. The required connection of several host computers in two countries was made via internet using a so-called Distributed Interactive Simulation connection (DIS).

The experiments are split in two phases, the first of which has been conducted by four crews of professional pilots from two major European airlines in 2013. This first phase of experiments focussed on the evaluation of the nominal procedures of all manoeuvre phases, and also included a forced abort manoeuvre due to a too high approach speed.

The evaluation is based on the feedback by the pilots on the cruiser-feeder concept as a whole, the operational procedure, the Human-Machine Interface and recommendations for improvement. All pilots who flew the experiments reported that they had the impression that air-to-air refuelling of civil aircraft, can be performed within present day safety levels with such a highly automated flight control system. They also indicated that the proposed air-to-air refuelling manoeuvre does not require specific additional skills from the pilots. With the results of the successful first phase of simulator sessions, the operational concept and the developed flight control and monitoring systems has been improved. For example, additional and improved information on the refuelling process are offered to the pilots in the cockpit.

The improved concept has been evaluated in the phase 2 flight simulation experiments during eight experiment days between September 30th and October 16th 2014.
These phase 2 simulation experiments included more complex manoeuvres, and non-nominal and emergency condition

In the second part of the experiment days, the experimental scenarios were flown. These scenarios included a couple of critical situations where pilots needed to closely observe the manoeuvre and decide whether the safety of the operation was still maintained. The following conditions were introduced during the different experiment scenarios:

- Light turbulence
- Increasing turbulence up to moderate
- Engine failure on the cruiser aircraft
- Engine failure on the feeder aircraft
- Refuelling system malfunction, decreasing fuel flow until complete blockage
- Failure of the Estimated Safety Margin indicator during the approach
- Very low visibility, only anti-collision lights visible at close range
- Uncommanded speed brake deflection on cruiser aircraft during refuelling
- Multiple failures introduced one after the other, Relative Position Indicator on feeder aircraft, Estimated Safety Margin indicator, refuelling system and engine failure on feeder aircraft.

The most important question of the experiment has been whether the pilots feel that the RECREATE system that was presented in the simulation will provide sufficient safety and the required level of control when it will be implemented in real life. After all the experiment runs and during the debrief at the end of the experiment day the pilots rated the overall acceptance of the presented RECREATE system between 6 - “Some improvement needed” and 10 - “Very acceptable”. The average rating from all experiment runs is 7.7 for the cruiser pilots and 7.4 for the feeder pilots. With an average rating between 7 - “A few improvements needed” and 8 - “Acceptable” this is a very good result and this shows that all pilots feel that the presented RECREATE system can really work when it will be implemented in real life.

Besides the acceptance of the RECREATE system it is also important that the work load of the pilots remains within acceptable limits and preferably comparable to present day levels. From the selected concept where the cruiser approaches the feeder from behind it is clear that the workload of the cruiser pilots would be higher than the workload of the feeder pilots. The ratings from the pilots confirmed this. It can be concluded that the workload of performing the air refuelling operation with the RECREATE system and procedures is comparable or less than present day approach and landing operations. The pilots noted that it was very easy to learn how to operate the RECREATE system and monitor the execution of the automated approach and station keeping. Figure 9 gives an impression of the view of the tanker and the markers on the tanker aircraft, seen from the cruiser cockpit during refuelling

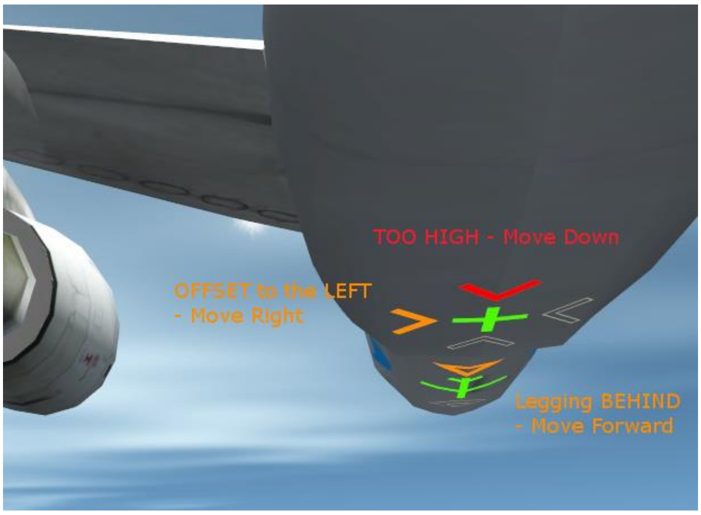

Figure 9: View from the cruiser cockpit of the safety indicators on the tanker aircraft

The safety of the operation was on average rated between "Good" and "Satisfactory". In just a couple of experiment runs some pilots rated the safety "Unacceptable". But again this was during scenarios where deliberately multiple systems were failed simultaneously. This is not a realistic condition but a test case to see the reaction of the pilots to extreme situations. There has not been a single experiment run where the safety of the operation actually got compromised. It can be concluded that the safety of the operation under realistic conditions was at least satisfactory.

In 97% of the experiment runs the cruiser pilots indicated that they had sufficient control over the automated RECREATE system and the aircraft when required. During the debrief even 100% indicated that in general they had sufficient control. Overall it can be concluded that if the systems are working properly, the pilots had sufficient control of the RECREATE systems and their aircraft.

The overall conclusion of the human-in-the-loop evaluations of the presented RECREATE concept is that all pilots that participated in the experiments believe that this concept can be implemented in real life and can be operated by the pilots from the cruiser and the feeder aircraft while maintaining the required safety levels and with an acceptable workload for the pilots. They also indicated that little training will be required to get used to the operation of the automated execution of the air refuelling by the RECREATE system. Of course some aspects still need to be improved before actual implementation on an aircraft but no major issues were identified that would be hard to solve. It would be very interesting to investigate if this RECREATE concept can be developed further towards actual implementation.

Potential Impact and Main Dissemination Activities

When considering a potential implementation of such a complete restructuring of the intercontinental long-range air transport system, as the one proposed in this feasibility study, the huge task of informing relevant groups becomes evident. WP7 had the objective to create impact of the RECREATE project on a European (and global) scale through focussed dissemination of the RECREATE project outcome to the aeronautical science community, advisory groups, policy makers and not in the least the general public, as the potential users of this service.

In order to communicate the results to the aeronautical sciences community and to policy makers, a total of 24 scientific papers have been published at authoritative international conferences (Royal Aeronautical Society - RAeS, AIAA, ICAS, DLRK and others) throughout the project run time. More than 20 additional presentations were given at various opportunities and to various audiences (e.g. RAeS, NATO RTO, AirTN Forum, university students) by members of the project consortium.

Scientific publications of the RECREATE project:

- K. de Cock, R.K. Nangia: Research on a CRuiser Enabled Air Transport Environment (RECREATE), AVT-209 Workshop 2012.
- F. Morscheck: Tanking Strategies for Transatlantic air-to-air refueling operations, DLRK 2012.
- R. McRoberts, J.M. Early, F. Morscheck, M. Price & B. Korn: Implication of Tanker Mission Concept on the Benefits Evaluation of a Civil Air-to-Air Refuelling Transport System, AIAA Aviation 2013.
- G. La Rocca, M. Li, M. Chiozzi: Feasibility study of a nuclear powered blended wing body aircraft for the Cruiser/Feeder concept, CEAS 2013.
- D. Löbl, F. Holzapfel: High Fidelity Simulation Model of an Aerial Refueling Boom and Receptacle, DLRK 2013.
- F. Morscheck: Analyses on a Civil Air to Air refueling Network in a Traffic Simulation, ICAS 2014.
- G. La Rocca, P. van der Linden, M. Li, Elmendorp: Conceptual Design of a Passenger Aircraft for Aerial Refueling Operations, ICAS 2014.
- D. Löbl, F. Holzapfel: Simulation Analysis of a Sensor Data Fusion for Close Formation Flight, AIAA GNC 2014.
- H.S. Timmermans, G. La Rocca: Conceptual Design of a Flying Boom for Air-to-Air Refueling of Passenger Aircraft, ICCMSE 2014.
- R. McRoberts , J.M. Early , M. Price: Improving Feasibility of Point to Point Operations Through Civil Aerial Refuelling, AIAA Aviation 2014.

- S. Zajac, K. de Cock: Overview of the Research on a Cruiser Enabled Air Transport Environment (RECREATE) project, RAES AAC 2014.
- T. Mårtensson, R. Nangia: Towards Design of Efficient Cruiser-Feeder Concepts for Civil AAR, RAES AAC 2014.
- T. van Birgelen: Air-to-Air Refuelling of Civil Air Transport Aircraft - a Certification Approach, RAES AAC 2014.
- F. Morscheck: Interference Liability of a civil Air to Air refueling Traffic Network, RAES AAC 2014.
- M. Li, G. La Rocca: Conceptual Design of Joint-Wing Tanker for Civil Operations, RAES AAC 2014.
- L. Manfriani, M. Righi: Aerodynamic Design of a Boom for Air-to-Air Refuelling, RAES AAC 2014.
- W.W.M. Heesbeen, D. Löbl, J. Groeneweg: Human Aspects of Air-to-Air Refuelling of Civil Aircraft - A Human-in-the-Loop Study, RAES AAC 2014.
- J. Wang, D. Löbl, T. Raffler, F. Holzapfel: Kinematic Modeling and Control Design for an Aerial Refueling Task, RAES AAC 2014.
- H.S. Timmermans, G. La Rocca: Feasibility Study of a Forward Extending Flying Boom for Passenger Aircraft Aerial Refuelling, RAES AAC 2014.
- M. van Lith, H.G. Visser, H. Hosseini: Modeling an Operations Concept for Commercial Air-to-Air Refueling Based on a Vehicle Routing Problem Formulation, ICAS 2014.
- L. Manfriani, M. Righi: Aerodynamic Modelling of a Refuelling Boom, ICAS 2014.
- D. Löbl, F. Holzapfel: Closed-Loop Simulation Analysis of Automated Control of Aircraft in Formation Flight, DLRK 2014.
- R. McRoberts, J.M. Early, F. Morscheck, M. Price, B. Korn: Tanker Mission Implication on a Civil Aerial Refuelling Transport System's Benefit Evaluation, Journal of Aircraft, Vol. 52/Issue 1, 01/01/2015, pp. 320-328.
- D. Löbl, F. Holzapfel: Subset Simulation for Estimating Small Failure Probabilities of an Aerial System Subject to Atmospheric Turbulences, AIAA AFM 2015.

Furthermore, a dedicated session of the cruiser-feeder concept has been organized within the framework of the Applied Aerodynamics Conference 2014 of the Royal Aeronautical Society. A total of nine presentations, containing the intermediate results of all work packages, were given during this session. The conference was held in Bristol on 22-24 July 2014. The resulting papers have been published in the proceedings of the conference. Although difficult to measure, attention to the Cruiser-Feeder concept and the outcome of the RECREATE project has certainly been drawn by this successful session which was attended by aerospace scientists and managers from universities and companies worldwide. Useful discussions took place following the presentations. It has also received some attention by international journalists.

The final phase 2 of the flight simulator experiments in the research simulators of NLR and DLR, GRACE and GECO has been the climax of the research conducted in the RECREATE project, with the work of all work packages (but especially that of WP5 and 6) contributing to these experiments. The experiments were completed in October 2014. This was taken as opportunity to draw attention of the general public to the final results of RECREATE by publishing a press release on 27 October 2014. This directly resulted in four major and several small articles in newspapers and technical magazines, and in two radio interviews with RECREATE researchers.

During the project run time, a total of 18 newspaper and magazine articles in English, Dutch and German have been published. Three radio interviews were given on Dutch radio stations. A website with complete coverage of the dissemination efforts and two videos produced by NLR and presented via YouTube help to generate awareness of the concept for a broad public. It can be concluded that the dissemination activities of the project results have been very successful, especially in the Dutch press and for the (English speaking) aeronautical science community.

Public Project Website

All publishable outcome of the RECREATE projects is also being disseminated via the public RECREATE homepage: www.cruiser-feeder.eu. Contact information is also available via the webpage.

Appendix A Final results of WP1

RESearch on a
CRuiser Enabled Air
Transport Environment

WP1

Concepts for cruiser/feeder operations

The research leading to these results has received funding from the European Union Seventh Framework Programme (*FP7/2007-2013*) under *grant agreement* n° 284741.
This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.

Objectives

To substantiate through a collaborative research effort that viable and acceptable concepts for cruiser/feeder operations exist.

- Partners involved
  - DEUTSCHES ZENTRUM FÜR LUFT - UND RAUMFAHRT (**DLR**) 6 PM
  - TOTALFORSVARETS FORSKNINGSINSTITUT (**FOI**) 5 PM
  - TECHNISCHE UNIVERSITAET MÜNCHEN (**TUM**) 1 PM
  - TECHNISCHE UNIVERSITEIT DELFT (**DUT**) 2 PM
  - DR RAJENDAR KUMAR NANGIA (**RKN**) 10 PM
  - NUCLEAR RESEARCH AND CONSULTANCY GROUP (**NRG**) 3.1 PM

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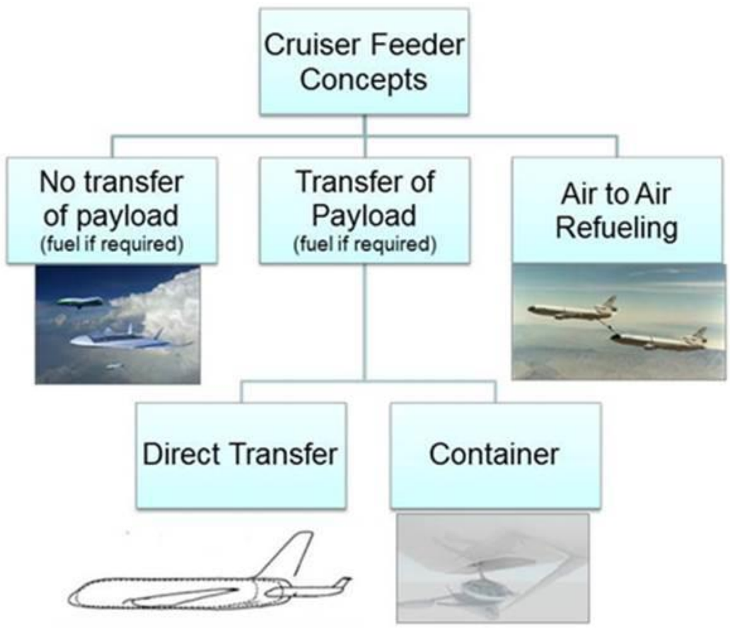
This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.

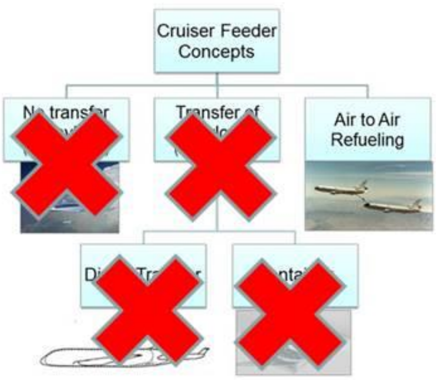
What is the cruiser/feeder concept?



3

Conclusions initial assessment (2012)

Based on efficiency considerations accounting for technology levels, environmental impact, fuel and weight savings we noted:



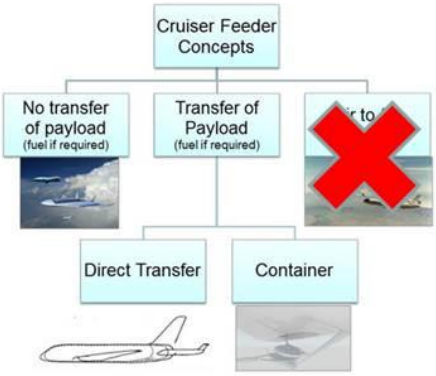
Traditional designs based on engines ***burning kerosene with transfer of payload cannot be seen as viable***.

The overall weight of the aircraft and the total amount of fuel burnt is too high.

The only ***viable concept design is to transfer only fuel*** for this type of aircraft.

4

Conclusions initial assessment (2012)



However, if the Cruiser can be propelled by a ***nuclear power source the efficiency parameters are very high*** compared to the used reference case even if the weight of the system is higher.

5

Level of ambition on selected concepts

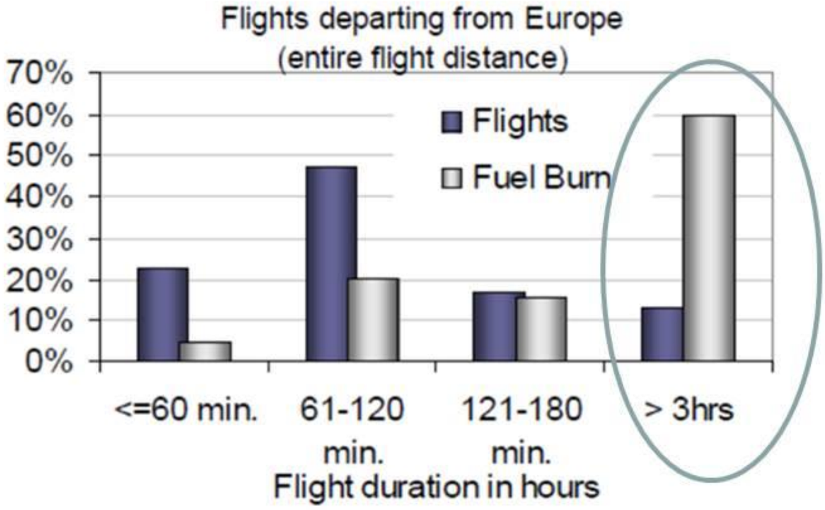
WP	AAR	Orbiting Nuclear Cruiser
WP 1 Concept	X	X
WP2 Airworthiness	X	(x) To some extent
WP3 Benefits	X	(x) To some extent
WP4 Design	Concept Design and Preliminary Design	Concept Design only
WP5 Controle	X (conventional AAR)	-
WP6 Simulation	X (conventional AAR)	-
WP7 Dissemination	X	X

21:st Century Network
Long distance travel via hubs

7

Concept of operations (CONOPS) for the cruiser feeder system

- **Mission** – Long flights



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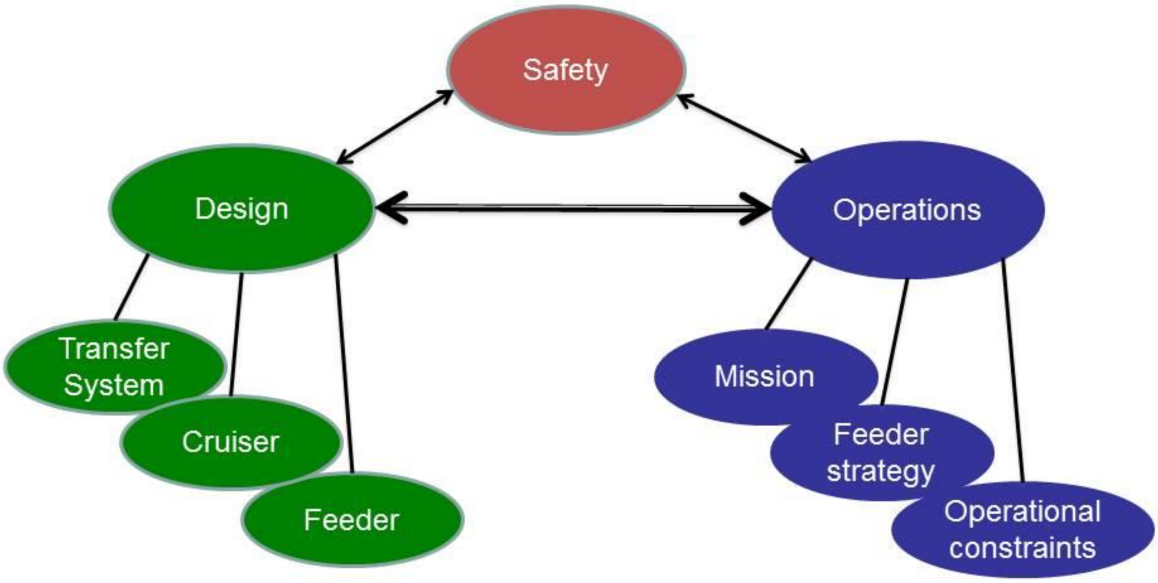
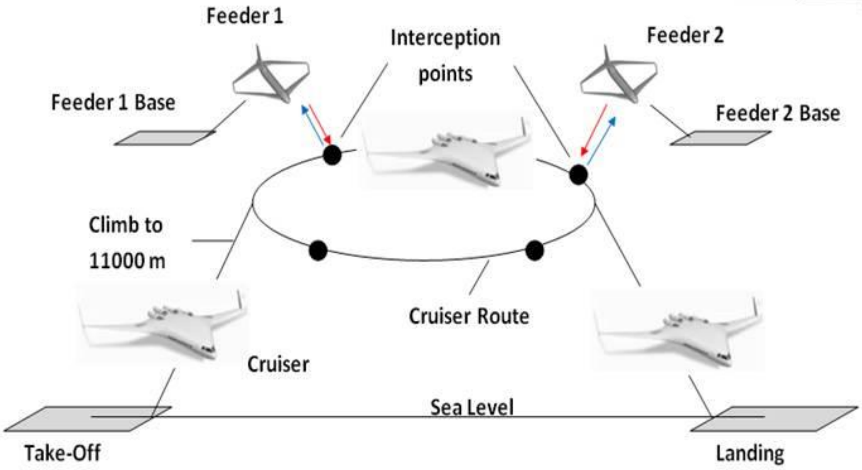
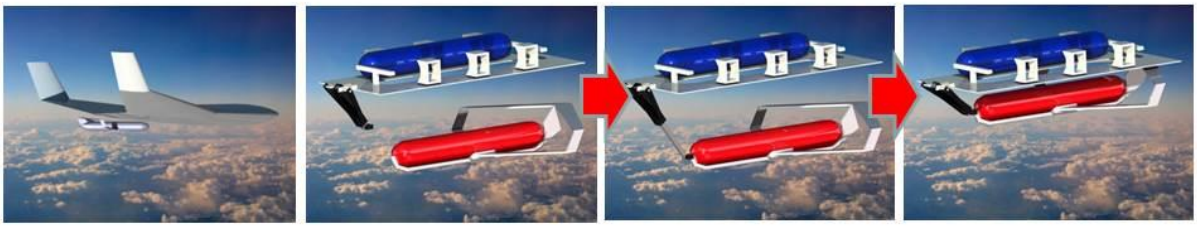
Concept design cruiser/feeder



Concept description of orbiting nuclear powered cruiser (1)

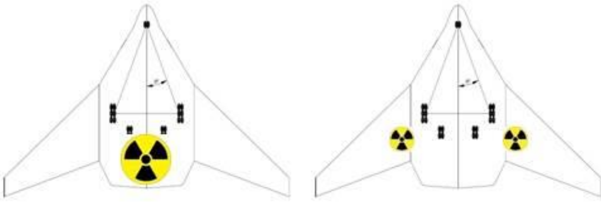




Concept description of orbiting nuclear powered cruiser (2)

Aircraft and systems design:

- Hybrid propulsion
- Two concepts being analyzed for nuclear propulsion.(Brayton and Rankine
- Reactor safety systems
- Impact design
- Coolant inertia
- Aircraft design process
- Emergency operations design



Operations and infrastructure:

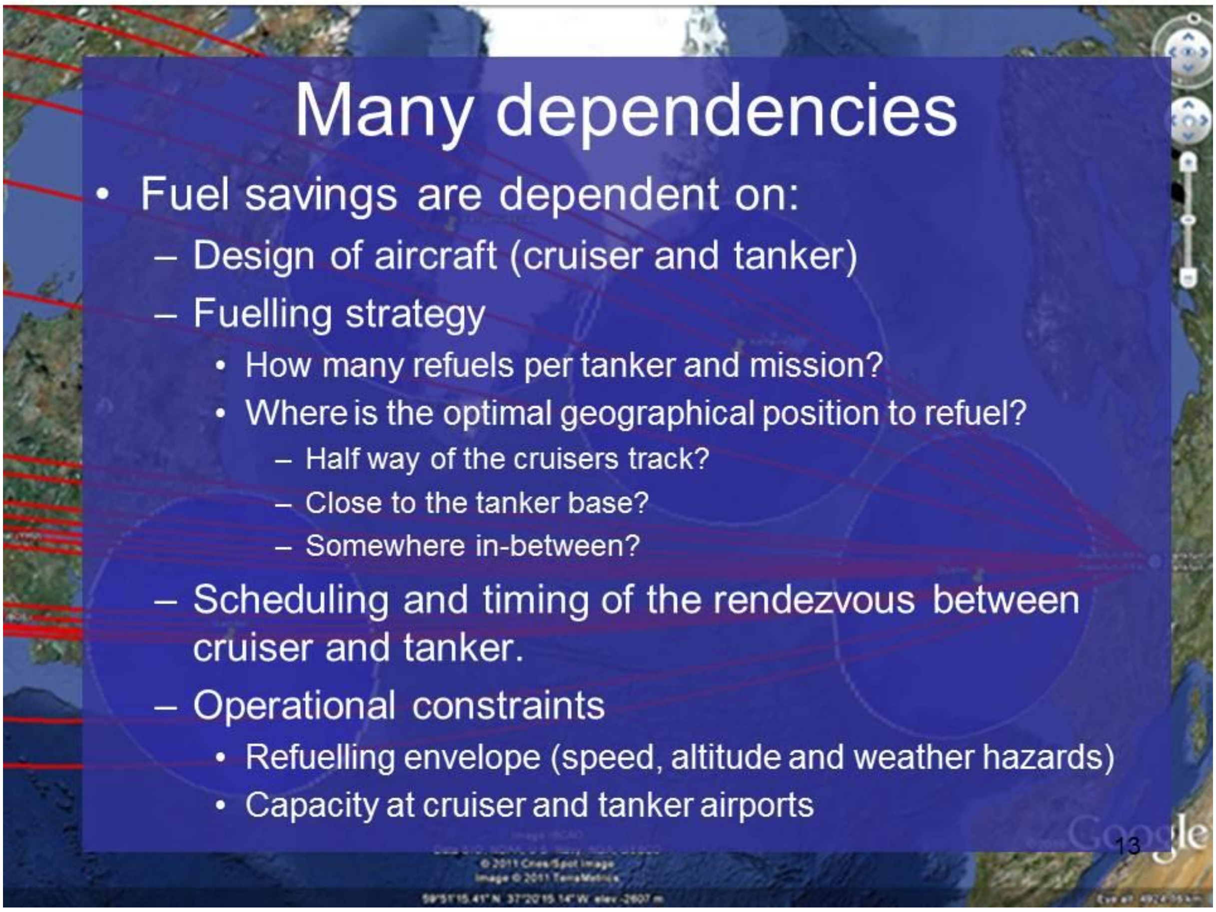
- Airfield requirements
- Maintenance
- Post-crash operations
- Nuclear flight routing

T. Schuwer, *Design of a nuclear propulsion system for large passenger aircraft*. MSc thesis, Delft, 2014.

11

Concept 2 – Air to Air refuelling

Cruiser	Air to Air Refuelling	Feeder
250 passenger capacity Design Range 2500-3000 nm Max Take Off Weight 240 000 lb Specific Fuel Consumption (SFC) 0.525	 **Fuel transfer system** • AAR procedure - 20 minutes including a wet contact for five minutes	Offload capability - 35 000 lb total fuel, able to refuel a Cruiser, up to three times Flight profile – Two to Three hours total flying time. Least the better


Many dependencies
• Fuel savings are dependent on:
– Design of aircraft (cruiser and tanker)
– Fuelling strategy
• How many refuels per tanker and mission?
• Where is the optimal geographical position to refuel?
– Half way of the cruisers track?
– Close to the tanker base?
– Somewhere in-between?
– Scheduling and timing of the rendezvous between cruiser and tanker.
– Operational constraints
• Refuelling envelope (speed, altitude and weather hazards)
• Capacity at cruiser and tanker airports
13

Method

- We have built knowledge with analytical methods and traffic simulations. Stepping up from simple scenarios to global simulations with thousands of flights.

- Trade offs has to be made between design and operational constraints.

14

Feeder Strategy
Trade-off results

- To have a reasonable workload on tanker airports, ***three refuels per tanker*** is the best choice.
- For the lowest fuel burn in the system ***re-fuelling usually takes place close to the tanker base*** (meaning that most cruisers make a detour for refuelling)

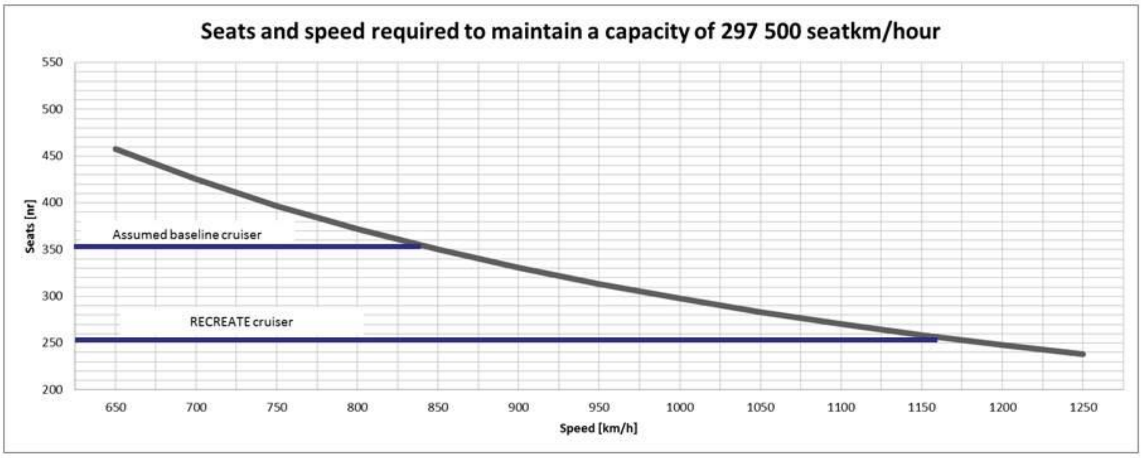
15

RECREATE C/F

Fuel savings

10-20%

Capacity aspects of cruiser/feeder operations

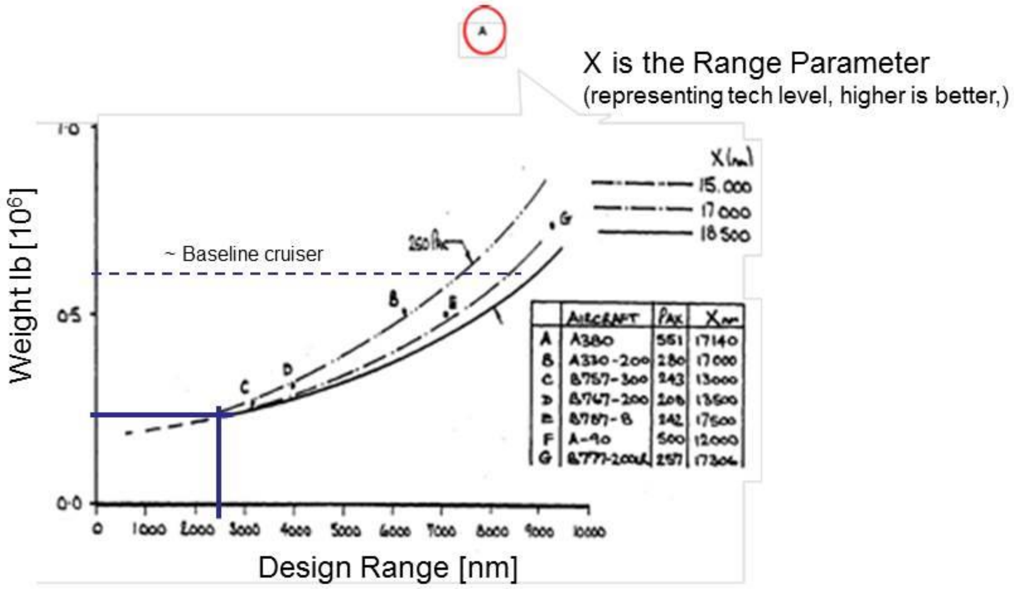


The RECREATE cruiser is smaller and more efficient!

Loss in transport capacity? More movements needed?

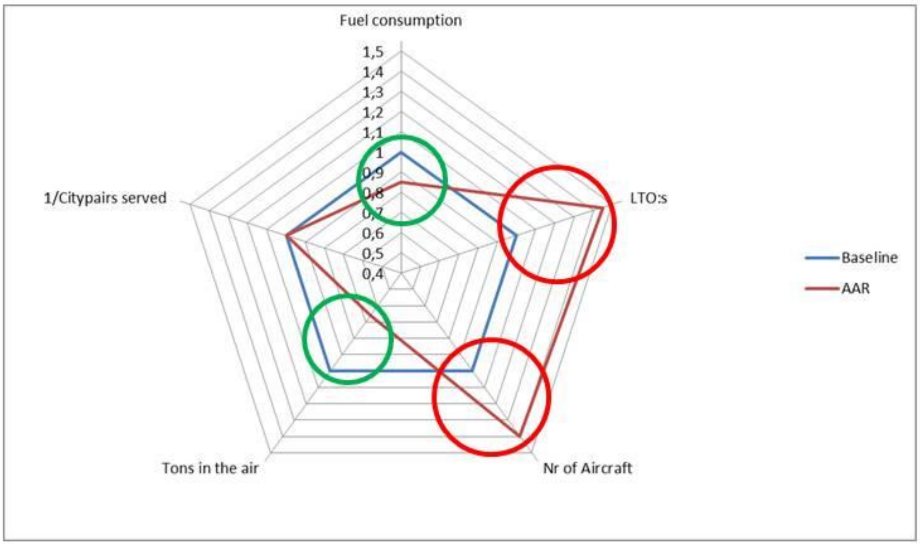
17

Weight versus design range for a 250 passenger AAR cruiser

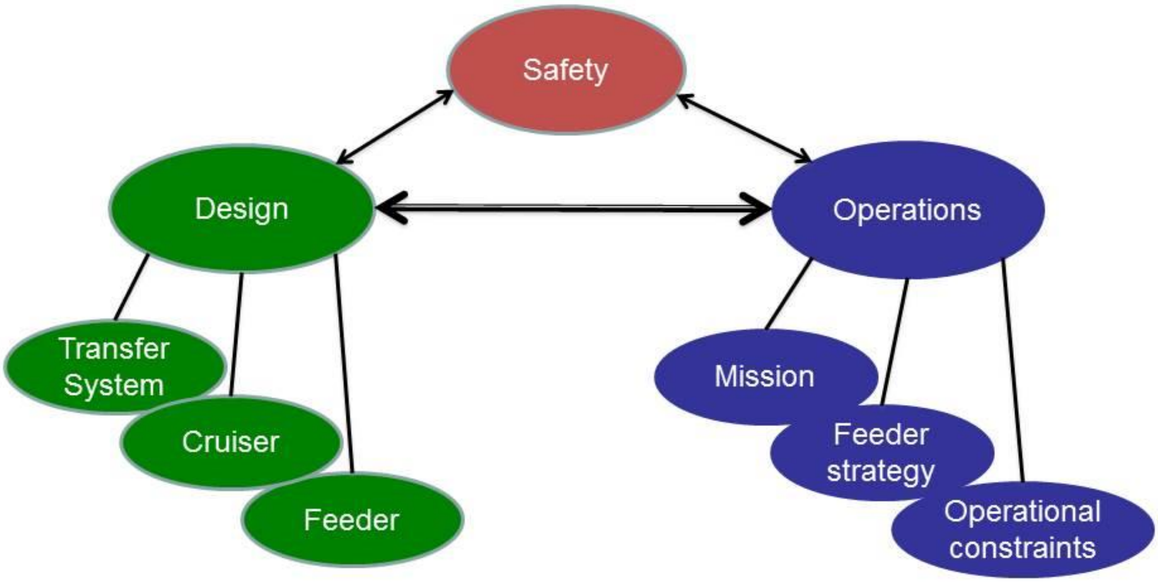


The RECREATE cruiser is small and very efficient!

AAR vs Baseline



Cruiser/feeder design versus operations



Operational constraints

- Refuelling envelope
- Significant weather
- Contingency planning
- Turbulence
- Air Navigation Service

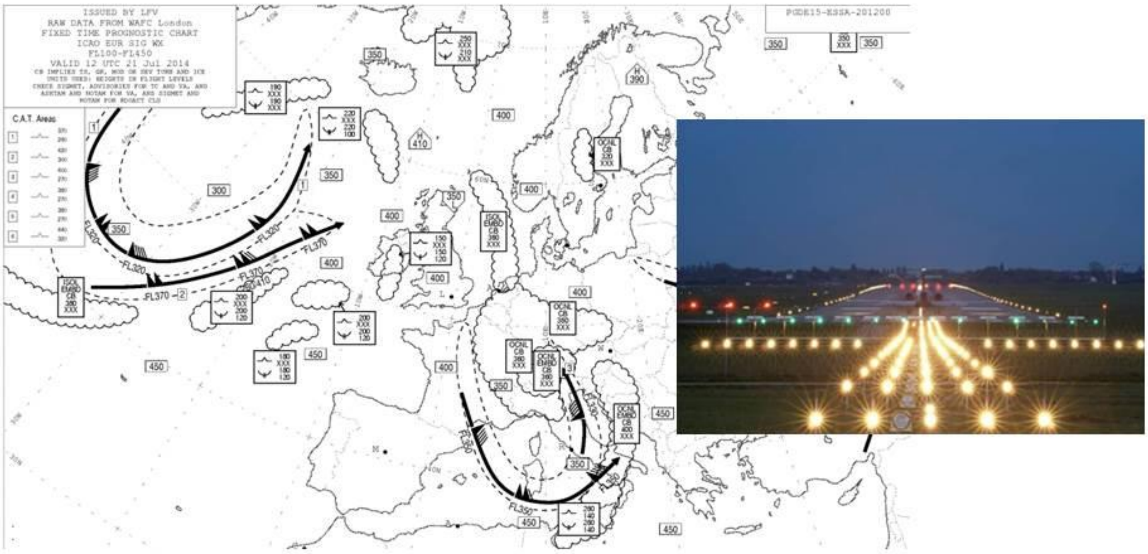
Refuelling envelope
Mach < 0,8 and < FL260

- Access power from cruiser flying in the downwash from the tanker is very limited at cruise altitude.
- Higher control authority on the boom at lower altitude.
- Descending from cruise to < FL260 and back → loss 1 % fuel savings.
- Refuelling < FL260 decrease risk of encountering turbulence while refuelling.
- Vertical separation between cruising and refuelling aircraft (ATC).

Significant Weather SIGWX

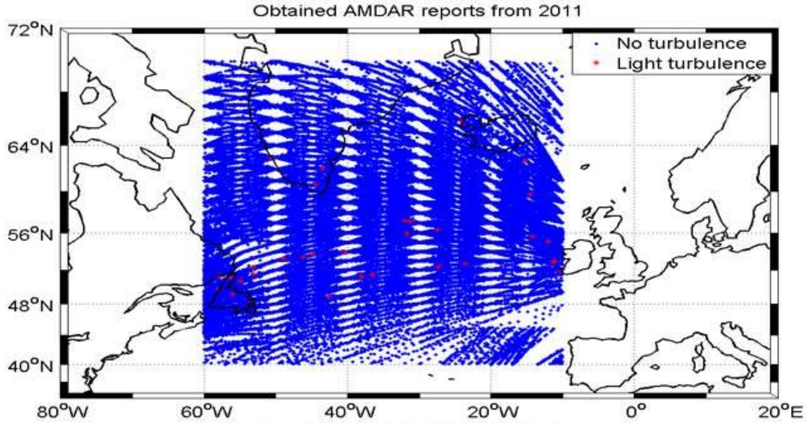
- Technical failures and/or dangerous events caused by weather during refuelling is the main concern.
- Weather impact
  - Poor Visibility — Clouds
  - Lightning — Cumulonimbus clouds
  - In-flight icing — Clouds with temperature below freezing
  - Turbulence — Clouds, Jetstream, mountain waves…

Significant Weather SIGWX
Contingency planning



Valid 12 UTC 21JUL2014

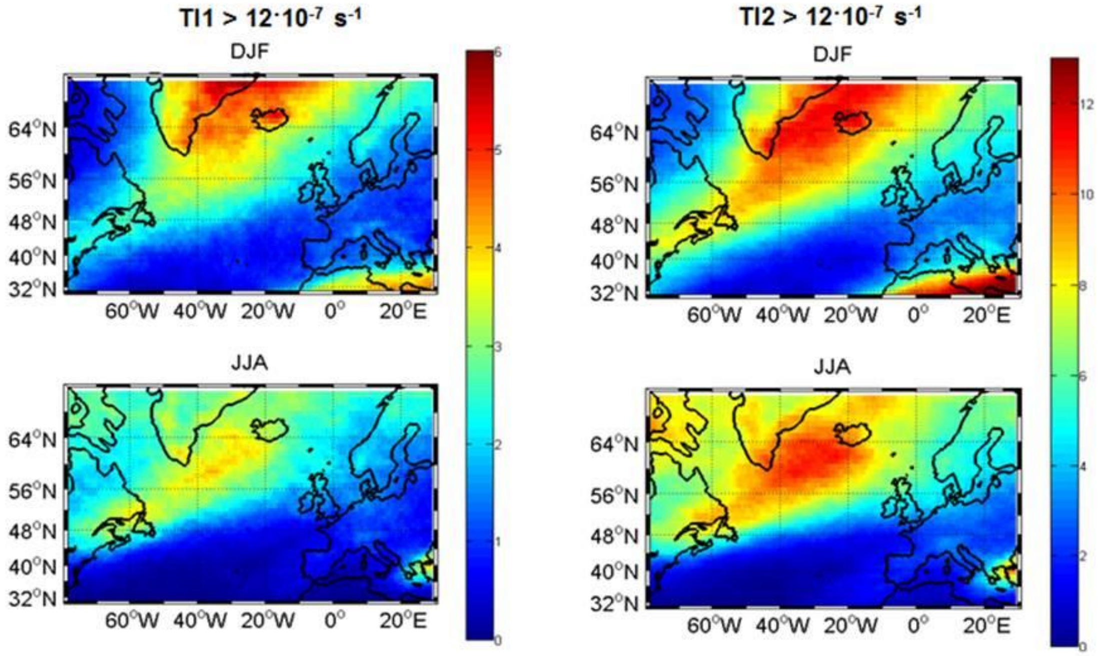
Clear Air Turbulence (CAT)



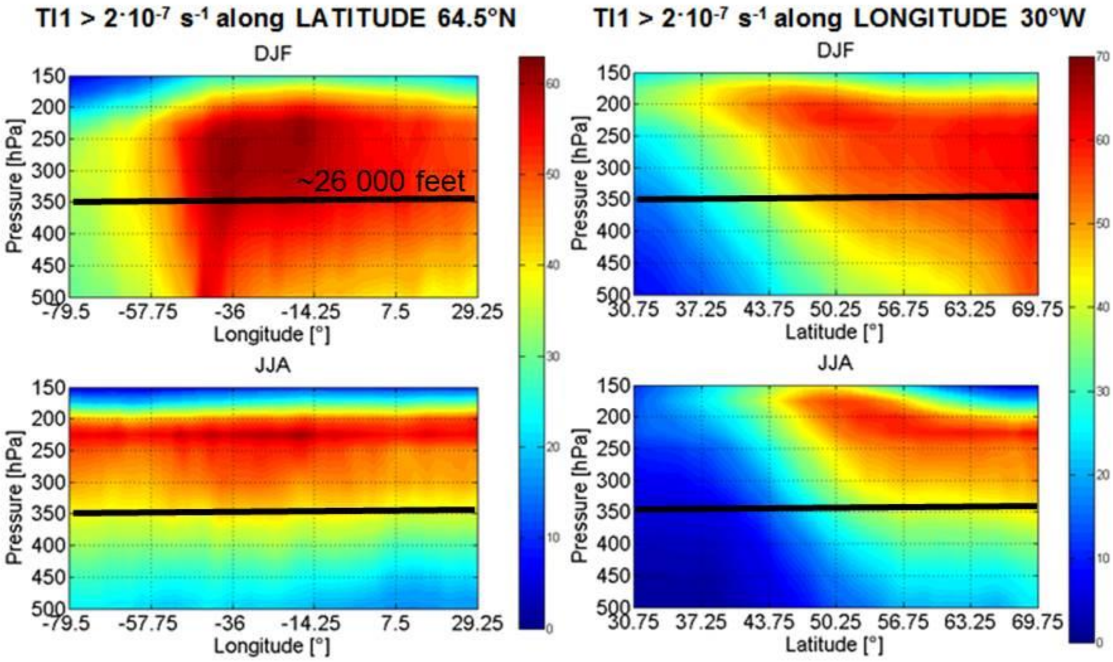
AMDAR = Aircraft Meteorological Data

- CAT is non-convective turbulence at high altitude and caused by either the Jet Stream (Kelvin-Helmholtz Instability) or mountain waves
- Several forecasting indices exist:
  TI1, TI2, Brown, Dutton, VWS, HWS, GTG, GTG2

Frequency distribution 30 years data (ERA40)



Frequency distribution
30 years data (ERA40)



Air Navigation Service

- Standard flight planning like today. New separation rules (allowing for zero separation in the refuelling area and responsibility and liability issues.
  - Procedures for setting up “refuelling area of the day” (like NAT OTS)
  - ATM planning tools for optimising tanker scheduling
  - New software in the on-board Flight Management Systems (FMS) dealing with increases weight during flight.

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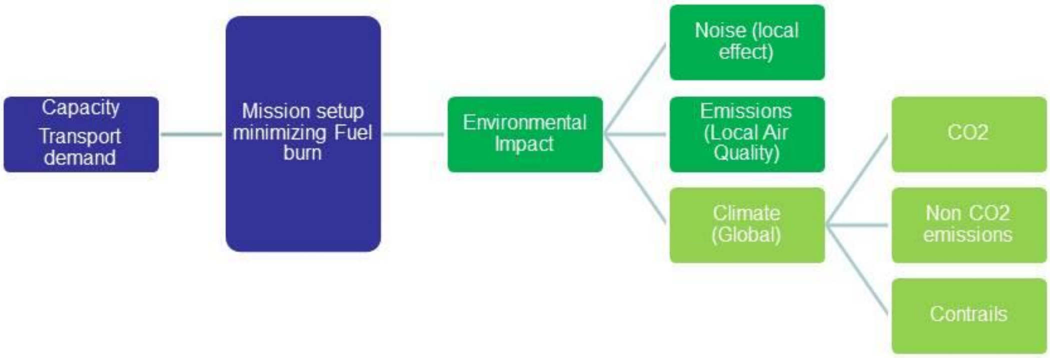
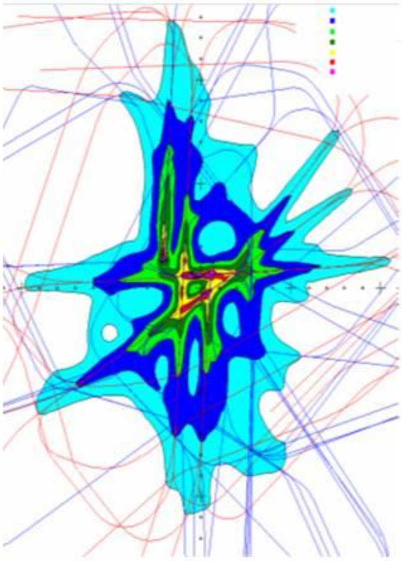
Environmental aspects of AAR operations



Noise and Local Air Quality

- Lower absolute noise levels (smaller cruisers), average noise levels about the same.
- Lighter AAR cruisers with smaller engines will (in general) emit less particles (Depends on emitted substance and phase of flight)

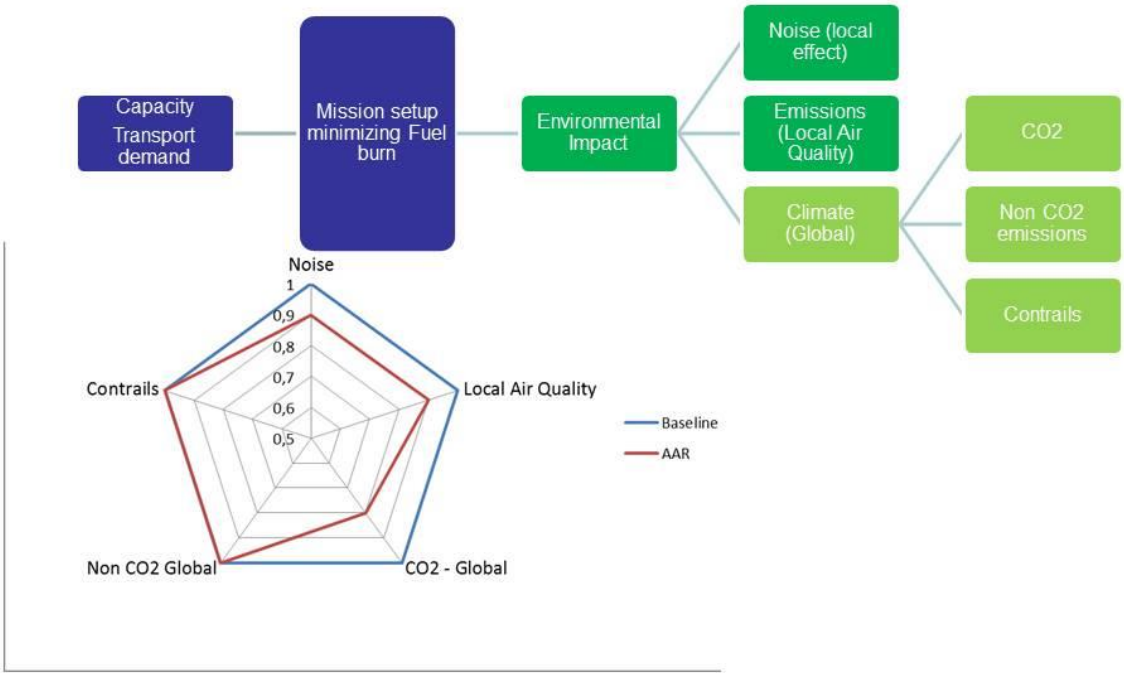


30

AAR - Climate Impact

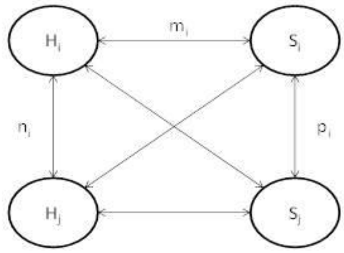
- Main benefit is the saving in CO_2. It is proportional to fuel savings.
- Non CO_2 emission and contrails.
  - Reduction per flight compared today, however more flights expected…

Conclusion environmental impact - AAR



The full potential of an AAR system…

- What is the effect of the interaction between continental and intercontinental travel?
- The smaller more efficient AAR-cruisers inherently gives opportunity to serve more point to point connections.
- It will also be easier for the airline companies to make a business case for new point to point connections compared to the today´s larger baseline cruiser

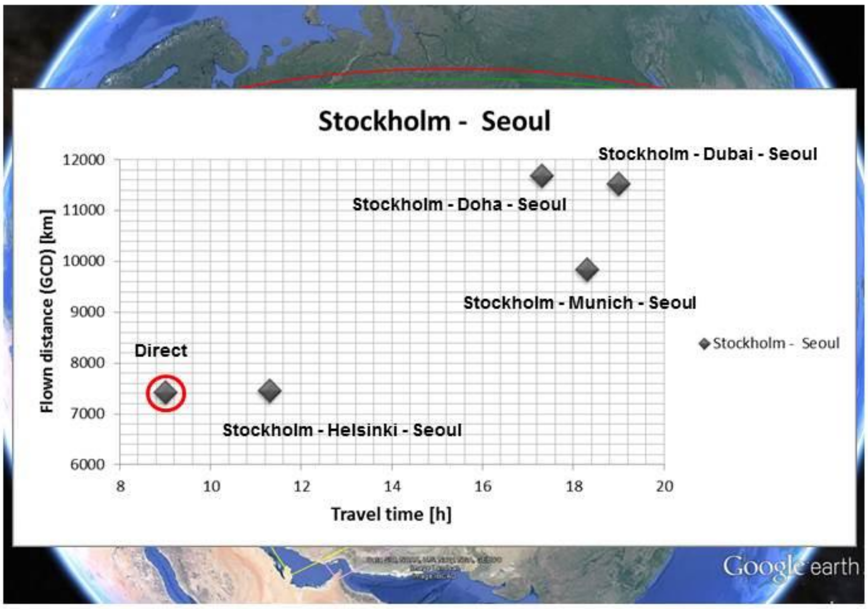


A recent example…

Suggested routes from a commonly used Swedish internet travel site: lowest price (2), shortest travel time (1), longest stay (1)

34

Time, environmental impact and cost…



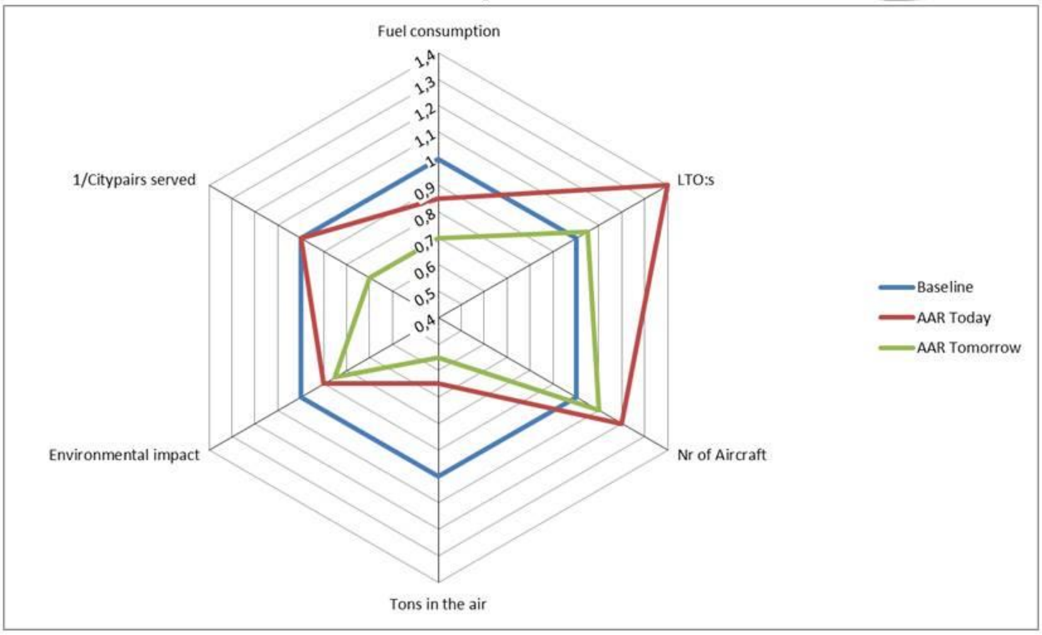
Lowest price about double travel time and flown distance – does this make sense?

35

An upcoming example

36

Expected improvements from cruiser/feeder operations



(for the same transport capacity per unit of time)

Conclusions

- The two studied concepts address long-distance air travel but with very different techniques.
- The AAR concept, as outlined in this report, is clearly within reach for aviation if the industry and concerned legal bodies decides to go in this direction.
- As for the orbiting nuclear concept it is not within reach anytime soon but the concept, as such, has great potential.

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Conclusions – concept 1

The future or history?

Conclusions AAR

- Replacing today´s intercontinental air transport system (as it is) with AAR can reduce fuel burn and direct CO_2 emission by 10-20%.
- Number of movements and aircraft will increase, however, the total mass of the system will be lower.
- Operational constrains on the system with present traffic load seems manageable (scheduling, workload on feeder bases and impact from weather (mainly turbulence)
- Local environment – better or same (Noise, LAQ)

Conclusions AAR

AAR can play an important role dealing with the sustainability challenge aviation faces. Short flight has to be mitigated to other transport modes as far as possible. AAR will give large benefits (fuel, direct CO_2 emissions and mass) and for long flights where no viable option exists

- The smaller more efficient AAR-cruisers inherently gives opportunity to serve more point to point connections.
- It will also be easier for the airline companies to make a business case for new connections compared to the larger baseline cruiser
- A variation of AAR cruiser size (200-300 pax) and AAR design ranges (2500-3000 nm) must be allowed for in order to optimize savings.
- Other, novel transfer configurations (tanker in front, or non centerline) can improve aircraft efficiency, system performance and safety
- Civil AAR should not be viewed in isolation. Other new concepts of air operations and new technologies can be used together with civil AAR (formation flying)

Thank you for your attention

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Appendix B Final results of WP2

WP2- Airworthiness assessment of cruiser-feeder operations

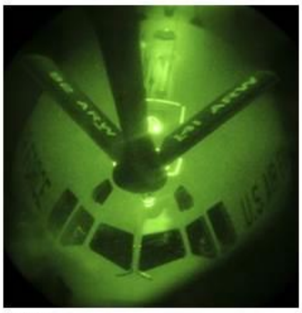
Amsterdam

28-29 January 2015

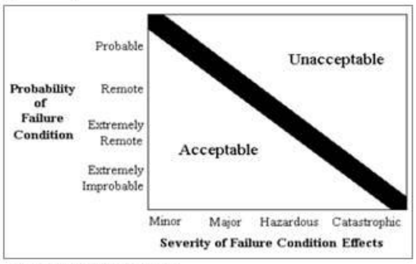
The research leading to these results has received funding from the European Union Seventh Framework Programme (*FP7/2007-2013*) under *grant agreement* n° 284741.
This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.

Safety considerations of cruiser - feeder concepts

- Air-to-air refuelling and mid-air docking are potentially **hazardous**.
- To allow future cruiser-feeder operations, **safety** of air-to-air refuelling and mid-air docking must be assured with an **equivalent level of safety** compared to today's operations.



USAF



CS 25 AMC 25.1309

- **No** commercial air transport **regulations** covering air-to-air refuelling and mid-air docking exist.
- **New or amended** airworthiness, operations and flight crew licencing **regulations** and acceptable means of compliance are required.

2

Objectives of WP2

- First, assess the feasibility of safe cruiser-feeder operations by performing a system safety analysis and proposing safety measures.
- Subsequently, identify the required new or amended regulations and acceptable means of compliance for certification of cruiser-feeder operations.
- Finally, identify the steps that need to be taken to establish the regulations.

3

Two cruiser-feeder concepts

Cruiser-shuttle concept
Exchange of passengers fuel, cargo, crew

Docking system with trapeze and containers

Cruiser with nuclear propuslion

Receiver-tanker concept
Exchange of fuel using a controllable boom

4

Safety analysis of receiver-tanker concept

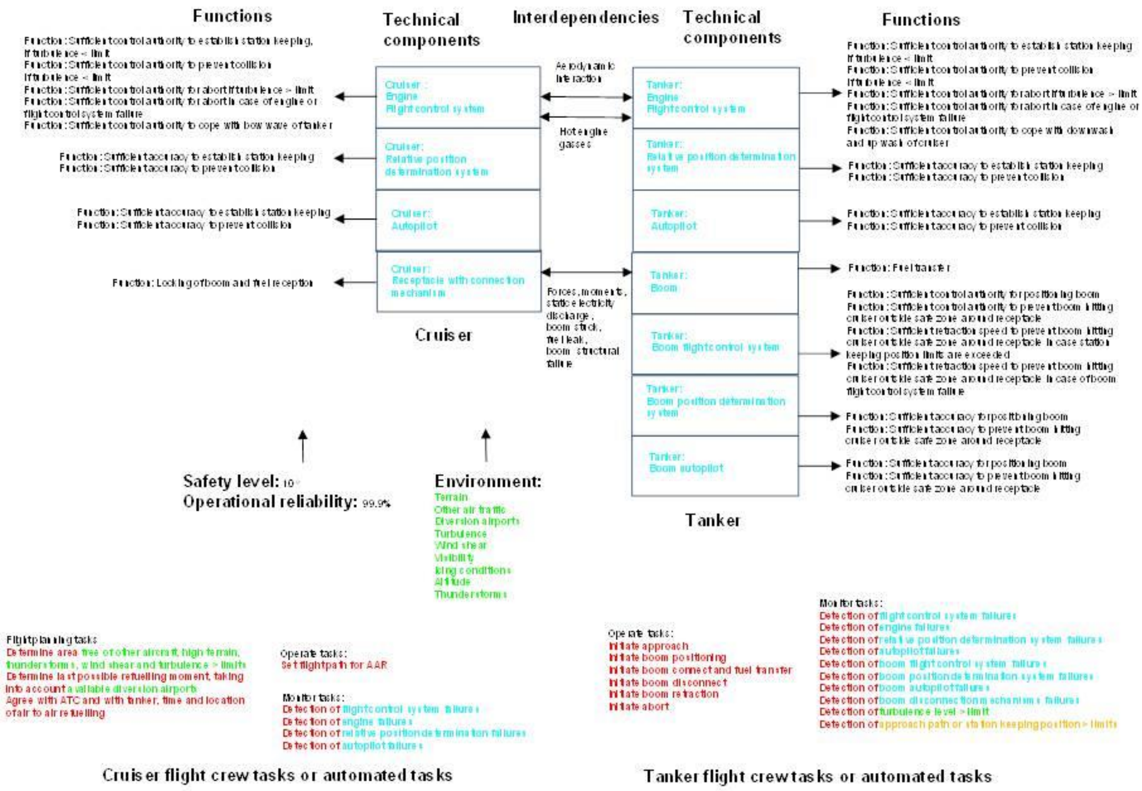
- Safety and operational reliability objectives
- A description of the receiver-tanker technical system components and their collision risk-related functions as well as its operation (operational scenarios) is provided.
- Based on the operational scenarios, performance, availability and integrity requirements for the functions of the technical system components have been determined
- Simulations based on models of the technical system design have been performed in WP5 for the most critical scenarios to verify that the air-to-air refuelling system design provides the required performance to achieve the required safety and operational reliability.
- Non-collision risk related hazards of air-to-air refuelling have been identified, and safety measures to mitigate these hazards have been defined.

5

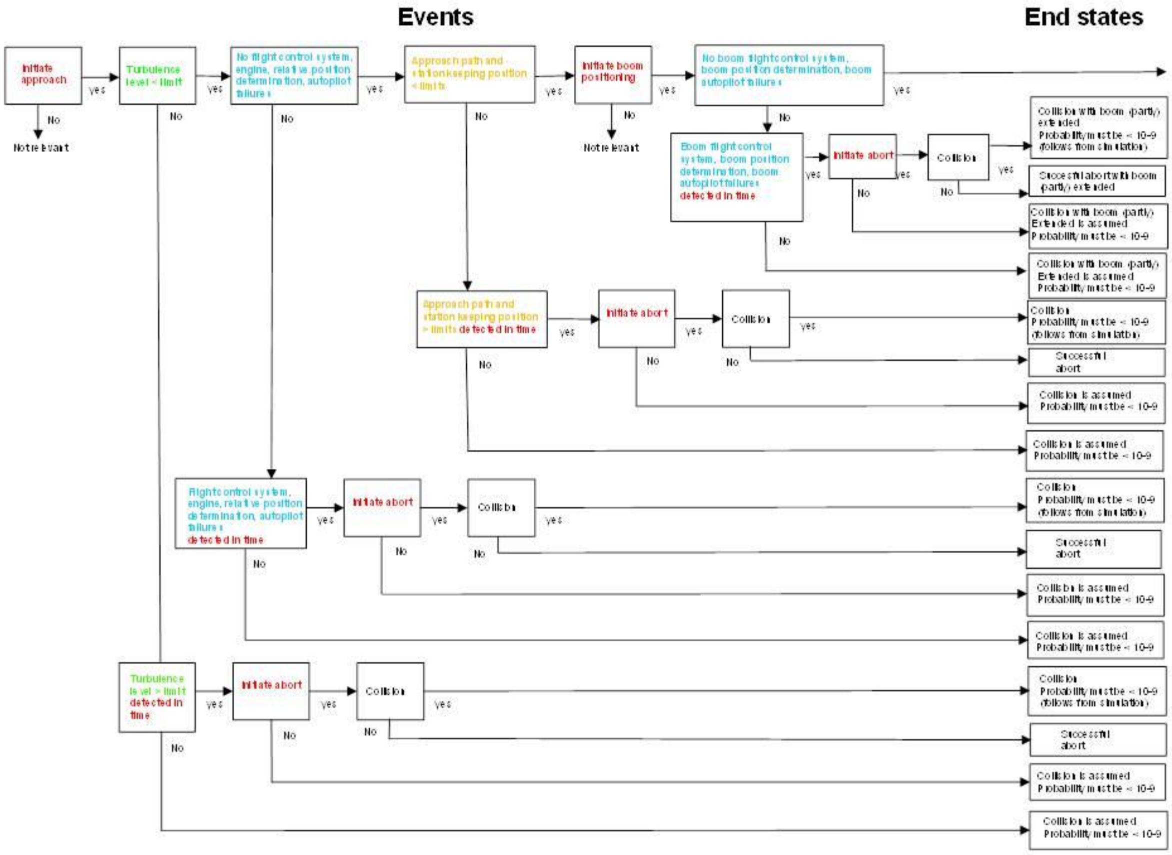
Safety and operational reliability objectives

- Top level function of receiver-tanker concept:
  - Transfer of fuel from tanker to receiver.
- Catastrophic failure conditions related to air to air refuelling must have a probability of occurrence smaller than 10^{-9} per flight hour.
- Availability of the air to air refuelling function must be such that the receiver is able to achieve its operational reliability (e.g. 99%) target taking into account refuelling failures.
- It is assumed that air to air refuelling contributes 10% to the operational unreliability of the cruiser and consists of 10 contributing factors. Therefore each contributory factor must have a availability of at least 99.99%.

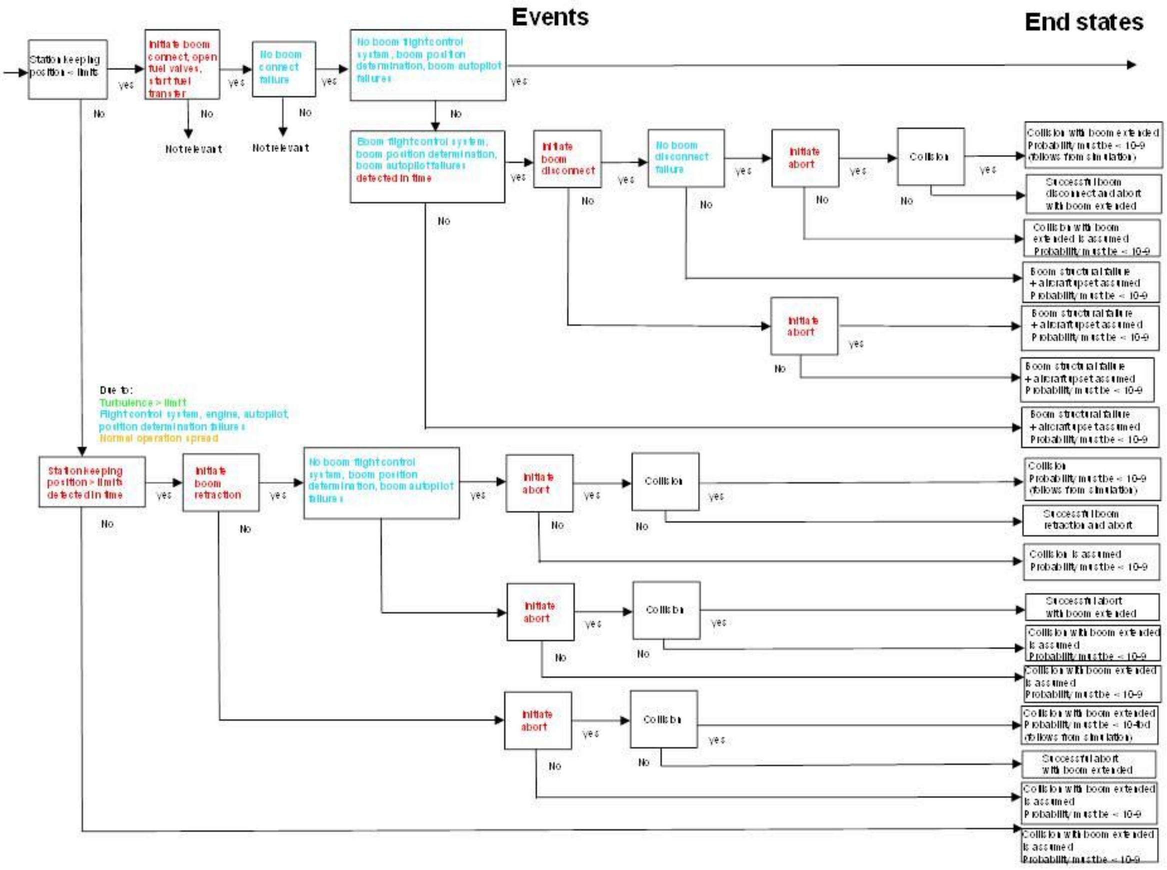
6



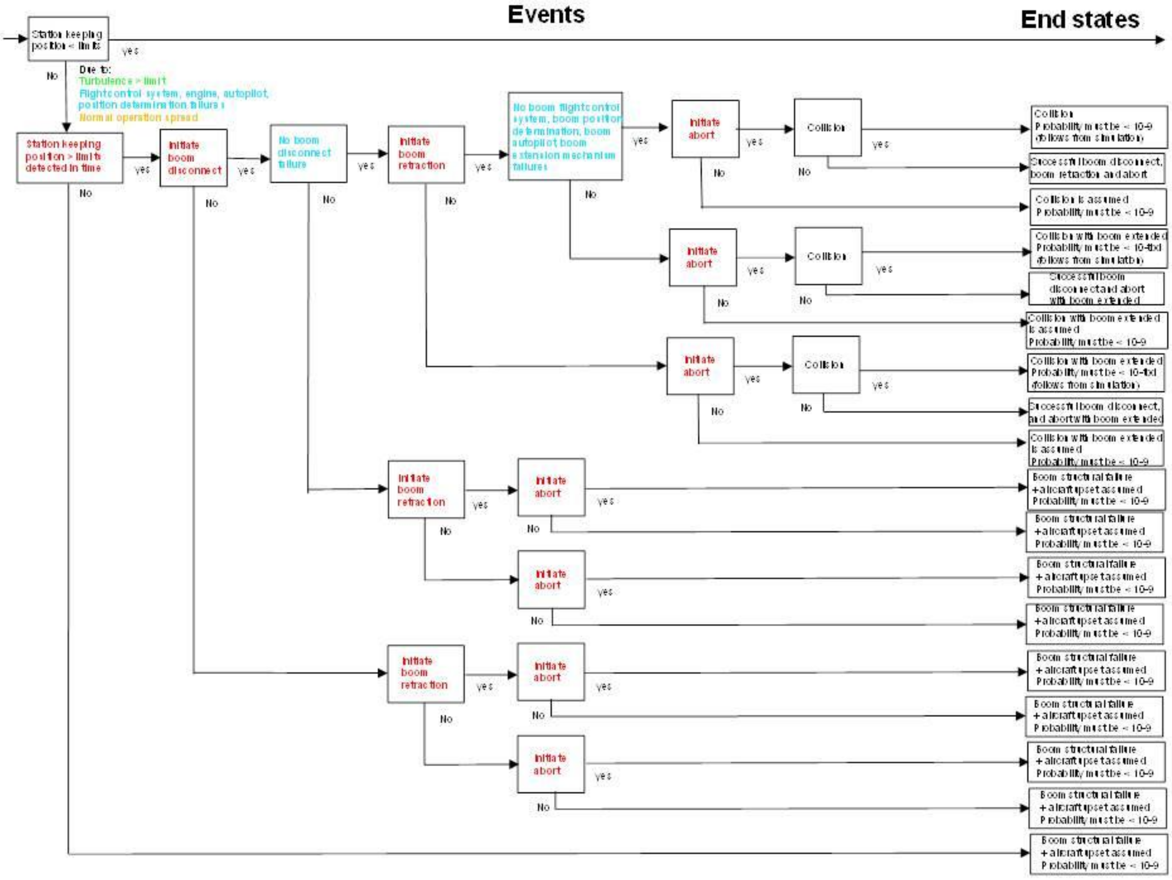
Functions
Technical components
Interdependencies
Technical components
Functions
Function: Sufficient control authority to establish station keeping, if turbulence < limit
Function: Sufficient control authority to prevent collision if turbulence < limit
Function: Sufficient control authority for abort if turbulence > limit
Function: Sufficient control authority for abort in case of engine or flight control system failure
Function: Sufficient control authority to cope with bow wave of tanker
Cruiser: Engine Flight control system
Aerodynamic interaction
Hot engine gasses
Tanker: Engine Flight control system
Function: Sufficient control authority to establish station keeping if turbulence < limit
Function: Sufficient control authority to prevent collision if turbulence < limit
Function: Sufficient control authority for abort if turbulence > limit
Function: Sufficient control authority for abort in case of engine or flight control system failure
Function: Sufficient control authority to cope with downwash and upwash of cruiser
Function: Sufficient accuracy to establish station keeping
Function: Sufficient accuracy to prevent collision
Cruiser: Relative position determination system
Tanker: Relative position determination system
Function: Sufficient accuracy to establish station keeping
Function: Sufficient accuracy to prevent collision
Function: Sufficient accuracy to establish station keeping
Function: Sufficient accuracy to prevent collision
Cruiser: Autopilot
Tanker: Autopilot
Function: Sufficient accuracy to establish station keeping
Function: Sufficient accuracy to prevent collision
Function: Locking of boom and fuel reception
Cruiser: Receptacle with connection mechanism
Forces, moments, static electricity discharge, boom stuck, fuel leak, boom structural failure
Tanker: Boom
Function: Fuel transfer
Cruiser
Tanker: Boom flight control system
Function: Sufficient control authority for positioning boom
Function: Sufficient control authority to prevent boom hitting cruiser outside safe zone around receptacle
Function: Sufficient retraction speed to prevent boom hitting cruiser outside safe zone around receptacle in case station keeping position limits are exceeded
Function: Sufficient retraction speed to prevent boom hitting cruiser outside safe zone around receptacle in case of boom flight control system failure
Tanker: Boom position determination system
Function: Sufficient accuracy for positioning boom
Function: Sufficient accuracy to prevent boom hitting cruiser outside safe zone around receptacle
Tanker: Boom autopilot
Function: Sufficient accuracy for positioning boom
Function: Sufficient accuracy to prevent boom hitting cruiser outside safe zone around receptacle
Safety level: 10
Operational reliability: 99.9%
Environment:
Terrain
Other air traffic
Diversion airports
Turbulence
Wind shear
Visibility
Icing conditions
Altitude
Thunderstorms
Tanker
Flight planning tasks
Determine area free of other aircraft, high terrain, thunderstorms, wind shear and turbulence > limits
Determine last possible refuelling moment, taking into account available diversion airports
Agree with ATC and with tanker, time and location of air to air refuelling
Operate tasks:
Set flightpath for AAR
Monitor tasks:
Detection of flight control system failures
Detection of engine failures
Detection of relative position determination failures
Detection of autopilot failures
Operate tasks:
Initiate approach
Initiate boom positioning
Initiate boom connect and fuel transfer
Initiate boom disconnect
Initiate boom retraction
Initiate abort
Monitor tasks:
Detection of flight control system failures
Detection of engine failures
Detection of relative position determination system failures
Detection of autopilot failures
Detection of boom flight control system failures
Detection of boom position determination system failures
Detection of boom autopilot failures
Detection of boom disconnection mechanisms failures
Detection of turbulence level > limit
Detection of approach path or station keeping position > limits
Cruiser flight crew tasks or automated tasks
Tanker flight crew tasks or automated tasks



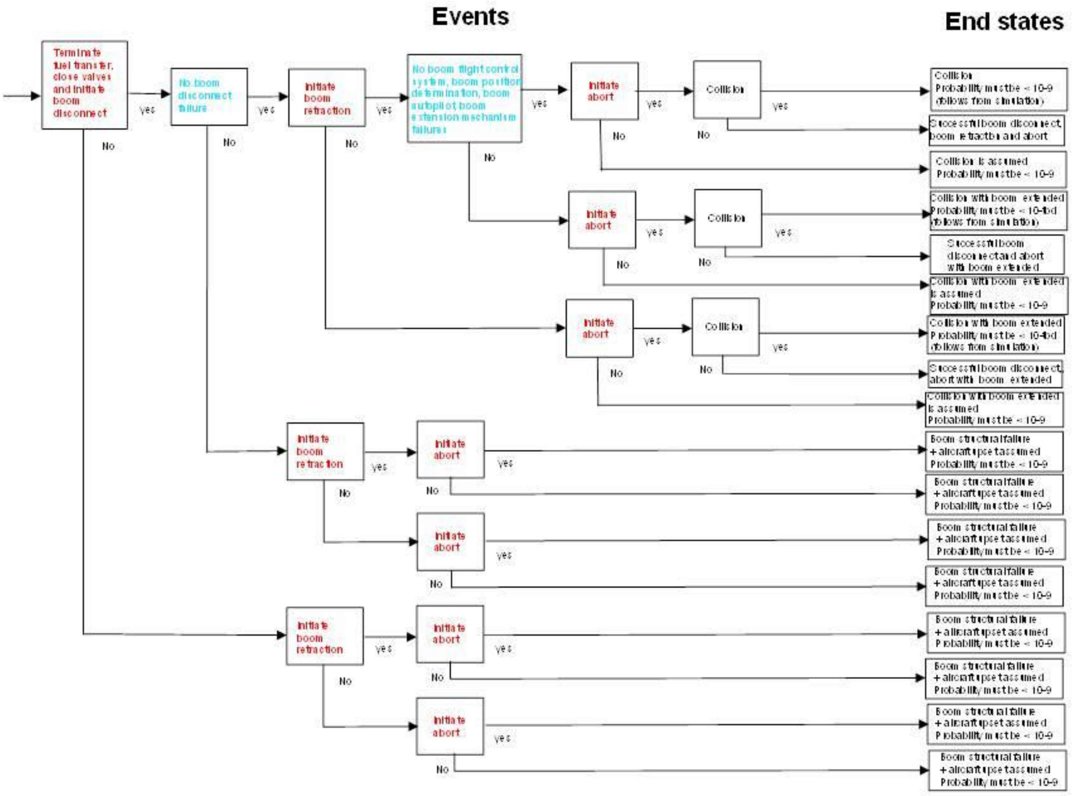
Events
End states
Initiate approach
Turbulence level < limit
No flight control system, engine, relative position determination, autopilot failures
Approach path and station keeping position < limits
Initiate boom positioning
No boom flight control system, boom position determination, boom autopilot failures
Not relevant
Boom flight control system, boom position determination, boom autopilot failures detected in time
Initiate abort
Collision
Collision with boom (partly) extended Probability must be < 10-9 (follows from simulation)
Successful abort with boom (partly) extended
Collision with boom (partly) Extended is assumed Probability must be < 10-9
Approach path and station keeping position > limits detected in time
Collision Probability must be < 10-9 (follows from simulation)
Successful abort
Collision is assumed Probability must be < 10-9
Flight control system, engine, relative position determination, autopilot failures detected in time
Turbulence level > limit detected in time
yes
No



Events
End states
Station keeping position < limits
Initiate boom connect, open fuel valves, start fuel transfer
No boom connect failure
No boom flight control system, boom position determination, boom autopilot failures
Not relevant
Not relevant
Boom flight control system, boom position determination, boom autopilot failures detected in time
Initiate boom disconnect
No boom disconnect failure
Initiate abort
Collision
Collision with boom extended Probability must be < 10-9 (follows from simulation)
Successful boom disconnect and abort with boom extended
Collision with boom extended is assumed Probability must be < 10-9
Boom structural failure + aircraft upset assumed Probability must be < 10-9
Due to:
Turbulence > limit
Flight control system, engine, autopilot, position determination failures
Normal operation spread
Station keeping position > limits detected in time
Initiate boom retraction
Collision Probability must be < 10-9 (follows from simulation)
Successful boom retraction and abort
Collision is assumed Probability must be < 10-9
Successful abort with boom extended
Collision with boom extended is assumed Probability must be < 10-9
Collision with boom extended Probability must be < 10-tbd (follows from simulation)
yes
No



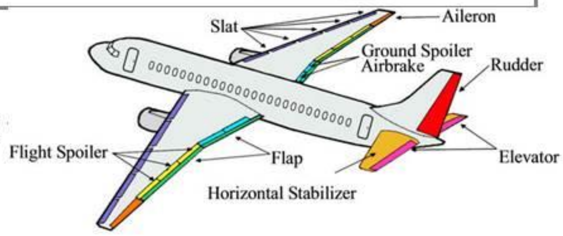
Events
End states
Station keeping position < limits
yes
No
Due to:
Turbulence > limit
Flight control system, engine, autopilot, position determination failures
Normal operation spread
Station keeping position > limits detected in time
Initiate boom disconnect
No boom disconnect failure
Initiate boom retraction
No boom flight control system, boom position determination, boom autopilot boom extension mechanism failures
Initiate abort
Collision
Collision Probability must be < 10-9 (follows from simulation)
Successful boom disconnect, boom retraction and abort
Collision is assumed Probability must be < 10-9
Collision with boom extended Probability must be < 10-tbd (follows from simulation)
Successful boom disconnect and abort with boom extended
Collision with boom extended is assumed Probability must be < 10-9
Successful boom disconnect, and abort with boom extended
Boom structural failure + aircraft upset assumed Probability must be < 10-9



Events
End states
Terminate fuel transfer, close valves and initiate boom disconnect
No boom disconnect failure
Initiate boom retraction
No boom flight control system, boom position determination, boom autopilot boom extension mechanism failures
Initiate abort
Collision
yes
No
Collision Probability must be < 10-9 (follows from simulation)
Successful boom disconnect, boom retraction and abort
Collision is assumed Probability must be < 10-9
Collision with boom extended Probability must be < 10-tbd (follows from simulation)
Successful boom disconnect and abort with boom extended
Collision with boom extended is assumed Probability must be < 10-9
Collision with boom extended Probability must be < 10-tbd (follows from simulation)
Successful boom disconnect, abort with boom extended
Collision with boom extended is assumed Probability must be < 10-9
Boom structural failure + aircraft upset assumed Probability must be < 10-9

Performance requirements – flight control system

- Control authority of the tanker and cruiser shall be sufficient to keep the tanker position and speed relative to the cruiser and and angular movements of tanker and cruiser < certain limits, if wind shear and turbulence levels remain within certain limits.



- In case of engine or flight control system failures the control authority shall be sufficient for a safe abort maneuver.

- If the wind shear or turbulence level is greater than certain limits during any air to air refueling phase control authority shall be sufficient for a safe abort.

- The tanker shall be designed with sufficient control authority to cope with the downwash and up wash of the cruiser.

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Performance requirements - autopilot

- Autopilot accuracy shall be sufficient to keep the tanker position and speed relative to the cruiser and the attitude and angular movements of tanker and cruiser < certain limits, if wind shear and turbulence levels remain within certain limits.

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Performance requirements – relative position determination system

- The optical sensors / transponder based relative position determination system accuracy shall be sufficient to keep the tanker position and speed relative to the cruiser and the attitude and angular movements of tanker and cruiser < certain limits, if wind shear and turbulence levels remain within certain limits.

- If the optical sensors / transponder based relative position determination system fails, an abort shall be possible using the less accurate GNSS based position determination system.

14

Performance requirements – boom flight control system

- The boom control authority shall be sufficient to steer the boom towards the receptacle without hitting the cruiser outside the safe zone around the receptacle, and without hitting the safe zone around the receptacle in such a way that boom structural failure occurs, if the tanker position and speed relative to the cruiser and the attitudes and angular movements of the tanker and cruiser are within certain limits.
- In case of boom control system failures, the boom shall be retracted without hitting the cruiser outside the safe area around the receptacle, or hitting the safe area around the receptacle in such a way that it causes boom structural damage.
- If the tanker position and speed relative to the cruiser and the attitudes and angular movements of the tanker and cruiser > certain limits during station keeping, the boom shall stop connecting or shall be disconnected, and shall be retracted without hitting the cruiser outside the safe zone around the receptacle, and without hitting the safe zone around the receptacle in such a way that boom structural failure occurs.

15

Performance requirements – boom autopilot

- The boom autopilot accuracy shall be sufficient for positioning the boom without hitting the cruiser outside the safe area around the receptacle, and without hitting the safe area around the receptacle in such a way that it causes boom structural damage, if the tanker position and speed relative to the cruiser and the attitude and angular movements of tanker and cruiser remain within certain limits.

- In case of boom autopilot failures while connecting the boom shall be retracted without hitting the cruiser outside the safe area around the receptacle, or hitting the safe area around the receptacle in such a way that it causes boom structural damage.

16

Performance requirements – boom position determination system

- The boom position determination system accuracy shall be sufficient for positioning the boom without hitting the cruiser outside the safe area around the receptacle, and without hitting the safe area around the receptacle in such a way that it causes boom structural damage, if the tanker position and speed relative to the cruiser and the attitude and angular movements of tanker and cruiser remain within certain limits.

- In case of boom position determination system failures while connecting the boom shall be retracted without hitting the cruiser outside the safe area around the receptacle, or hitting the safe area around the receptacle in such a way that it causes boom structural damage.

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Simulation of operational scenarios

- In WP5 simulations have been performed based on physical models of the technical system design and the environment for the most critical operational scenarios of section 2.1.3. to verify that the technical system design provides the required performance to achieve the required safety and operational reliability targets.
- Simulations have been performed for normal operation and the most critical scenarios:
  - For wind shear or turbulence encounter the most critical situation is the station keeping position with the boom almost connected or just disconnected (boom very close to cruiser) and a sudden downward movement of the cruiser.
  - For system failures the most critical situation is the station keeping position and a sudden engine failure, with or without the boom almost connected or just disconnected.
- All scenarios were proven sufficiently safe (probability of Catastrophic Failure Condition , 10^{-9})

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Non– collision risk related hazards – boom

- Boom nozzle stuck in receptacle of cruiser aircraft => receiver aircraft and tanker stuck together
  Safety measure: design the boom for controlled structural failure near the nozzle, in case an abort is executed with the boom connected.
- Boom stowage failure during cruise flight => insufficient fuel to reach airport due to delta drag
  Safety measure: additional reserve fuel
- Boom not stowed during take-off => longer take-off run required due to increase drag
  Safety measure: take-off warning system for boom configuration
- Boom not stowed during landing => potentially higher stall speed of tanker
  Safety measure: design tanker for acceptable landing speed with boom not stowed.
- Boom instability caused by aerodynamic interference between two aircraft => boom hits tanker => safety critical damage tanker
  Safety measure: design boom such that probability $< 10^{-9}$

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Non– collision risk related hazards – fuel system

- Wrong input of amount of fuel to be transferred => fuel overflow out of vent outlet of fuel system => ignition of fuel by hot sources on tanker aircraft
  Safety measure: design vent outlet locations of cruiser fuel system, and location of hot sources on tanker, such that contact of fuel with hot sources is not possible + use cross checks
- CG limit exceeded during refuelling => unstable aircraft => collision risk or loss of control
  Safety measure: design tank layout and tank refuelling sequence such that exceeding the CG limit is not possible
- Electrostatic discharge between the receiver aircraft and tanker during refuelling => ignition of fuel vapour
  Safety measure: limit the fuel flow rate
- Failure to stop refuelling => fuel overflow out of vent outlet of fuel system => ignition of fuel by hot sources on tanker aircraft
  Safety measure: design vent outlet locations of cruiser fuel system, and location of hot sources on tanker, such that contact of fuel with hot sources is not possible

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Non– collision risk related hazards – fuel system

- Fuel leak => ignition of fuel by hot sources on tanker aircraft
  Safety measure: design vent outlet locations of receiver fuel system, and location of hot sources on tanker (external lights, heated windscreen, pitot tubes, engines, auxiliary power unit, environmental control system) such that contact of fuel with hot sources is not possible or keep the temperatures of the contact areas of these systems below the auto-ignition temperature.
- Fuel leak => ignition of fuel spray by engines on tanker aircraft => engine surge
  Safety measure: locate engines on tanker such that fuel spray cannot be ingested
- Fuel leak / spray => ingestion of fuel into pitot tubes => erroneous air data => collision risk
  Safety measure: due to its lower viscosity, fuel will flow away more easily than water for which the pitot probes are designed

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Summary of safety analysis of receiver-tanker concept

- No safety showstoppers for air-to-air refuelling of air transport aircraft from a technical perspective.
- Air-to-air refuelling can be designed to have an equivalent level of safety compared to today's operations.

Safety analysis of cruiser-shuttle concept

- Collision risk related hazards are assumed to be similar to receiver-tanker concept
- Focus on non-collision risk related hazards

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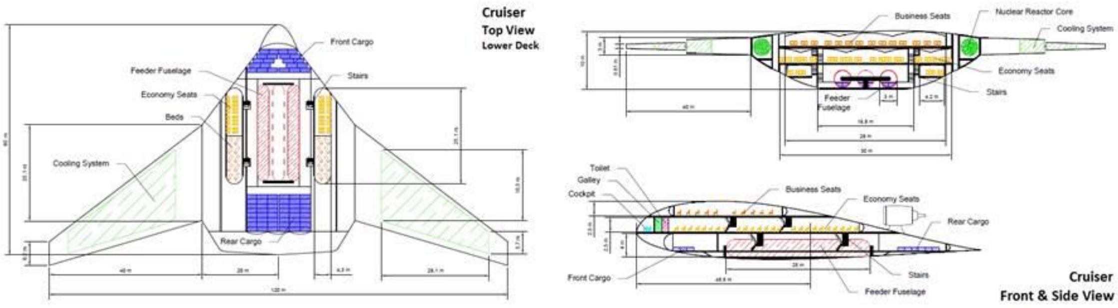
Safety analysis of cruiser-shuttle concept



- The nuclear propulsion concept is the result of a meeting between NRG, TU Delft and NLR, and is based on a number of assumptions about the future availability of certain technologies. The design choices made for must be taken into consideration for the final cruiser-shuttle concept.

24

Reactor containment

- Failure of the reactor containment would result in release of radioactive material into the environment.
- Materials and construction methods shall be developed such that the reactor containment can withstand a mid-air collision, crashes into water or terrain, and all aircraft failure conditions like engine rotor burst and explosive decompression.

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Cooling system

- Leaks within the pipes that contain the water that cools the reactor core could result in radioactive water mixing with the secondary fluid. Subsequent leaks within the pipes that contain the secondary fluid could result in radioactive secondary fluid entering the atmosphere.

- Materials and construction methods that allow leaks free pipes shall be developed

26

Cooling system

- In case of damage to the cooling system due to a mid-air collision, crashes into water or terrain, or aircraft failures conditions like engine rotor burst and explosive decompression or in case of cooling system components failures, the reactor core would not be cooled anymore, and a meltdown would occur even if the reactor has been shut down shortly before.

- A mechanism shall be developed that shuts down the reactor automatically after a mid-air collision or crash into water or terrain.

- After a mid-air collision or crash into water or terrain, it is likely that everything inside the containment is damaged. he containment shall be provided with crash resistant coolant pipes which allow water to flow through to cool all the damaged bits and pieces inside the containment. In case of a crash into the ocean, sea water will be used for cooling. In case of a crash into terrain externally supplied water will be used for cooling. In this case an emergency response team shall quickly arrive at the crash site.

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Cooling system

- In case of a cooling system failure, the reactor in its containment is jettisoned into the ocean and the sea water is used for cooling. A highly redundant cooling system design that can cope with aircraft failure conditions like engine rotor burst and explosive decompression shall result in a very low likelihood of having to jettison the reactor in its containment into the ocean.

- Valves shall be developed that automatically close the pipes of the reactor cooling system that go into and out of the containment, after a mid-air collision, or crash into water or terrain. This prevents radioactive water of the primary cooling system entering the environment after a mid-air collision, or crash into water or terrain.

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Very long duration flights

- The nuclear propelled cruiser will remain airborne for a very long time (e.g. 1000 hours).

- To ensure availability of the aircraft system functions during these very long duration flights, the reliability of the aircraft system components and/or the amount of redundancy must be increased.

- Assuming an aircraft system component failure rate of 10^{-4} per flight hour and an average flight duration of 10 hours of a conventional airliner, three redundant components are required to achieve a functional failure rate of 10^{-9} per flight hour: $(10^{-4} \times 10)^3 = 10^{-9}$.

- Assume the reliability of components can be increased by a factor 10. Then for a flight duration of 1000 hours of the nuclear propelled cruiser, 5 redundant components are required to achieve a functional failure rate of 10^{-9} per flight hour $(10^{-5} \times 1000)^5 = 10^{-10}$.

- The increased weight of the aircraft systems must be taken into account.

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Summary of safety analysis of cruiser-shuttle concept

- The nuclear propulsion of the cruiser is not sufficiently safe with current technology.
- Advanced materials that can withstand a high energy crash must be developed.
- Advanced materials and construction methods for leak free cooling systems must be developed.

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Certification

- For certification of a system, compliance with a certification basis, as agreed with the certification authorities, must be demonstrated.
- Specific certification approaches for air-to-air refueling as well as for nuclear propulsion have been worked out.

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Certification of air-to-air refuelling operations

- Identification of applicable regulations for current commercial air transport operations and military air-to-air refuelling
- Combined with identified hazards and proposed safety measures, they form the basis for the definition of proposed new or amended regulations for air-to-air refuelling operations
- Proposed means of compliance for air-to-air refueling operations of the receiver-tanker concept are described.

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Current airworthiness regulations

- ICAO Annex 8: Airworthiness of aircraft
- FAA Code of Federal Regulations, Title 14, part 25: Transport Category Airplanes
- EASA Certification Specifications 25: Large Aeroplanes
- EASA Certification Specifications: All Weather Operations

33

Current flight crew licensing regulations

- ICAO Annex 1: Personnel licensing
- EASA FCL:
  - Commercial Pilot Licence
  - Airline Transport Pilot License
  - Multi-crew Pilot License
  - Type rating
  - Instrument rating

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Current regulations – operations

- ICAO Annex 2 Rules of the air
- ICAO Annex 3 Meteorological Services for International Air Navigation
- ICAO Annex 6 Operation of aircraft
- ICAO Annex 10 Aeronautical telecommunications
- ICAO Annex 11 Air Traffic Services.
- EASA OPS

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Current military guidelines for air-to-air refuelling

- DoD MIL-HDBK 516B Airworthiness Certification Criteria
- DoD JSSG-2009 Air Vehicle Systems

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Proposed new or amended EASA CS-25, EASA OPS and EASA FCL regulations

- Taking into account the hazards identified and safety measures proposed in the safety analysis, as well as the the military guidelines, an evaluation of EASA CS-25, EASA OPS and EASA FCL regulations has been performed.

- Applicable and to be amended EASA CS-25, EASA OPS, EASA FCL regulations, as well as requirements for new regulations have been identified.

37

Proposed new or amended EASA CS-AWO regulations

- For the certification of air-to-air refueling system operation, an approach similar to the one used for automatic landing systems as specified by EASA CS-AWO (All Weather Operations) is proposed. Air to air refueling can be compared to automatic landing in the sense that in both cases an accurate and safe approach to a certain position is required.

- The CS-AWO regulations have been adapted for air-to-air refueling.

38

Proposed new or amended EASA CS-AWO Acceptable Means of Compliance

- In line with CS-AWO AMC's, the performance of the air-to-air refueling system may be demonstrated through simulations using a model of the air to air refueling system, with validation by flight tests.
- The CS-AWO AMC's have been adapted for air-to-air refueling.
- It should be noted that the required simulations match with the model of the air-to-air refueling system used in the safety analysis.

39

Required simulations

Normal operation

Demonstrate, if wind shear and turbulence levels < certain limits, in the absence of system failures, per approach and station keeping, that:

- The position and speed of the tanker relative to the cruiser, and the attitudes and angular movements of the cruiser and tanker remain within certain limits with a probability of 99.99%.
- The cruiser and tanker do not collide with a probability of at least $1 - 10^{-9}$.
- The boom connects successfully with a probability of 99.99% per approach and station keeping.
- The boom does not hit the cruiser outside the safe area around the receptacle and does not hit the safe area around the receptacle in such a way that boom structural failure occurs, with a probability of at least $1 - 10^{-9}$.
- The probability of a tanker or cruiser upset is $< 10^{-7}$ (assumed to be hazardous).
- The probability of a tanker all engine flame out due to cruiser engine hot gasses being ingested by tanker engines is $< 10^{-7}$ (assumed to hazardous).

40

Required simulations

Wind shear or turbulence encounter

Demonstrate, if wind shear or turbulence levels > certain limits, in the absence of system failures, per approach and station keeping, that:

- The wind shear or turbulence is detected, the boom is disconnected (if applicable), the boom is retracted (if applicable) and an abort is executed.
- The cruiser and tanker do not collide with a probability of at least $1 - 10^{-9}$.
- The boom does not hit the cruiser outside the safe area around the receptacle and does not hit the safe area around the receptacle in such a way that boom structural failure occurs, with a probability of at least $1 - 10^{-9}$.
- The probability of a tanker or cruiser upset is $< 10^{-7}$ (assumed to be hazardous).
- The probability of a tanker all engine flame out due to cruiser engine hot gasses being ingested by tanker engines is $< 10^{-7}$ (assumed to hazardous).

41

Required simulations

System failures

Demonstrate, for system failures that have impact on the position and speed of the tanker relative to the cruiser, the attitudes and angular movements of the cruiser and tanker, and for system failures that have impact on the position of the boom, for wind shear or turbulence levels < certain limits, that:

- The system failure is detected, the boom is disconnected (if applicable), the boom is retracted (if applicable) and an abort is executed.
- The cruiser and tanker do not collide with a probability of at least $1 - 10^{-9}$.
- The boom does not hit the cruiser outside the safe area around the receptacle and does not hit the safe area around the receptacle in such a way that boom structural failure occurs, with a probability of at least $1 - 10^{-9}$.
- The probability of a tanker or cruiser upset is $< 10^{-7}$ (assumed to be hazardous).
- The probability of a tanker all engine flame out due to cruiser engine hot gasses being ingested by tanker engines is $< 10^{-7}$ (assumed to hazardous).

42

Certification approach for nuclear propelled cruiser

- To verify the safe functioning of the nuclear propulsion concept, real world testing is considered too risky, as radioactivity may be released into the environment due to design, manufacturing or operator errors.

- Instead verification based on high fidelity simulation of all relevant characteristics is proposed. This assumes that sufficient computing power will be available in the future to perform these simulations, and that the simulation models can be validated with a very high level of confidence without having to perform risky real world testing.

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Future roadmap – flying prototype

- Current assessment: no safety showstoppers from a technical perspective. Further research required for full substantiation.
- For example by means of development of a flying prototype of representative air-to-air refuelling system using WP2 results as input.
- The prototype development would allow the establishment of a comprehensive set of proposed new and amended regulations and means of compliance.

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Future roadmap - ICAO

- ICAO must develop Standards anc Practices (SARP) for air-to-air refueling of commercial air transport aircraft, possibly using the set of proposed new and amended regulations from the prototype development process as input.
- ICAO Member States must implement the SARP's in their national regulations.

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Future roadmap - EASA

- EASA must consider the ICAO SARP's, possibly add further detail based on the proposed new and amended regulations and means of compliance from the prototype development process, and provide advice to the European Union for drafting new legislation.

- The European Union must introduce the new legislation for the EASA Member States.

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Future roadmap - EUROCAE

- Aircraft and equipment manufacturers must establish an EUROCAE and/or SAE 'air-to-air refuelling standards' working group with the objective to develop technical interface standards.

47

Future roadmap – Flights schools, ANSP's, airlines

- Flight schools must incorporate the air-to-air refuelling flight phase into their training program, according to the amended EASA FCL regulations.

- Air Navigation Service Providers must incorporate the air-to-air refuelling flight phase into their training program for Air Traffic Controllers.

- Airlines must show compliance with the new and amended EASA OPS regulations in order to obtain an Air Operator Certificate.

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The RECREATE project research receives funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 284741. This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.

Appendix C Final results of WP3

REsearch on a CRuiser Enabled Air Transport Environment

WP3

Benefits analysis of the cruiser-feeder concept

The research leading to these results has received funding from the European Union Seventh Framework Programme (*FP7/2007-2013*) under *grant agreement* n° 284741.
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Traffic Analysis

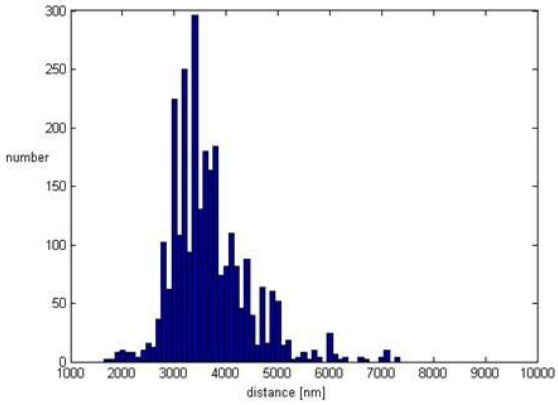
2

Method of Operation

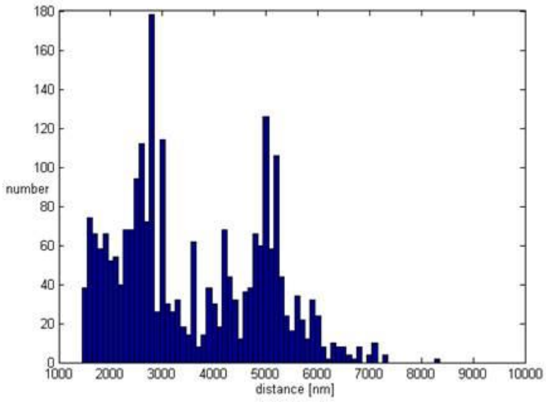
- Load Scenario Data
- Replace Aircraft
- Calculate Fuel Optimized Cruiser Routes
- Calculate Feeder Routes and Schedules
- Calculate Cruiser and Feeder Trajectories and Fuel consumption

Traffic Scenarios

- Transatlantic Scenario
  - 1388 flights (extended to 48 hours 2776 flight)

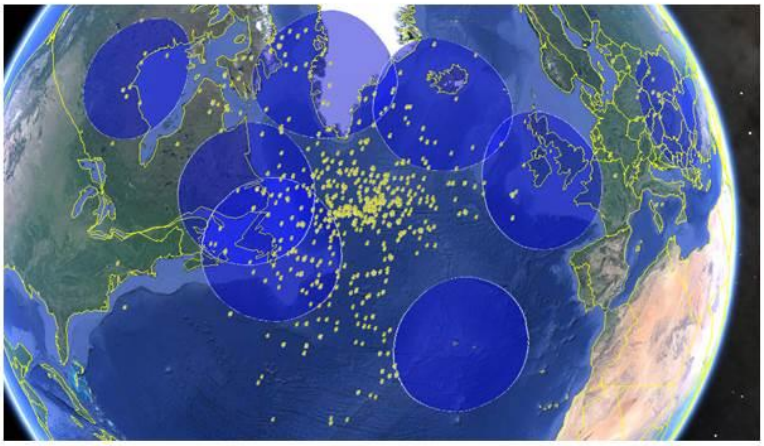


- Europe – Asia Scenario
  - 1387 flights (extended to 48 hours 2774 flight)

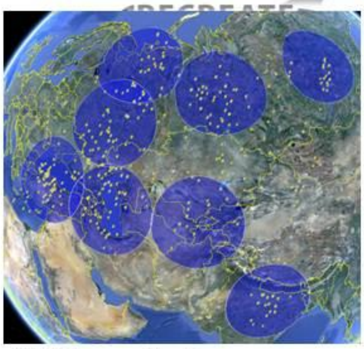


Feeder Base Selection

Depends on cruiser range:



2500 nm and 3000 nm Cruiser
(dots mark the optimal refueling position)



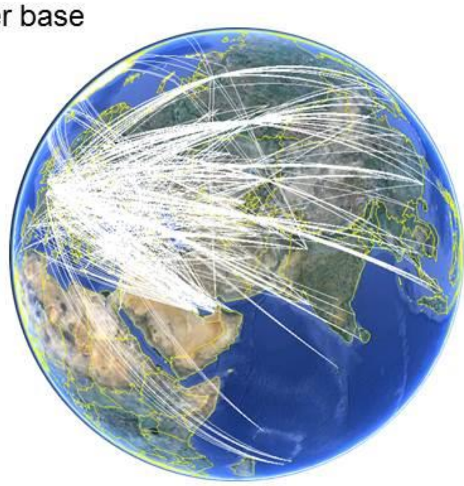
2500 nm Cruiser

3000 nm Cruiser

Cruiser Routing

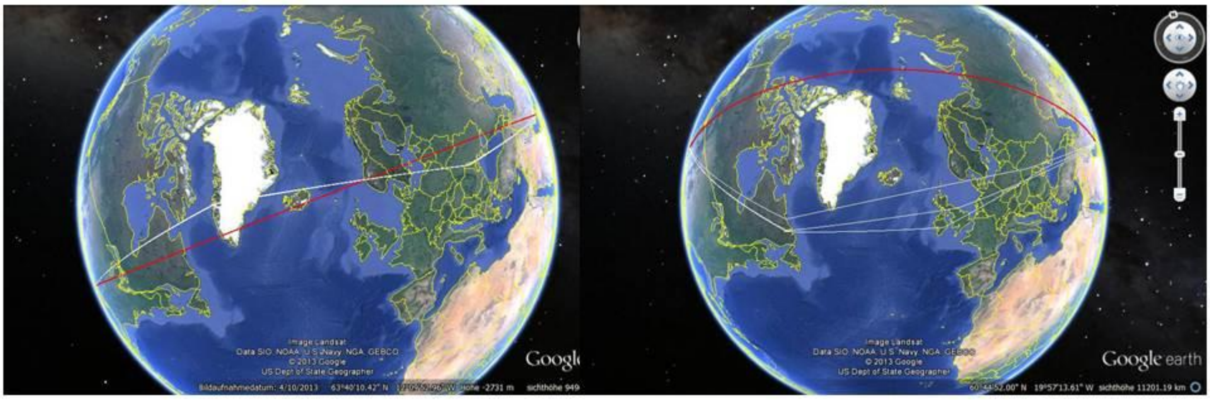
- Cruiser will fly fuel optimized routes
  - Most routes refueled close to the feeder base
  - Long detours possible
  - Multiple refueling operations possible

Transatlantic Scenario
3000nm Cruiser



Europe-Asia Scenario
3000nm Cruiser

Examples



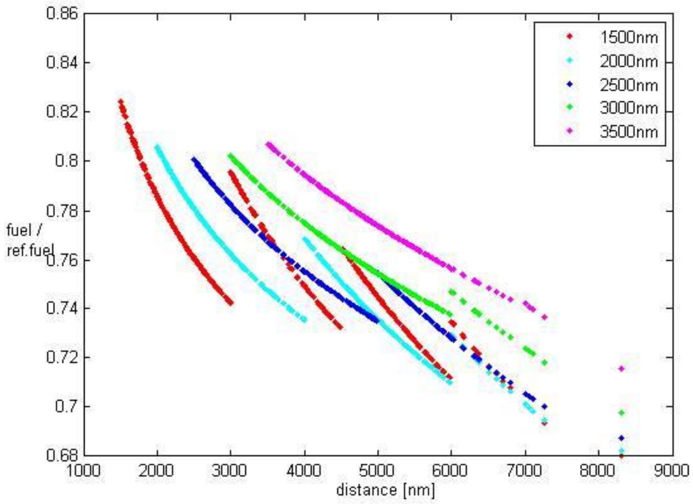
Highest fuel savings

Highest detour

Fuel Savings

Fuel savings with optimal Feeder and optimal Bases:

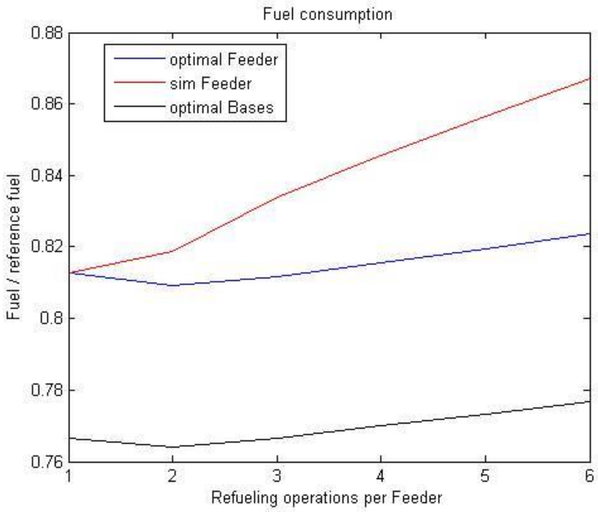
(6000nm reference Aircraft, optimal Feeder and Feeder Bases)



Fuel Savings

Fuel savings in Simulation:

(6000nm reference Aircraft)

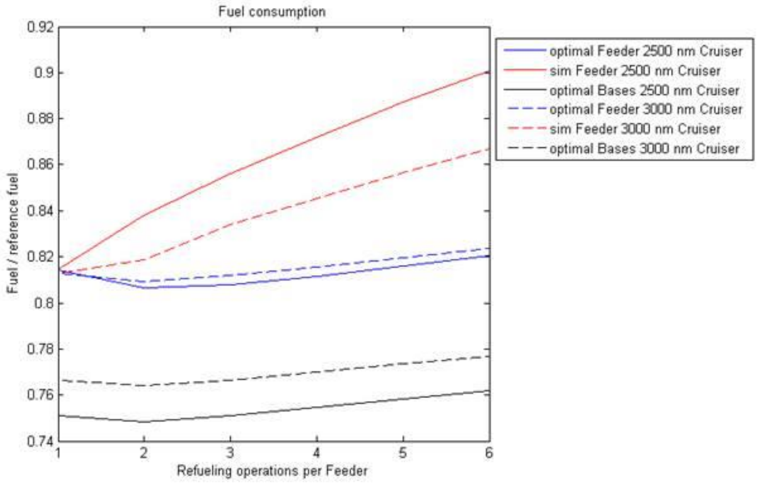


Transatlantic Scenario

Fuel Savings

Fuel savings in Simulation:

(6000nm reference Aircraft)

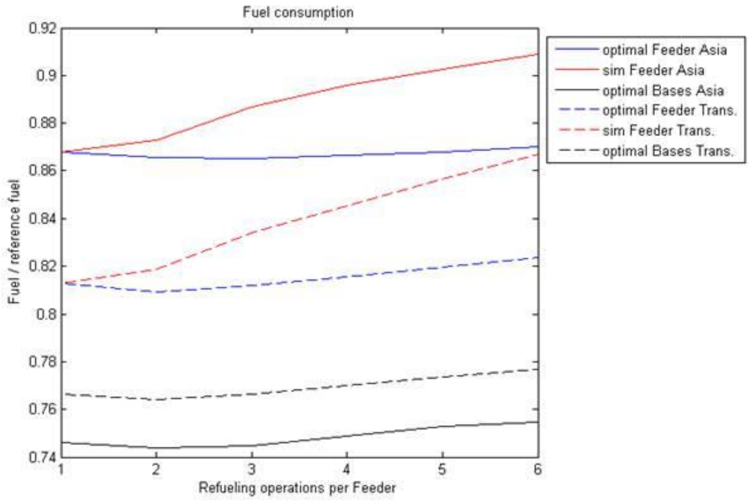


Transatlantic Scenario

Fuel Savings

Fuel savings in Simulation:

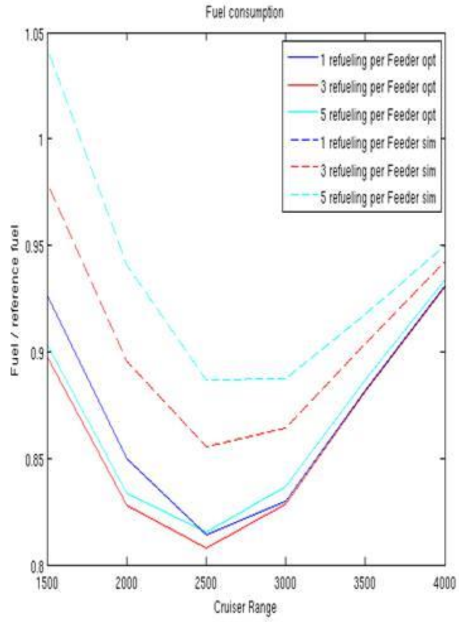
(6000nm reference Aircraft)

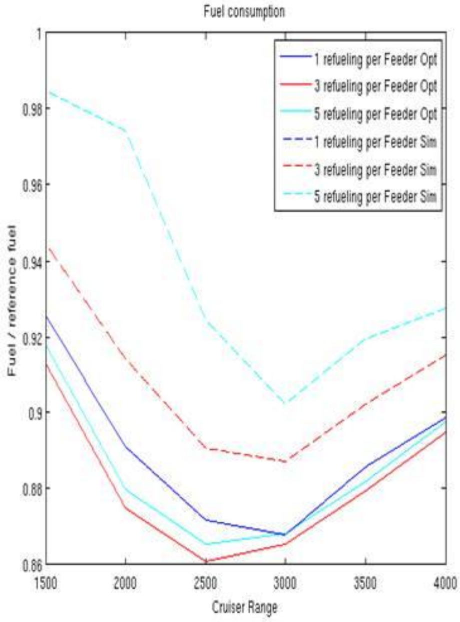


Europe-Asia Scenario

Fuel Savings

Fuel savings in Simulation with different Cruiser ranges



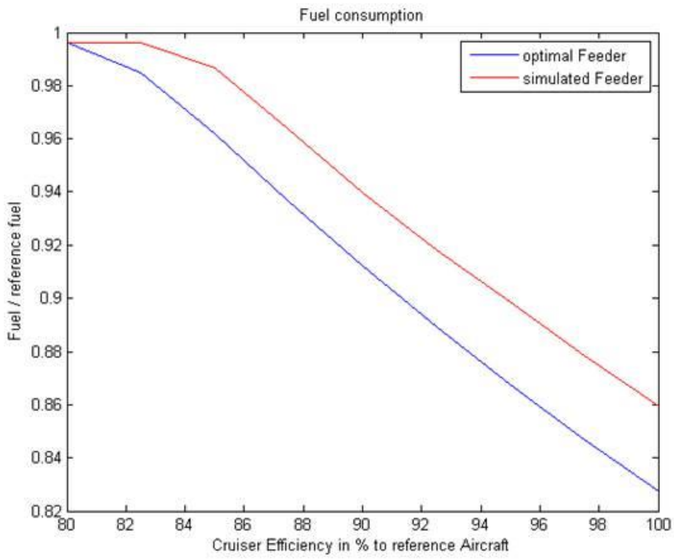


Fuel Savings

Fuel savings in Simulation with less efficient Cruiser:

(6000nm reference Aircraft)

- Cruiser is less efficier then the reference aircraft due a smaller wing area

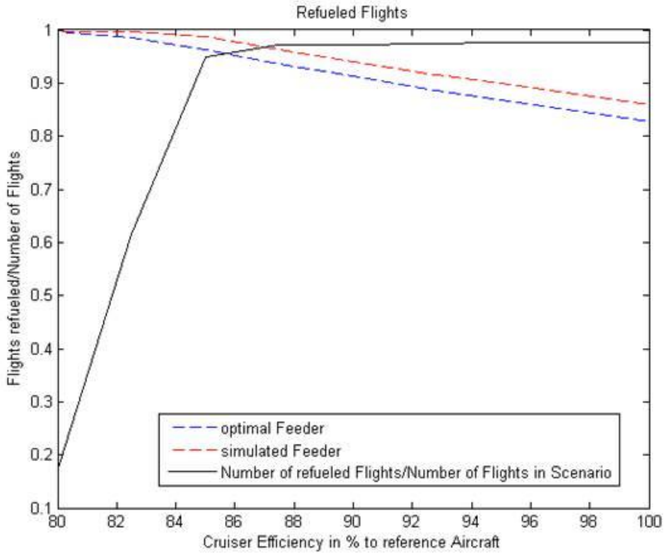


Transatlantic Scenario

Fuel Savings

Fuel savings in Simulation with less efficient Cruiser:

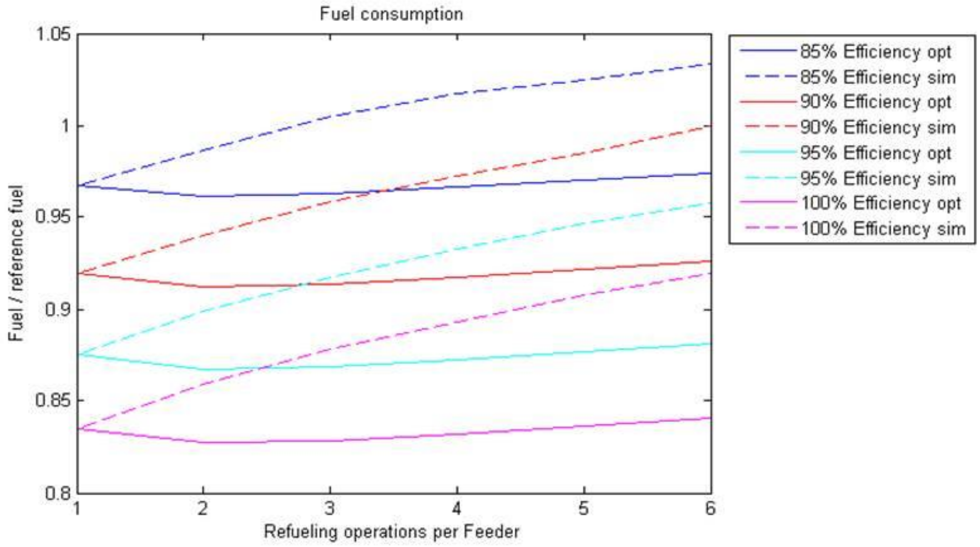
(6000nm reference Aircraft)



Transatlantic Scenario

Fuel Savings

Fuel savings in Simulation with less efficient Cruiser:
(6000nm reference Aircraft)

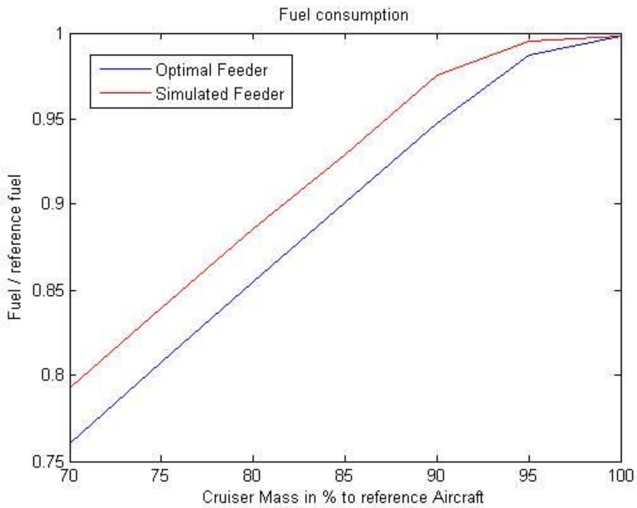


Transatlantic Scenario

Fuel Savings

Cruiser reference Aircraft mass ratio:

(6000nm reference Aircraft)

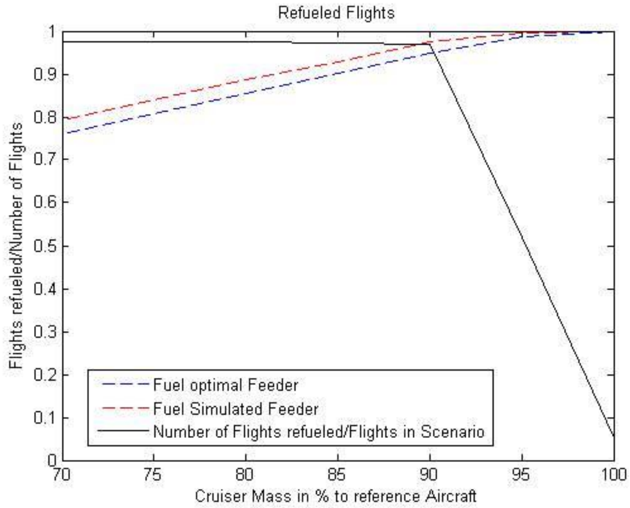


Transatlantic Scenario

Fuel Savings

Cruiser reference Aircraft mass ratio:

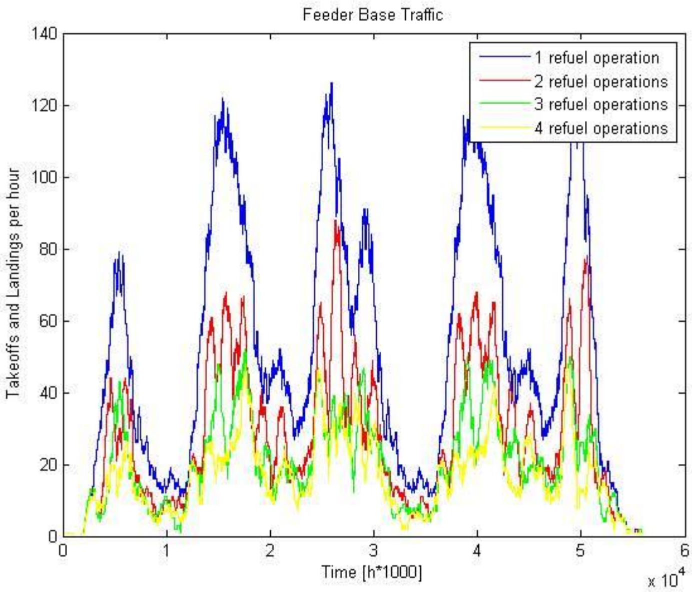
(6000nm reference Aircraft)



Transatlantic Scenario

Feeder Base traffic

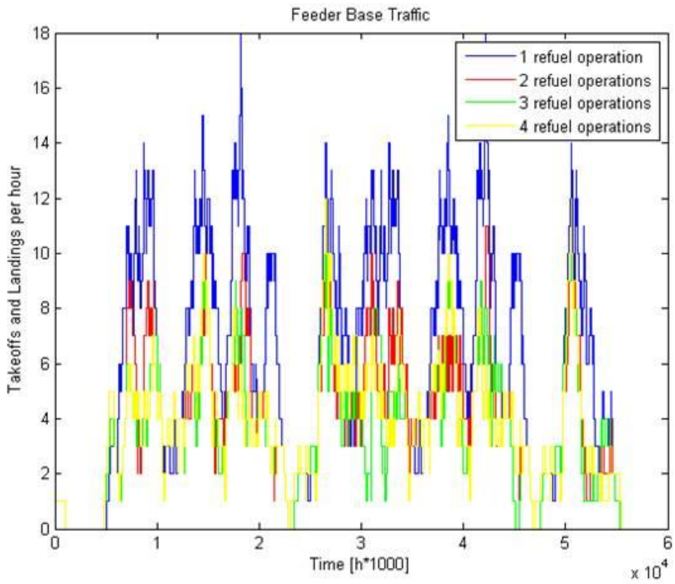
Feeder Base runway traffic varies with different Feeder sizes:



Number of Takeoffs and Landings per hour at Gander

Feeder Base traffic

Feeder Base runway traffic varies with different Feeder sizes:



Number of Takeoffs and Landings per hour at Kangerlussuaq

Disturbances

Effects of disturbances in the refueling Network:

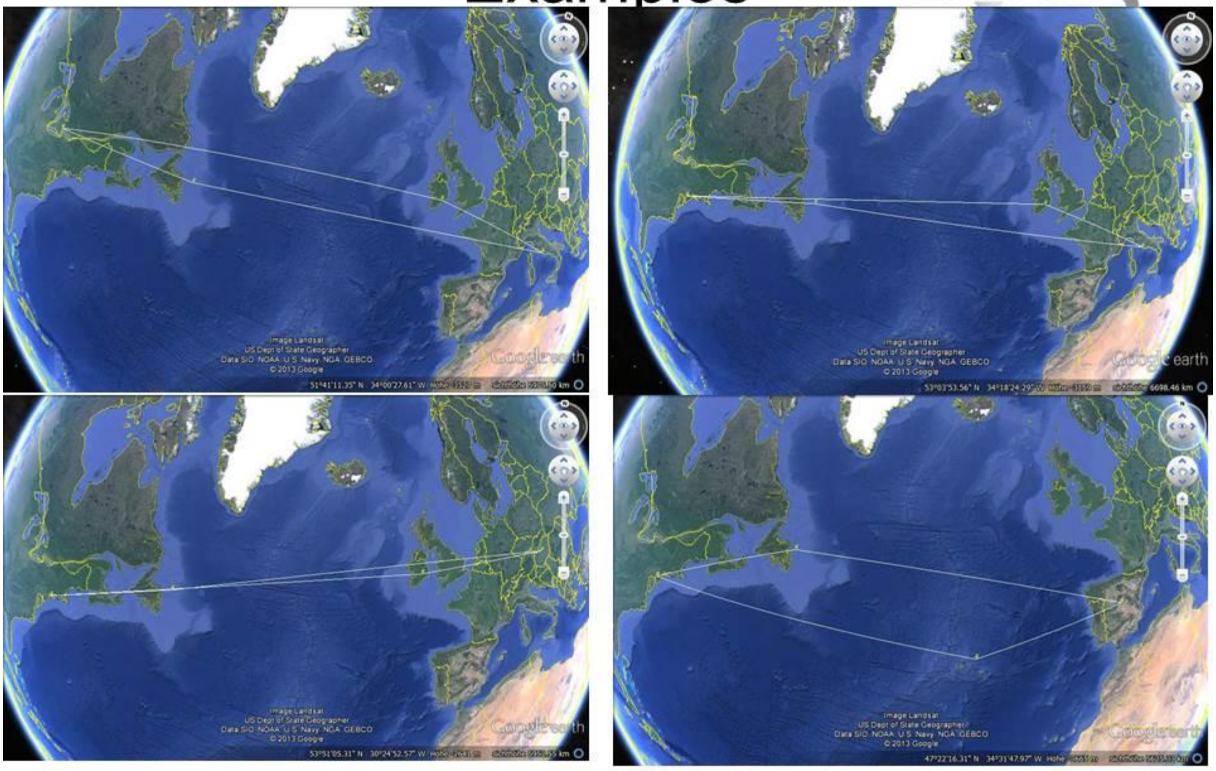
(Transatlantic Scenario with more realistic Cruiser)

- Delays on Cruiser and Feeder will delay the associated aircraft

- Cancelled Feeder will have to be covered by other feeder and will result in more delays
    - With enough time lead time Cruiser rerouting is possible
    - Without other feeder and enough time the Cruiser will have to land at an alternate airport

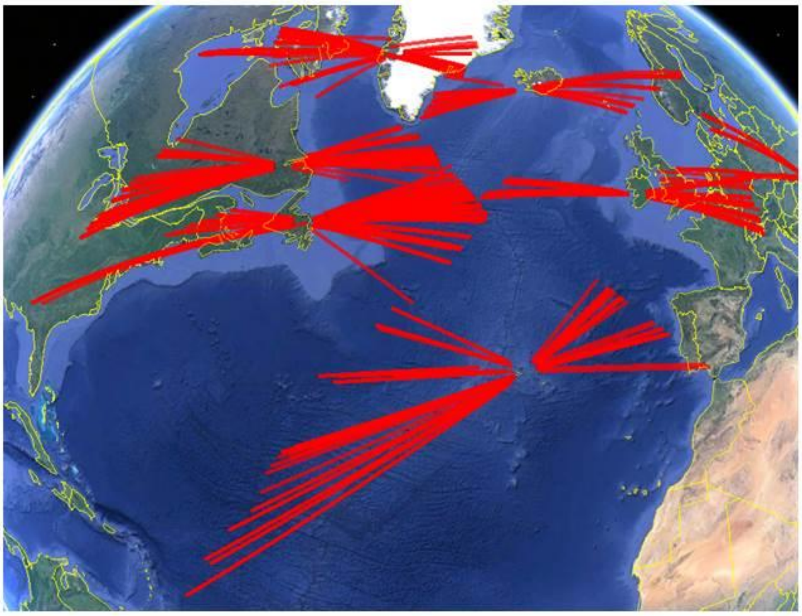
- Unavailable Feeder bases result in rerouting and alternate landings

Examples



Rerouting options

Parts of flight without enough lead time for rerouting:



Simulation Results

Simulation with feeder bases unavailable:

Feeder base unavailable between 15:00-18:00

1 Shannon

2 Keflavik

3 Kangerlussuaq

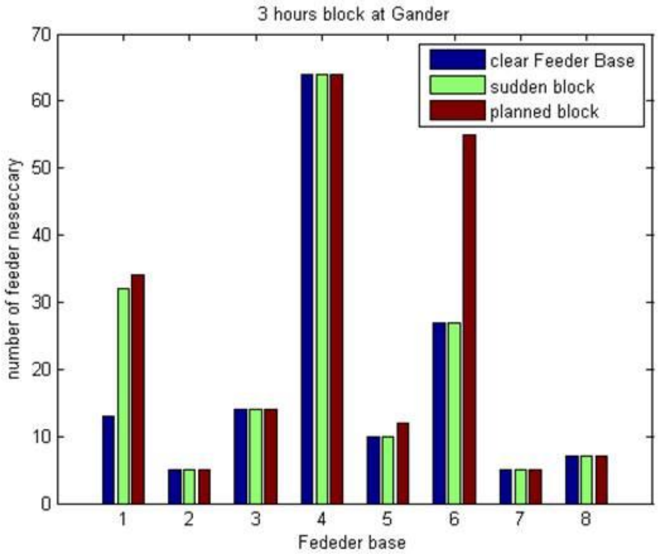
4 Gander

5 Lajes

6 Goose Bay

7 Chisinau

8 Churchill



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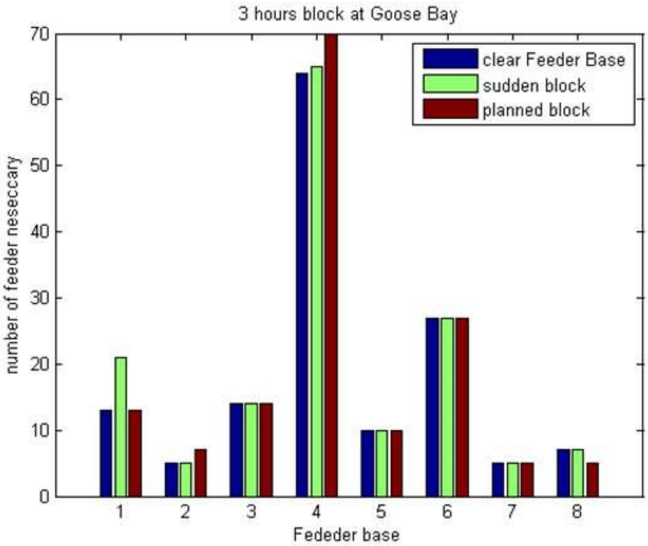

Simulation Results

Simulation with feeder bases unavailable:

Feeder base unavailable between 15:00-18:00

3 hours Block at	Rel. Fuel spend
Gander	100,01 %
Goose Bay	100,05%
Lajes	100,03%
Keflavik	100,00%

Sudden 3 hours Block at	Aborted flights
Gander	44
Goose Bay	12
Lajes	11
Keflavik	0

Conclusions

- Even more pessimistic approaches on the Cruiser design and the refueling system result in fuel savings

- Situation specific Cruiser and Feeder designs could improve the savings and the robustness of the system

- Several Feeder base of similar size would lead to a more robust system then a traffic concentration on one feeder base

- Spare feeders are needed to deal with disturbances but with a reasonable forecast alternate landings could be avoided

Economic Benefit Analysis

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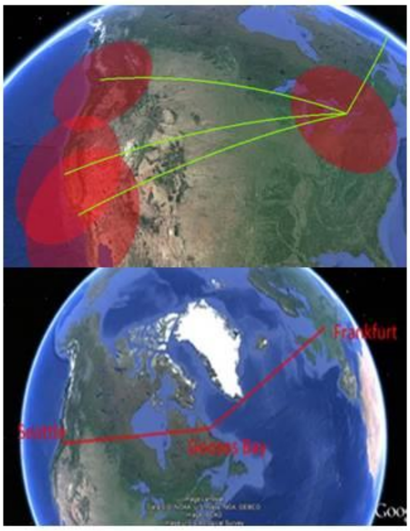
Purpose of the Economic Benefit Analysis

To highlight economic benefits achievable from the implementation of the cruiser-feeder concept when considered as part of a network



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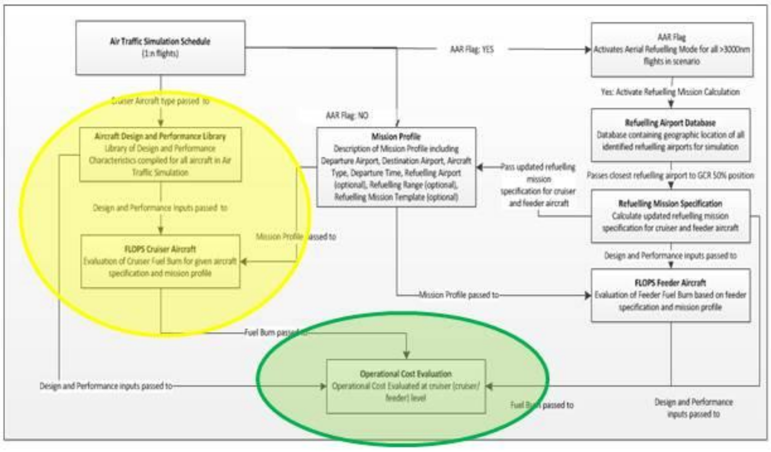
Quantification of Cost Benefits in a system-wide implementation

Trade Offs with Environmental Benefits

Identification of Major Cost Drivers within the system

Highlighting Cost Risks associated with the concept

Modelling the Cost Benefits of the Cruiser-Feeder Concept



$$\sum_{i=1}^{n}(C_{RDTE}+C_{MAN}+C_{PROFIT})+\sum_{i=1}^{n}\sum_{j=1}^{p}\int_{t_1}^{t_4} C_{OP}dt - Residual\,Value$$

Introduction of feeder operation requires changes to how operational cost is evaluated

Simulation environment developed to model flight mission operational costs.

Flight performance calculations undertaken using FLOPS for fuel burn estimate – routine modified to account for feeder exercise.

Operational cost module requires changes to account for feeder exercise

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Modelling the Cost Benefits of the Cruiser-Feeder Concept - Implications

$$\sum_{i=1}^{n}\sum_{j=1}^{p}\int_{t_1}^{t_4} C_{OP}\,dt$$

$$DoC = \sum_{i=1}^{n} DoC_{FLT} + DoC_{MAINT} + DoC_{DPR} + DoC_{LNR} + DoC_{FIN}$$

$$C_{POL} = \sum_{i=1}^{n}\left(C_{FGR} + \int_{t_1}^{t_2} C_{FCLI}\,dt + \int_{t_2}^{t_3} C_{FCR}\,dt + \int_{t_3}^{t_4} C_{FDES}\,dt\right)$$

$$\int_{t_2}^{t_{3a}} C_{F1}\,dt + \int_{t_{3a}}^{t_3} C_{F2}\,dt$$

Implication: if C_{F2} (the cost of fuel during a refuelling operation) is at a premium compared to C_{F1}, when $C_{F2} >> C_{F1}$, a longer diversion taking off at a heavier weight may be more cost effective.

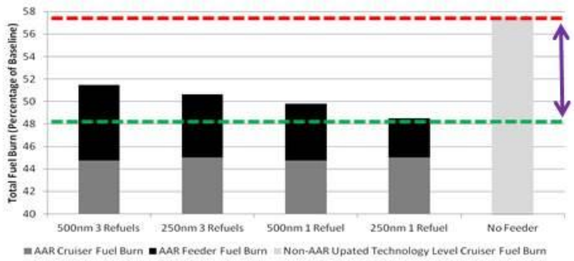
Fuel efficiency does not always equal cost savings 30

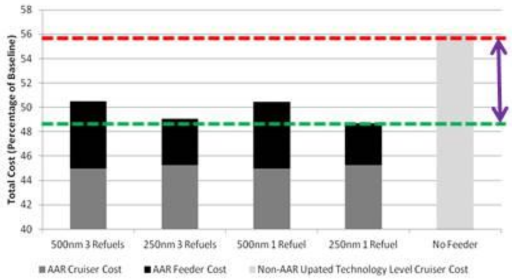
Comparison of Cruiser-Feeder versus Evolutionary Technology

	AAR Cruiser Aircraft	Non-AAR Cruiser Aircraft	Feeder Aircraft 3 Refuels	Feeder Aircraft 1 Refuel
Design Range (nm)	3000	6000	1000	1000
Operating Empty Weight (lb)	112337	154535	51818	19685
Payload	250 Passengers (1 Class)	250 Passengers (1 Class)	116317	38772
Maximum Take Off Weight (lb)	225288	357586	188282	65989
Design Fuel Delivered to Fuel Used Ratio	N/A	N/A	6.6	6.2

Three Configurations trialled:

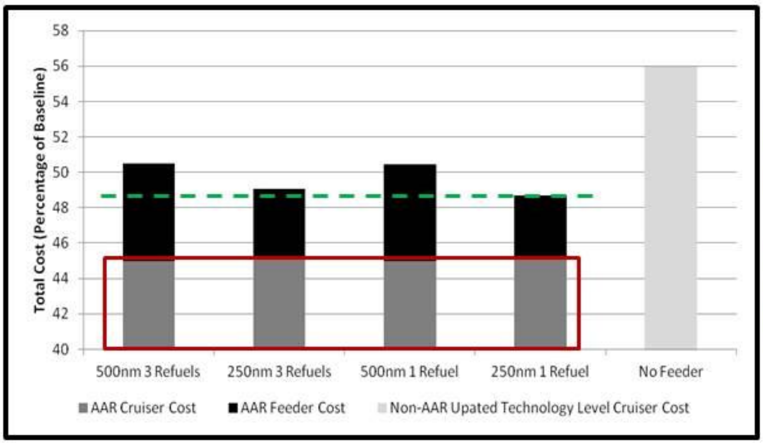
1. Cruiser-Feeder (single offload feeder concept)
2. Cruiser-Feeder (3 offloads feeder concept)
3. Direct Cruiser (no feeder, enhanced technology level)





Substantial reduction in both fuel burn and operational cost that can be attributed to the introduction of new technology into the system (43% fuel burn, 44% operational cost) Enhanced further by the introduction of the feeder operation (increment of 9% fuel burn maximum, 7% operating cost beyond technology level).

Comparison of Cruiser-Feeder versus Evolutionary Technology



For range of cruiser-feeder concepts the cost contribution is largely constant.

Major cost variations attributable to Feeder aircraft operational configuration.

250nm single refuel configuration is 'optimal' for baseline system due to cruiser schedule – optimal feeder usage would increase overall system cost benefits achievable.

However, there is an issue with system passenger capacity in this configuration.

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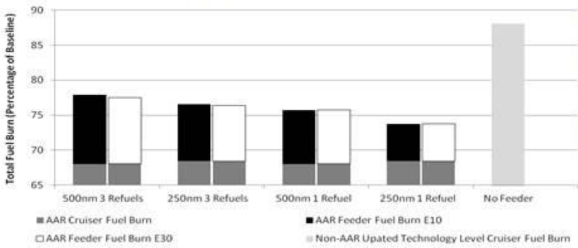
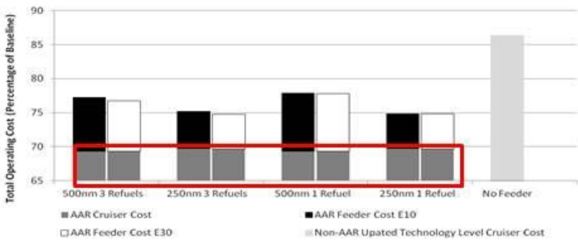
Impact of Maintaining Available Seat Miles

Direct replacement of aircraft has a significant impact on available seat miles Within the network, correlating with the profitability of the system (reduction of 30% in current simulation).

$$\sum_{j=1}^{\text{All flights}} \{(\text{Number of Seats of flight j}) * (\text{Distance flown of flight j})\}$$





401 additional flights required in order to achieve matching ASM in system.

6% spare capacity in system (unused)

Direct flight achieves 14% operating cost reduction

Maximum of 12% additional operating cost reduction with cruiser feeder

Again, influence of feeder concept evident as a dominant operational cost driver

Implications for Cost Benefits

1. In order to maximise benefits achievable from the system, it is necessary to reconfigure operations to an ideal feeder schedule.

2. By comparing the proposed cruiser-feeder configuration against a similar technology level direct cruiser configuration, operational cost reduction is in the order of an additional12%.

3. System profitability is a risk – direct transformation would reduce system capacity by 30%, and single class configuration introduces additional cost risk

4. It has been proposed that the cruiser-feeder could extend utilisation of regional airports - point to point operations.

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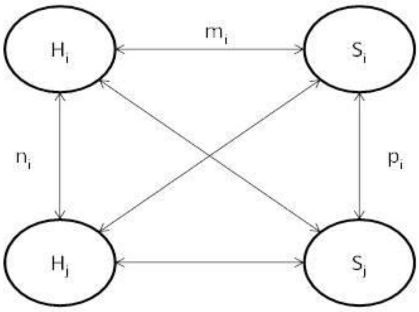
Sample Point to Point Network Study



$$n_{max} = \int_0^T \sum_{i,j=1}^{|N|} a_{ij} \left[\frac{d_{ij}}{C_{ij}}\right] dt \qquad \begin{cases} i \neq j \\ a_{ij} = 1 \; if \; a_{ij} \leq r_{ij} \\ a_{ij} = 0 \; if \; a_{ij} \geq r_{ij} \end{cases}$$

- Dij = route demand
- Cij = route capacity
- Aij = route length switch
- ij = route between two nodes

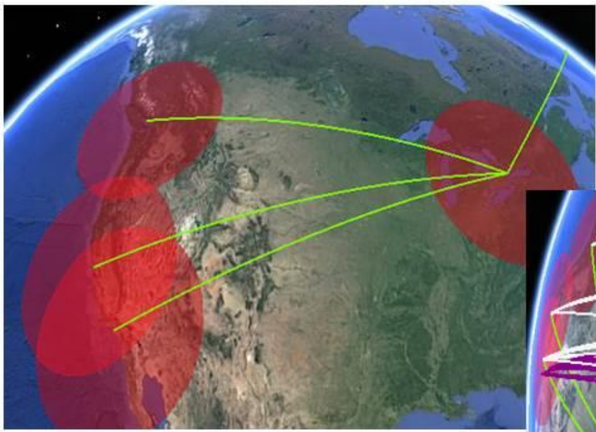
1. New network will have additional flights and therefore additional capacity.
2. ‘Unfeasible’ connections (ones with less than 20 pax) do not fly.

O-D Pairing Group	Percentage of Original Hub to Hub Passengers
Zone1 to Hub2	20%
Zone1 to Zone2	20%
Zone1 to Hub3	10%
Zone1 to Zone3	10%
Hub1 to Zone2	20%

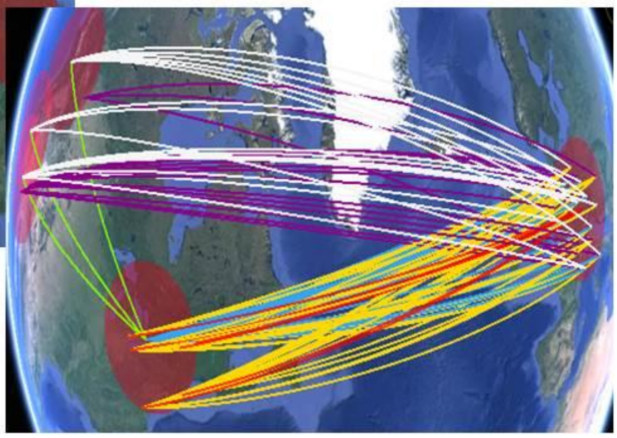
Redistribution rules established.

35

Example Decomposition



3 Hub to Hub Parings Identified



122 Point to Point Connections established

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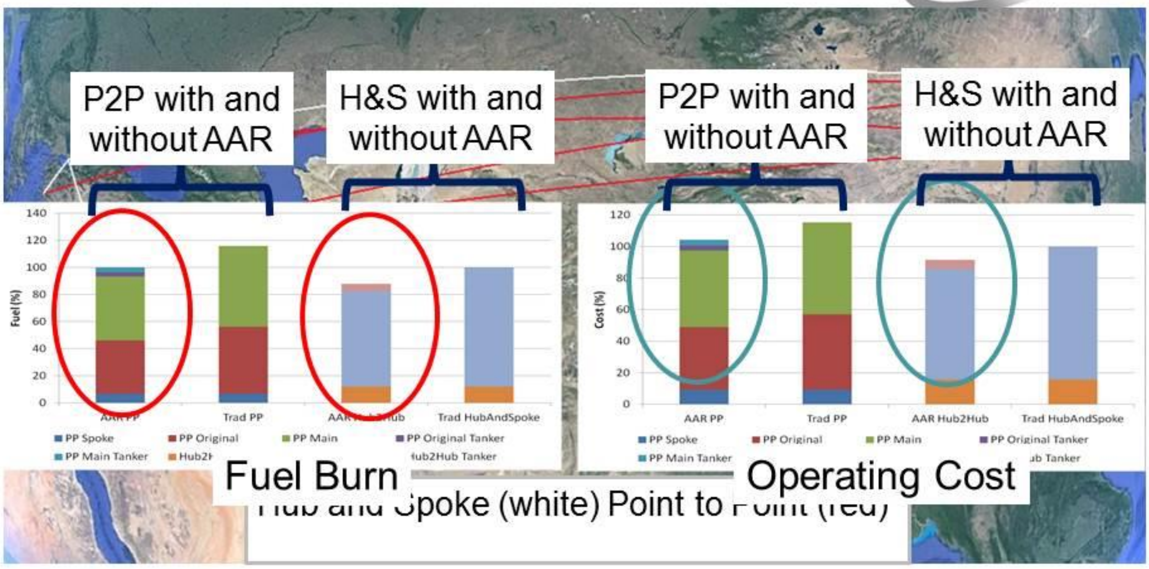
Small Network Study – Point to Point



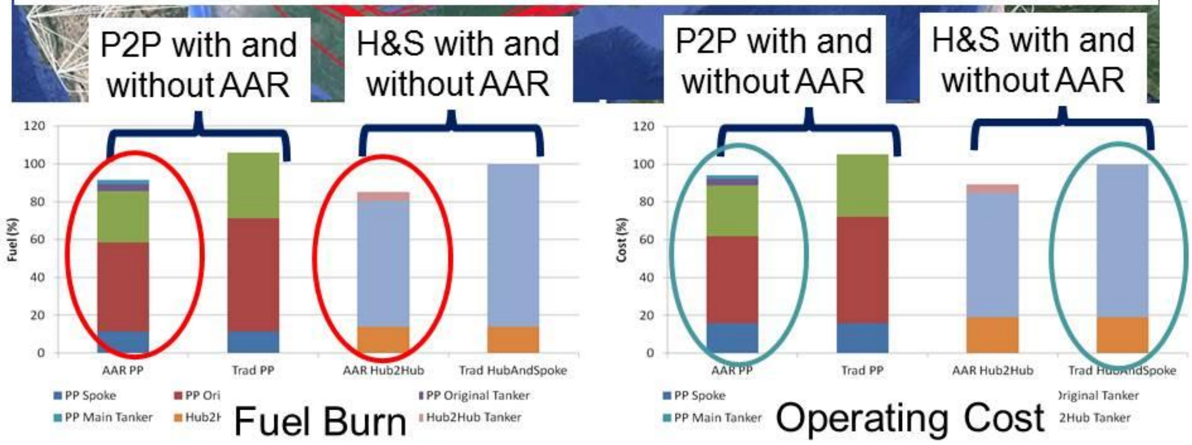
Both Hub and Spoke and Point to Point operations have reductions in fuel burn and operating cost if Aerial Refuelling is implemented

Point to Point increases ASM (~20%) without proportional increase in fuel/cost

Scalability of Results – Point to Point

As with smaller network study, the implementation of AAR reduces fuel burn for both H&S and PP networks

However increasing number of connections and range changes cost driver distribution, improving viability of AAR enhanced PP operations relative to 'traditional' hub and spoke



AAR Enabled System Benefits

- Upto14% fuel burn and 12% operating cost savings can be achieved when compared to a similar technology level aircraft concept without aerial refuelling, representing up to 26% in fuel burn and 25% in total operating cost over the existing operational model.

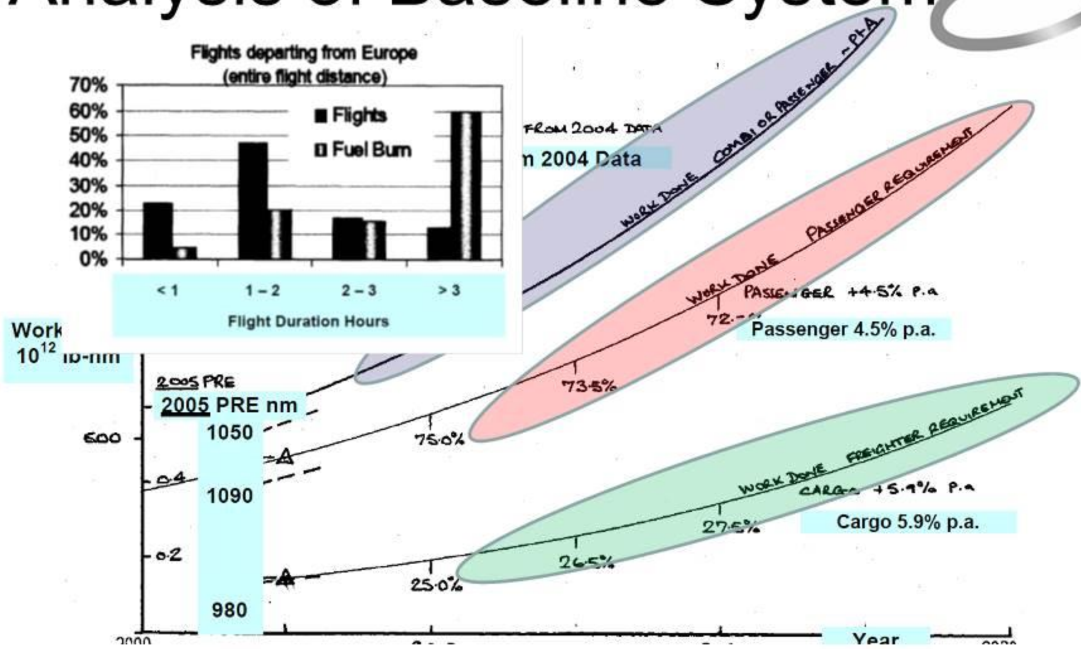
- Significant potential for increased Available Seat Miles in system without proportional increases in cost/fuel burn moving to point to point system.

39

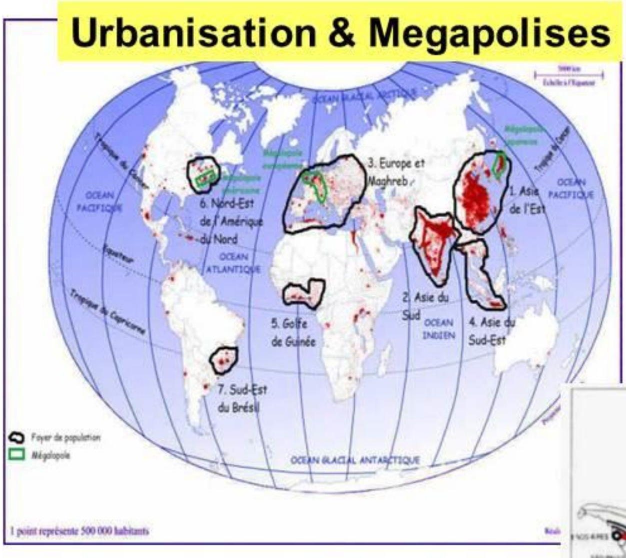
Overall Benefit Analysis

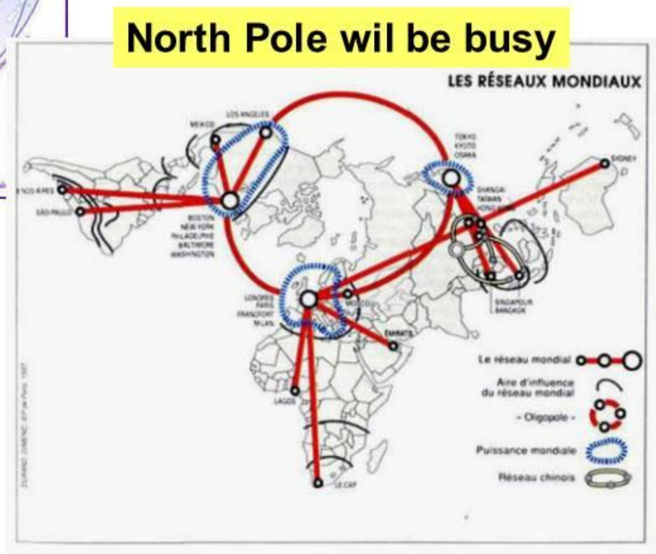
40

Analysis of Baseline System



For commercial traffic in Europe, flights greater than 3 hours represent 60% of fuel burn, although only 12% departures


Urbanisation & Megapolises
OCEAN GLACIAL ARCTIQUE
3. Europe et Maghreb
1. Asie de l'Est
6. Nord-Est de l'Amérique du Nord
OCEAN PACIFIQUE
OCEAN ATLANTIQUE
2. Asie du Sud
OCEAN INDIEN
4. Asie du Sud-Est
5. Golfe de Guinée
7. Sud-Est du Brésil
OCEAN GLACIAL ANTARCTIQUE
Foyer de population
Mégalopole
1 point représente 500 000 habitants


North Pole wil be busy
LES RÉSEAUX MONDIAUX
Le réseau mondial
Aire d'influence du réseau mondial
« Oligopole »
Puissance mondiale
Réseau chinois

Current Market Outlook 2013-2032 (Boeing)

Airplanes in service
2012 and 2032

Size	2012	2032
Large widebody	780	910
Medium widebody	1,520	3,610
Small widebody	2,310	5,410
Single aisle	13,040	29,130
Regional jets	2,660	2,180
Total	**20,310**	**41,240**

Demand by size
2013 to 2032

Size	New airplanes	Value ($B)
Large widebody	760	280
Medium widebody	3,300	1,090
Small widebody	4,530	1,100
Single aisle	24,670	2,290
Regional jets	2,020	80
Total	**35,280**	**4,840**

*$ values throughout the CMO are catalog prices.

Key indicators
2012 to 2032

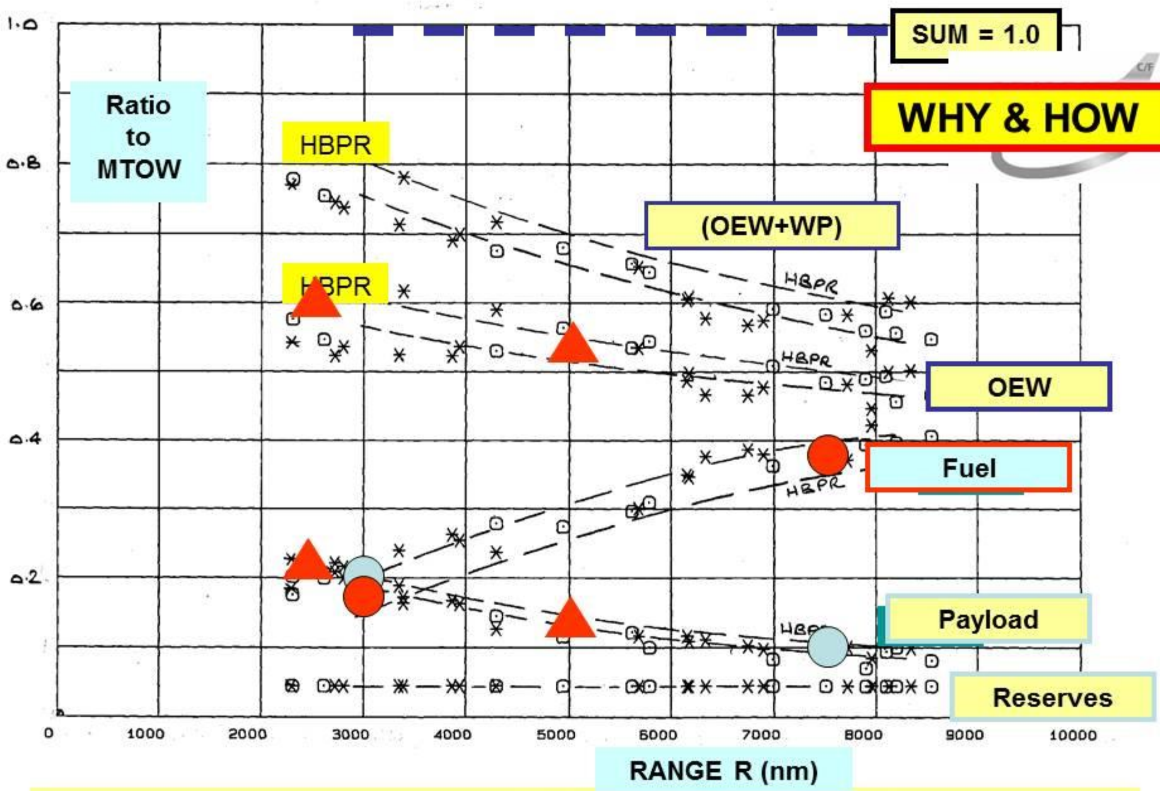
Growth measures	
World economy Gross domestic product (GDP)	3.2%
Airplane fleet	3.6%
Number of passengers	4.1%
Airline traffic Revenue passenger-kilometers (RPK)	5.0%
Cargo traffic Revenue tonne-kilometers (RTK)	5.0%

Demand by region
2013 to 2032

Region	New airplanes	Value ($B)
Asia Pacific	12,820	1,890
Europe	7,460	1,020
North America	7,250	810
Middle East	2,610	550
Latin America	2,900	300
CIS*	1,170	140
Africa	1,070	130
Total	**35,280**	**4,840**

*Commonwealth of Independent States.

Balance between Small, Medim & Large Wide-bodies
Changes with AAR



Pt D, OEW, FUEL & PAYLOAD RATIOS
Payload Ratio decreases, Fuel Ratio increases with Range, note 2500 & 5000 nm Values

Definitions for EFFICIENCY MOST IMPORTANT

WHY & HOW

Breguet Range Eqn

Range Parameter: X = V*L/D / SFC (nm)

Non-D Form Z = R/X = ln (W1/W2) ; WFB = W1-W2

Fuel Burnt per Payload: WFB/WP

Efficiency Parameters Payload*Range / Block-Fuel

Payload Range efficiency: PRE = WP*R/WFB (nm)

non-D Payload Range Efficiency PRE/X = WP/WFB*Z

2500 nm Cruiser

	TUD-1	TUD-2	TUD-3	DLR-1	DLR-2	Guide
MTOW kg	104614	115396	97412	125764	118614	108864
MTOW lb	230630	264400	214756	277257	261495	240000
WPD/WPA			0.8065		0.85	
WPDR			0.2720		0.2103	
WOER	0.55	0.54399	0.5128	0.61767	0.6123	
PRE, nm	2568	3166	4126	3219	3696	
WOER/(1-WOER)	1.2222	1.19293	1.0525	1.61554	1.5793	1.2-1.4
WP/WOE	0.37366	0.42215	0.5305	0.32114	0.3435	0.3
WP/WFB			0.8253	1.28932	1.4802	0.9-1.0
WFRR			0.0307		0.02894	
X nm			15322		16787	
R/X						
PRE/X						

Data Analyses TUD & DLR

Look for Assumptions & Inconsistencies

Absolute Predictions Vary

5000 nm Cruiser CASE 1

	TUD-1					
MTOW kg		163983	143004	168394	151315	
MTOW lb		361515	315270	371239	333587	
WPD/WPA			0.8065		0.85	
WPDR			0.1853		0.1649	
WOER		0.50891	0.4463	0.55985	0.5539	
PRE, nm		2844	3281	2783	3299	
WOER/(1-WOER)		1.0363	0.8060	1.27195	1.24164	1.0-1.2
WP/WOE			0.4152	0.25462	0.29765	0.24
WP/WFB			0.6563	0.57385	0.66962	0.45
WFRR			0.0860		0.0317	
X nm	11943	13493	16876		17632	
R/X			0.2963		0.27023	
PRE/X			0.1944		0.1785	

Ratios:

MTOW-2500/MTOW-5000	0.7041	0.6812	0.74184	0.78389
Weight saving	0.2959	0.3188	0.25816	0.21611
Del PRE	0.1132	0.2575	0.15666	0.12034

46

Fuel Reduction % over 5000 nm (from DLR)

Field Length 1500 m

refuelings		0	1	2
PRE/X		0.16740	0.21133	0.22366
X	nm	17068	16173	16059
PRE	nm	2857	3418	3592
			16.5%	20.5%

Field Length 2000 m (June 2013)

refuelings		0	1	2
PRE/X		0.16741	0.22334	0.24066
X	nm	17879	16866	16493
PRE	nm	2993	3767	3969
			20.5%	24.9%

Fuel Reduction % over 5000 nm (from TUD-3)

Field Length 2500 m June 2014

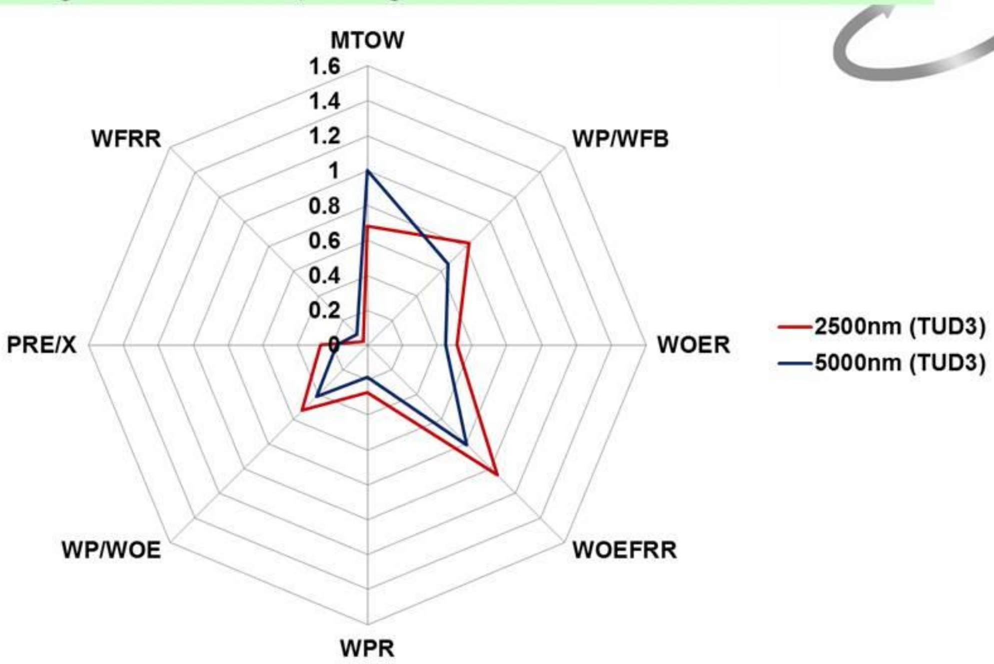
Refuels	0	1	
PRE/X	0.1944	0.2693	
X nm	16876	15322	
PRE nm	3281	4126	

25.7%

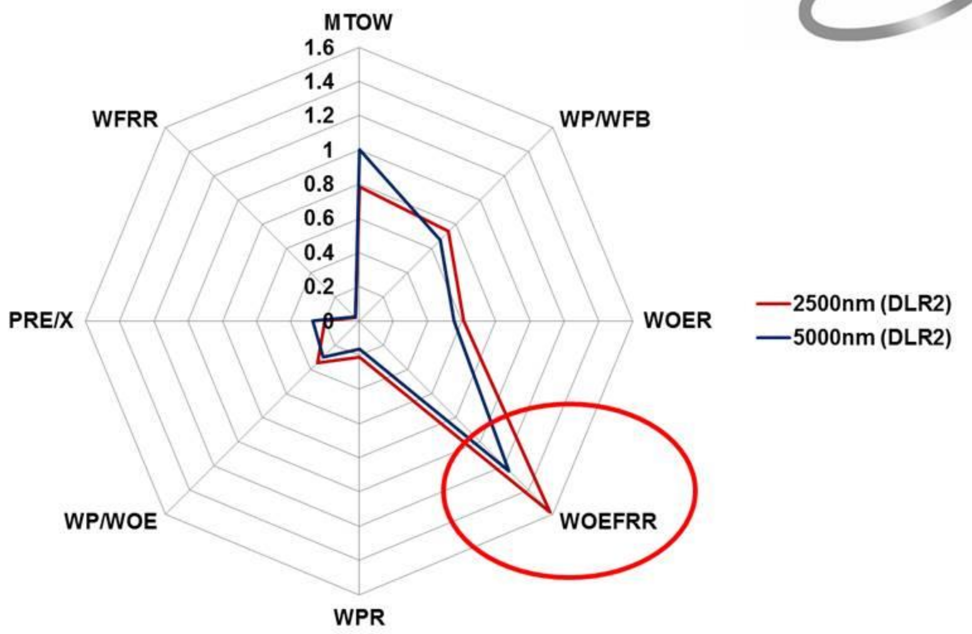
Refuels	0	1	
PRE/X	0.1770	0.2627	
X nm	17334	15464	
PRE nm	3068	4063	

32.4%

Weight ratio Comparing TUD-3, 2500nm & 5000nm

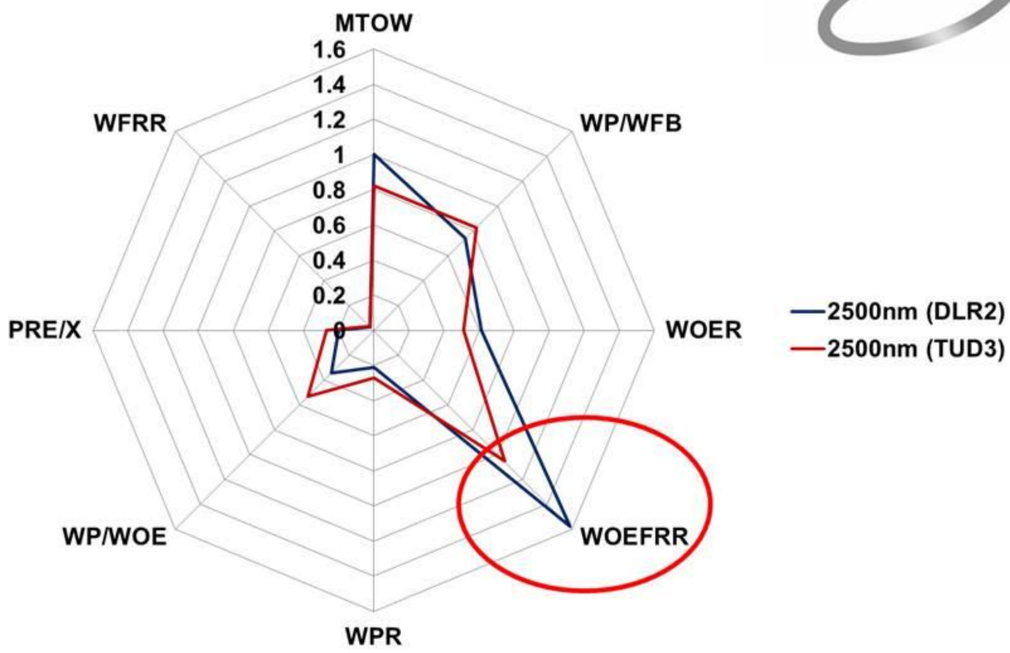


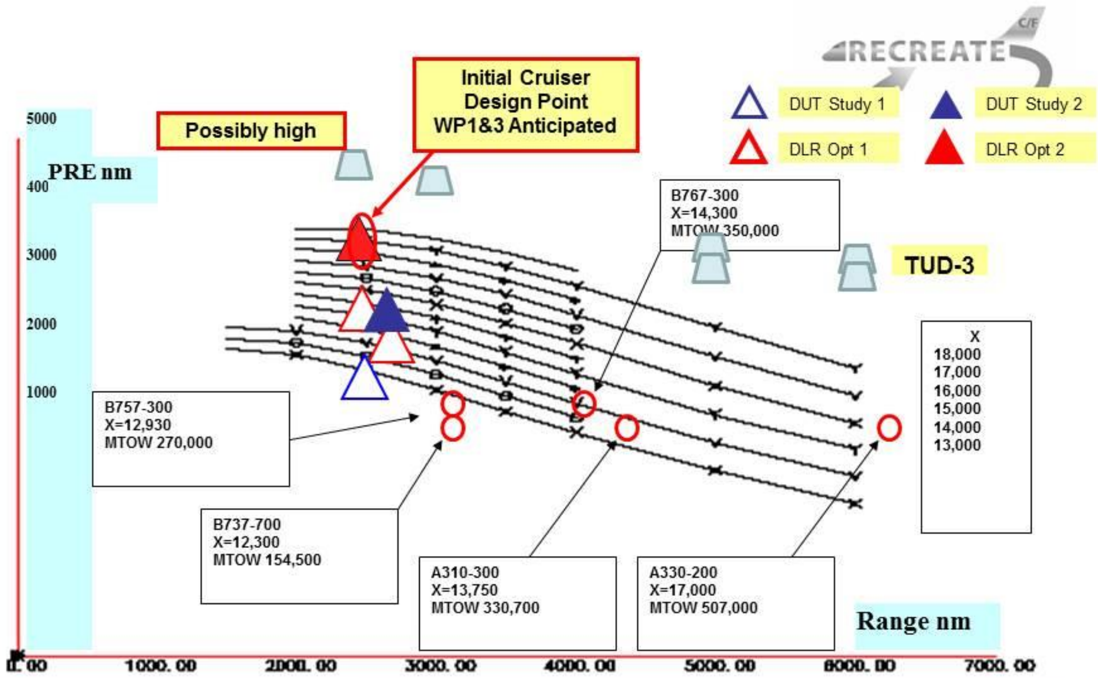
Spider, Comparing DLR-2, 2500nm & 5000nm



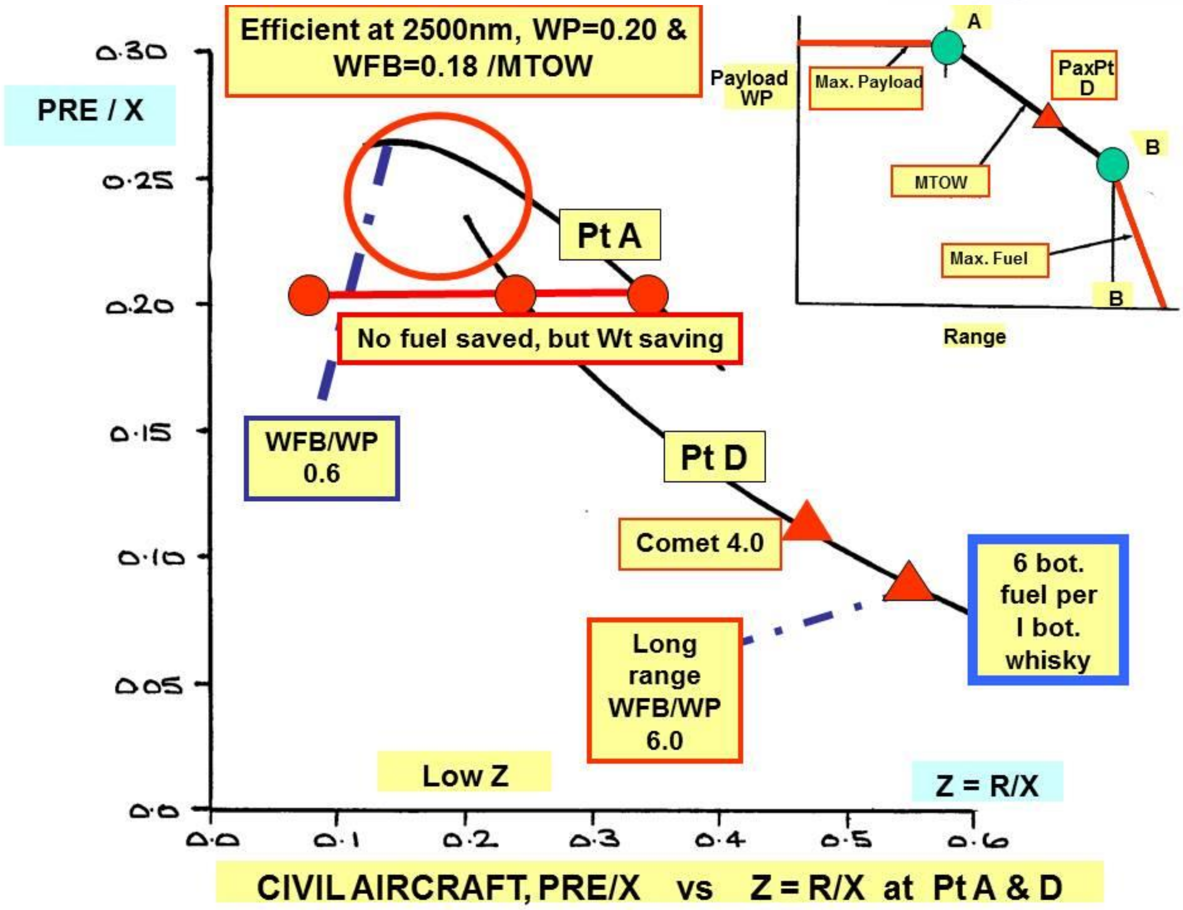
50

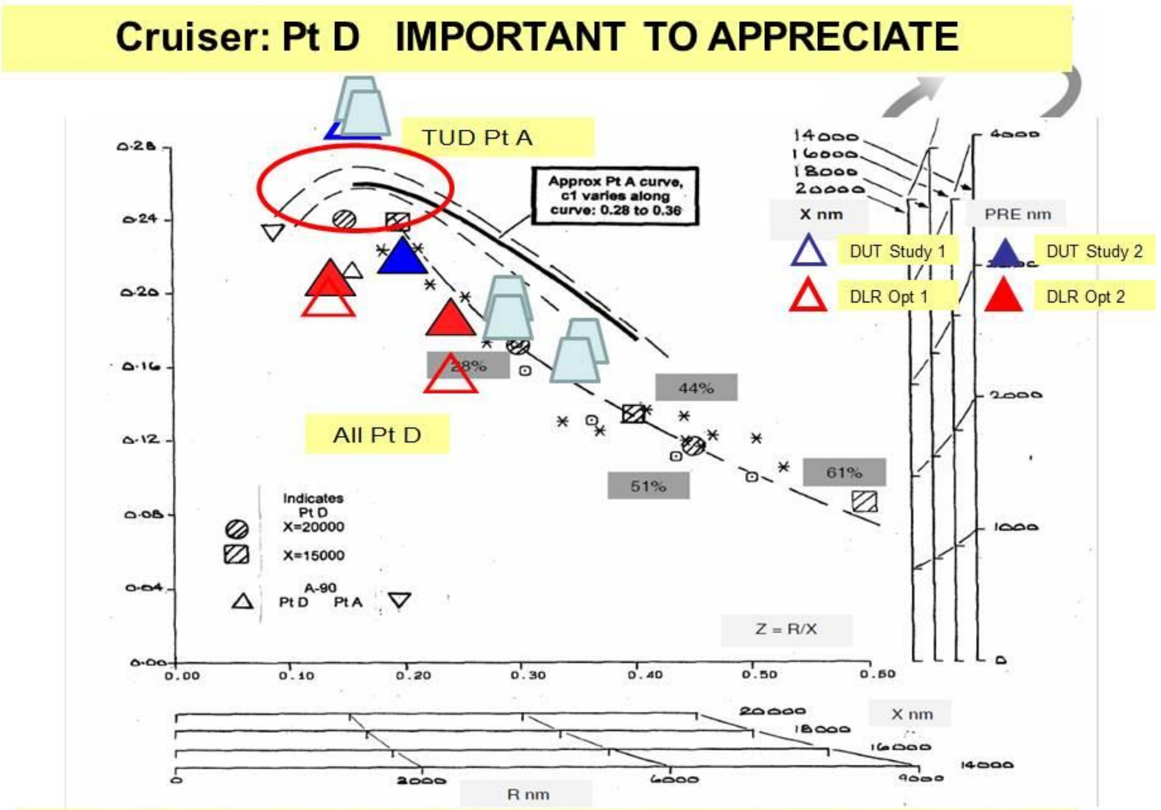
Spider, Comparing DUT-3 & DLR-2, 2500nm



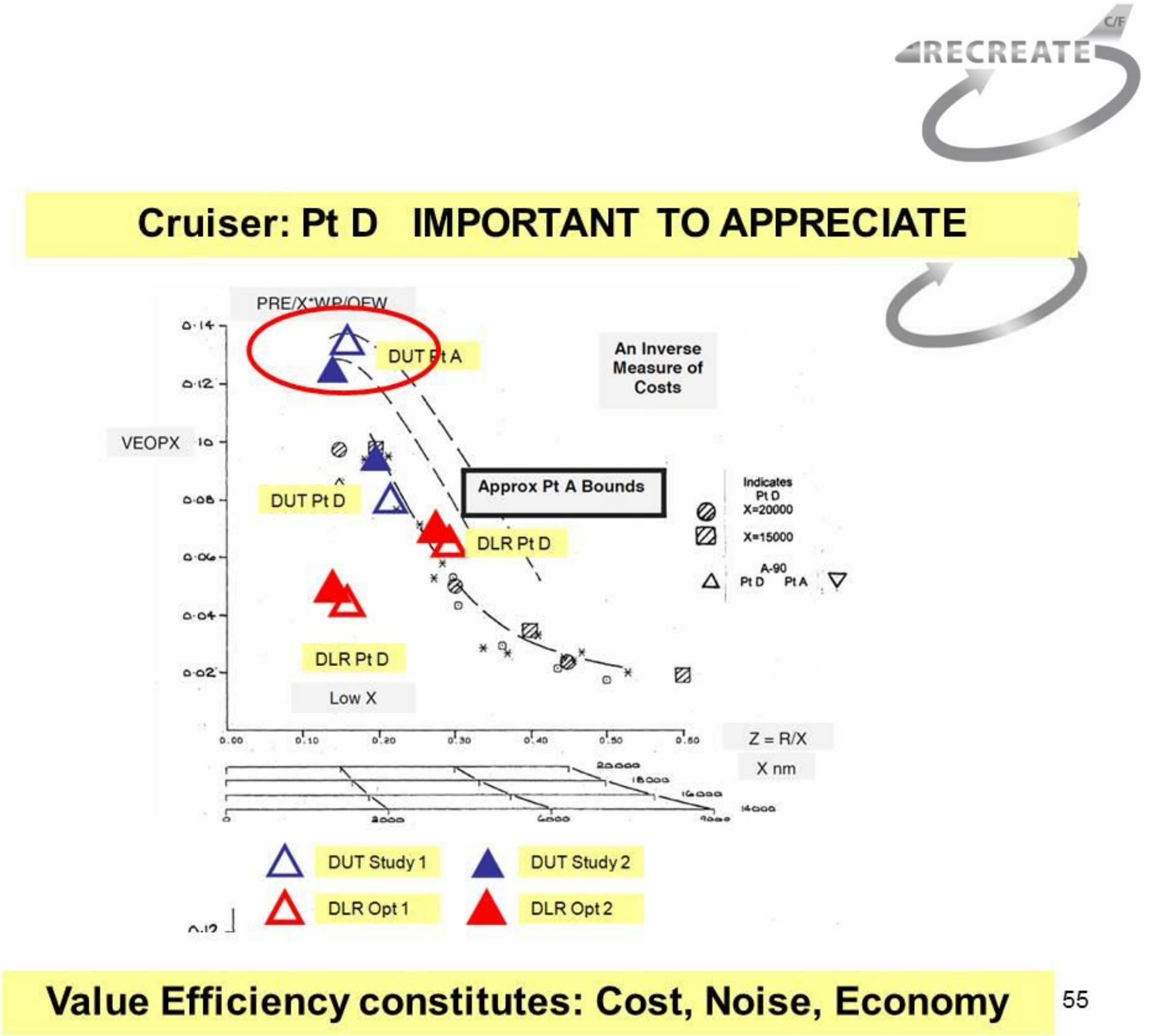


PRE (nm) v Design Range (nm)
Aircraft designed for 250 passengers, X from 13,000 to 18,500 nm
Ranges 1,500 - 6,000 nm, TUD & DLR – Some too high !!

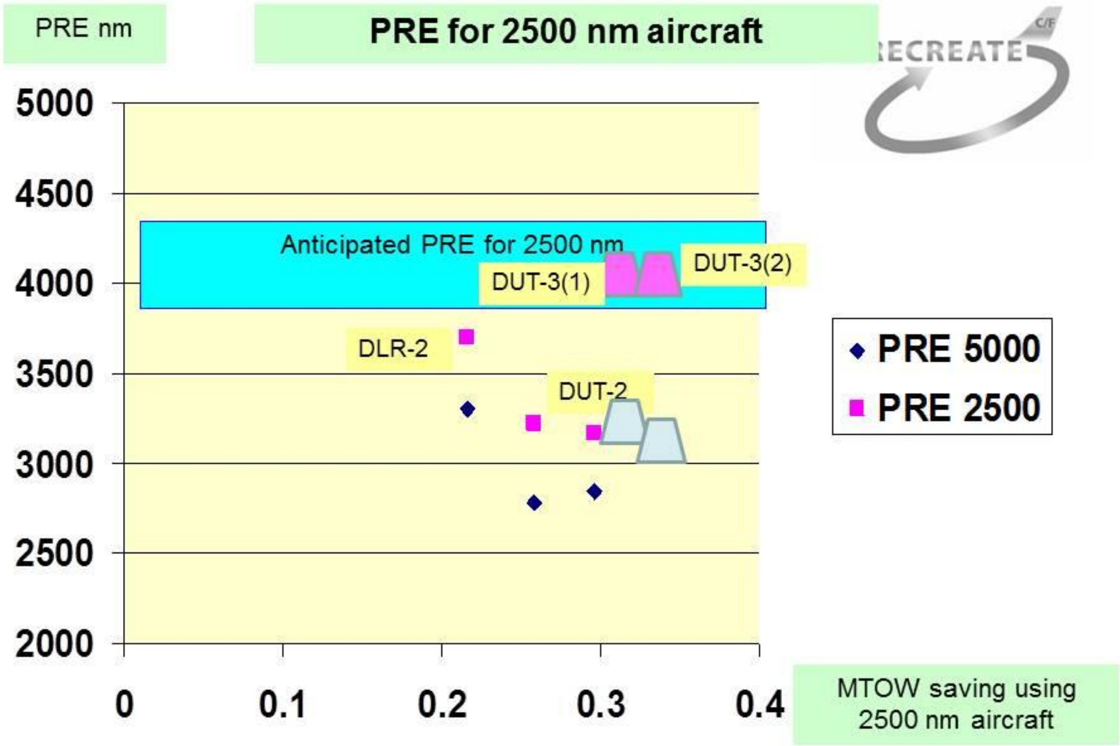

Efficient at 2500nm, WP=0.20 & WFB=0.18 /MTOW
PRE / X
0.30
0.25
0.20
0.15
0.10
0.05
0.0
Pt A
No fuel saved, but Wt saving
WFB/WP 0.6
Pt D
Comet 4.0
6 bot. fuel per I bot. whisky
Long range WFB/WP 6.0
Low Z
Z = R/X
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Payload WP
Max. Payload
A
PaxPt D
MTOW
B
Max. Fuel
B
Range
CIVIL AIRCRAFT, PRE/X vs Z = R/X at Pt A & D

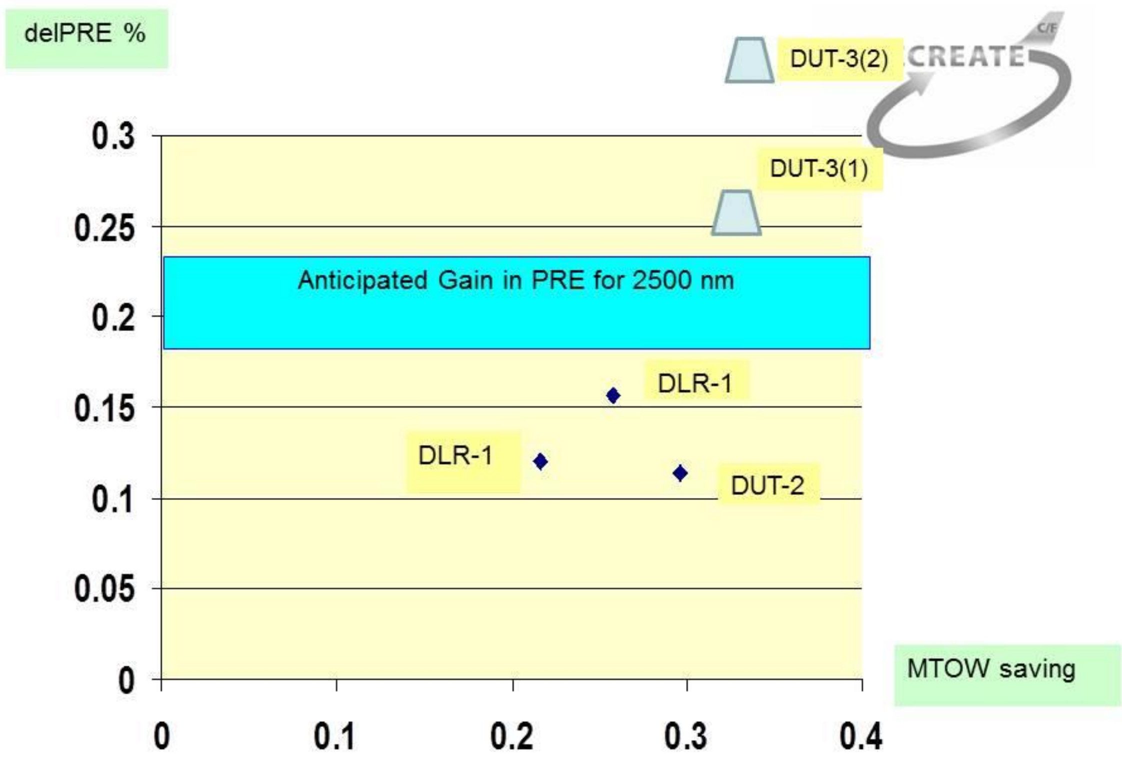


Fig, 3.5 PRE/X ~ Z variation. Note Parallel scales of R & PRE for different X

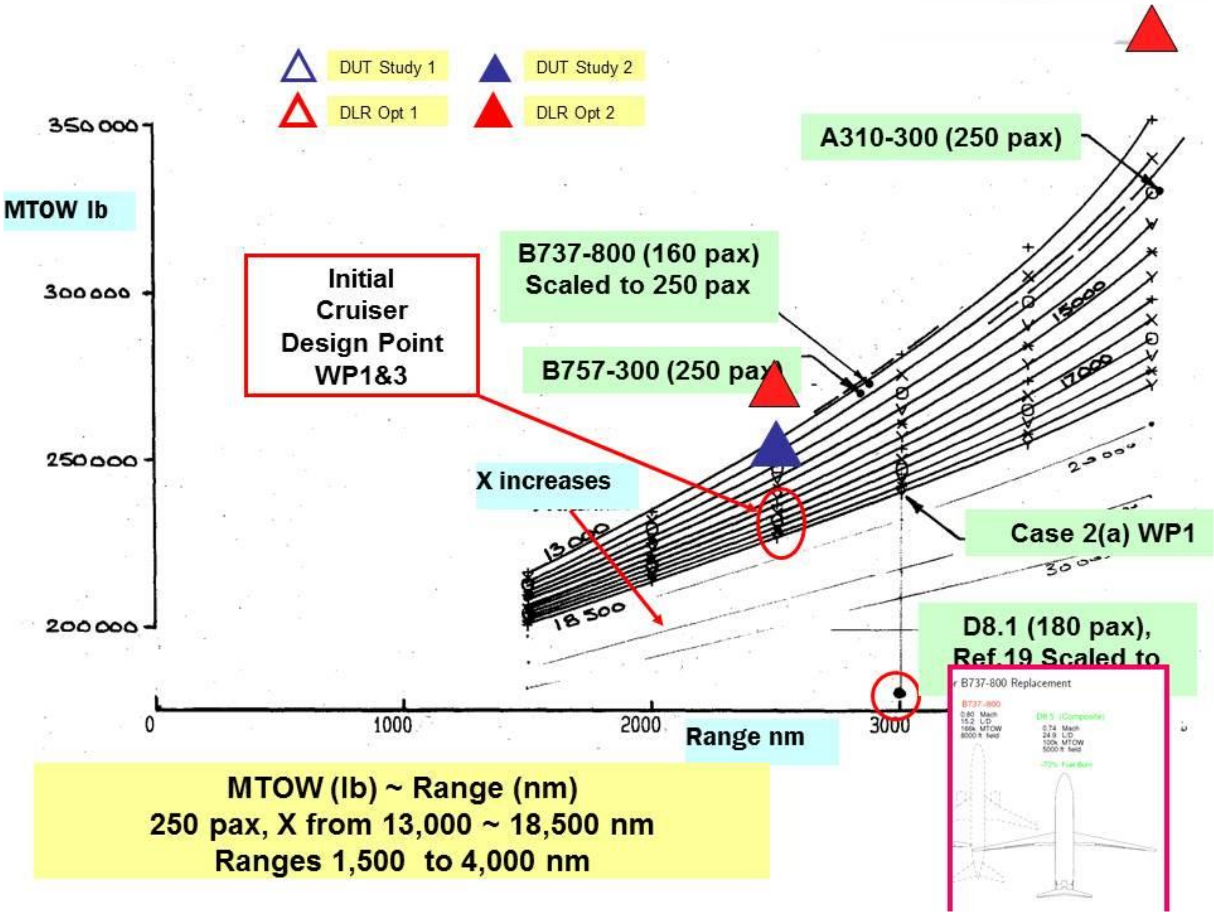


Cruiser: Pt D IMPORTANT TO APPRECIATE
PRE/X*WP/OEW
DUT Pt A
An Inverse Measure of Costs
VEOPX
DUT Pt D
Approx Pt A Bounds
Indicates Pt D X=20000
X=15000
A-90
Pt D Pt A
DLR Pt D
DLR Pt D
Low X
Z = R/X
X nm
DUT Study 1
DUT Study 2
DLR Opt 1
DLR Opt 2
Value Efficiency constitutes: Cost, Noise, Economy
55


PRE nm
PRE for 2500 nm aircraft
5000
4500
4000
3500
3000
2500
2000
Anticipated PRE for 2500 nm
DUT-3(1)
DUT-3(2)
DLR-2
DUT-2
PRE 5000
PRE 2500
0
0.1
0.2
0.3
0.4
MTOW saving using 2500 nm aircraft

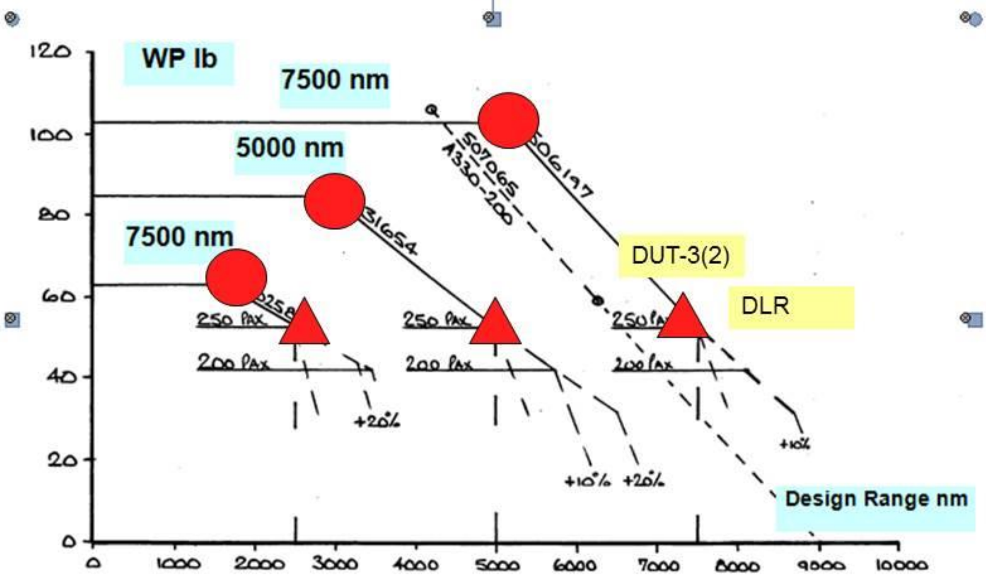


del PRE gain ~ del MTOW saving. Points from DUT & DLR studies



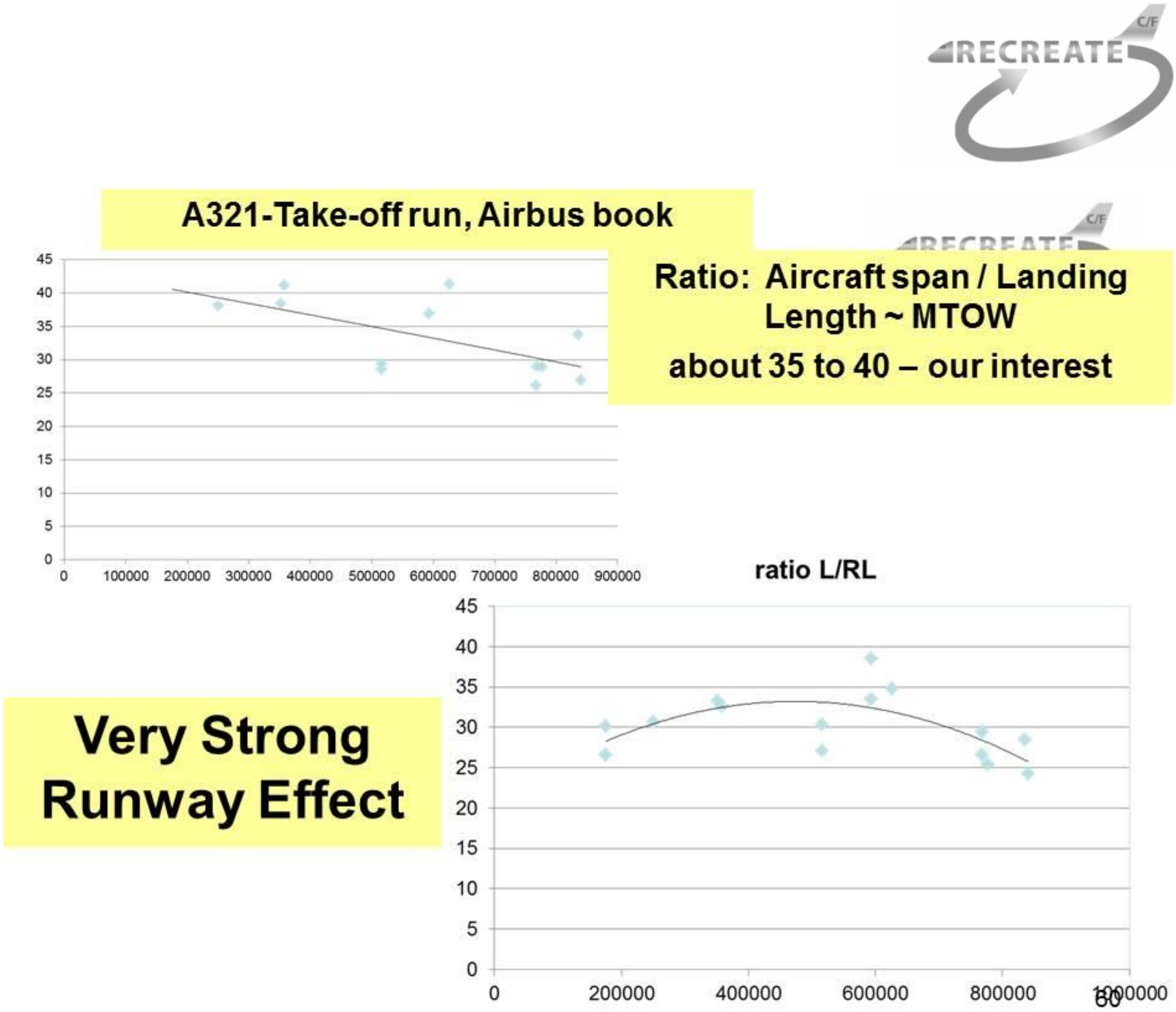
DUT Study 1
DUT Study 2
DLR Opt 1
DLR Opt 2
350 000
300 000
250 000
200 000
MTOW lb
A310-300 (250 pax)
B737-800 (160 pax)
Scaled to 250 pax
Initial
Cruiser
Design Point
WP1&3
B757-300 (250 pax)
X increases
Case 2(a) WP1
D8.1 (180 pax),
Ref.19 Scaled to
13000
15000
17000
18500
0
1000
2000
3000
Range nm
MTOW (lb) ~ Range (nm)
250 pax, X from 13,000 ~ 18,500 nm
Ranges 1,500 to 4,000 nm

Baselines: Payload – Range, 2500, 5000 & 7500 nm Aircraft

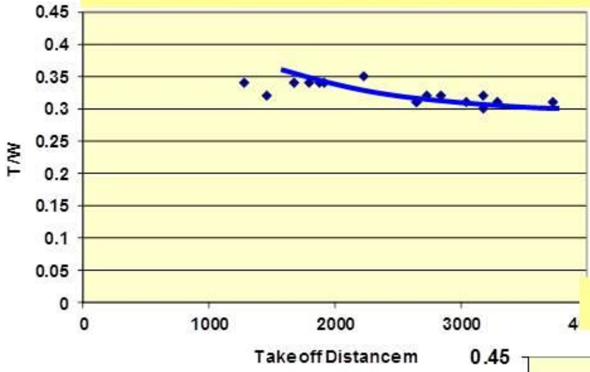


Future: other Payloads & Range Combinations Needed

59

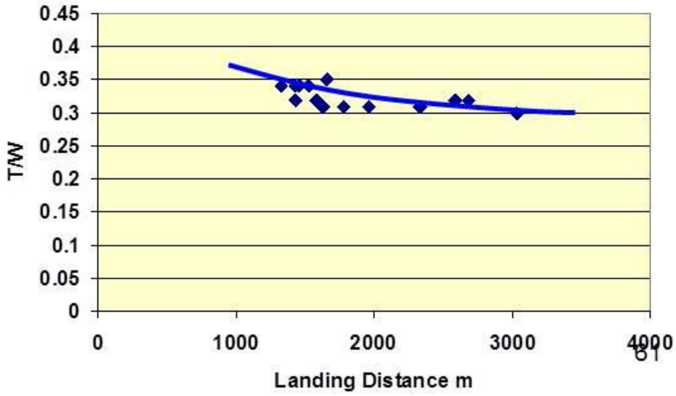

RECREATE
A321-Take-off run, Airbus book
Ratio: Aircraft span / Landing Length ~ MTOW
about 35 to 40 – our interest
ratio L/RL
Very Strong Runway Effect
60

T/W ~ Take-off Distance, Aviation Week Sourcebook 2008

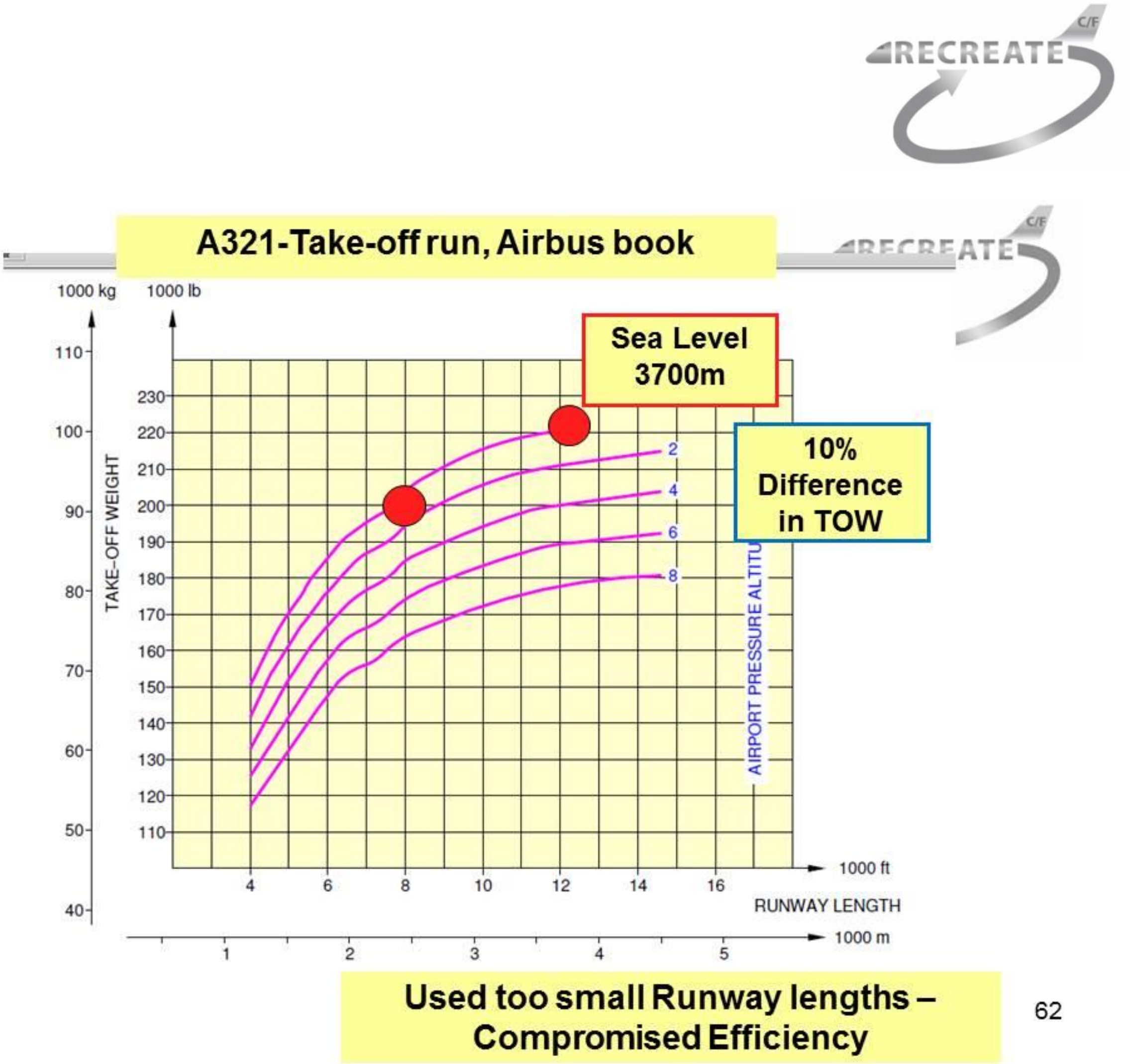


Need T/W 0.3

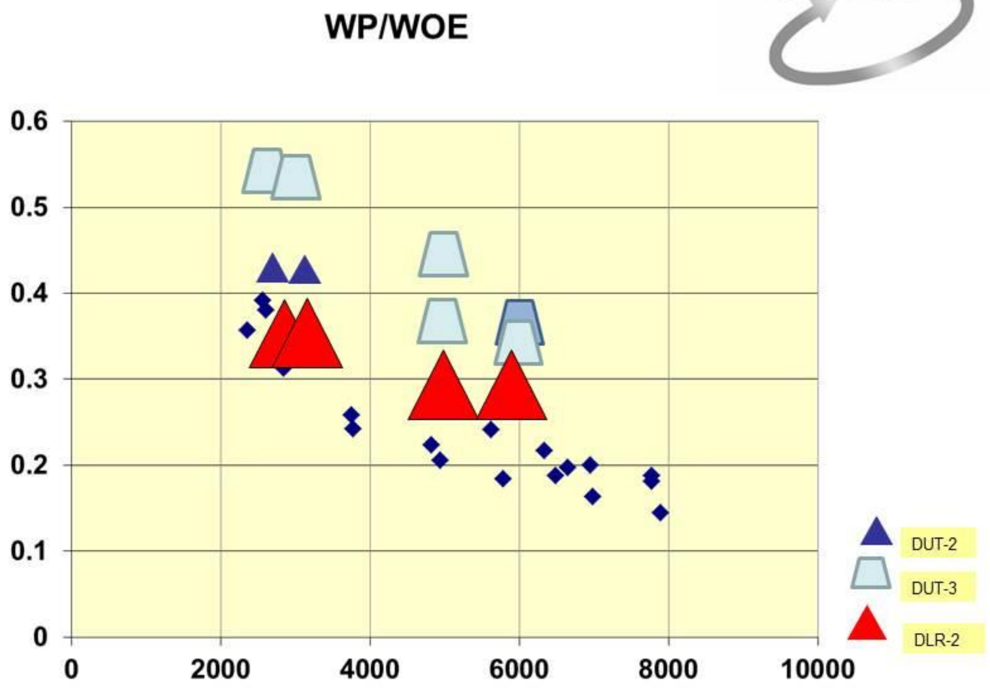
T/W ~ Landing Distance



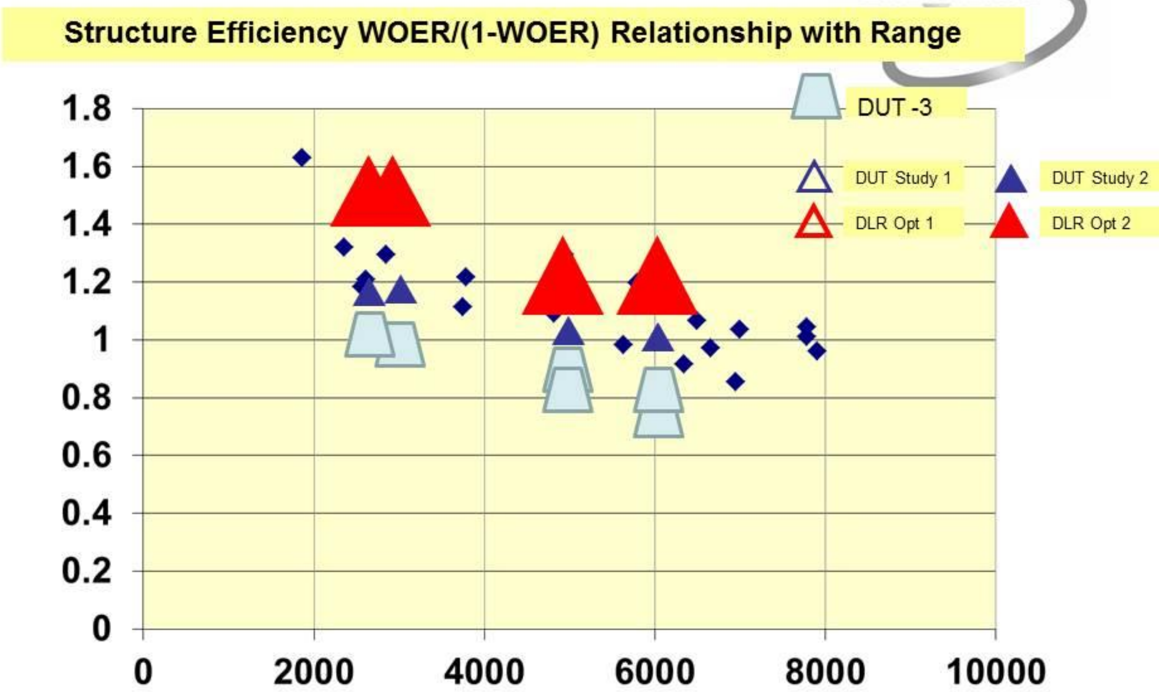
61



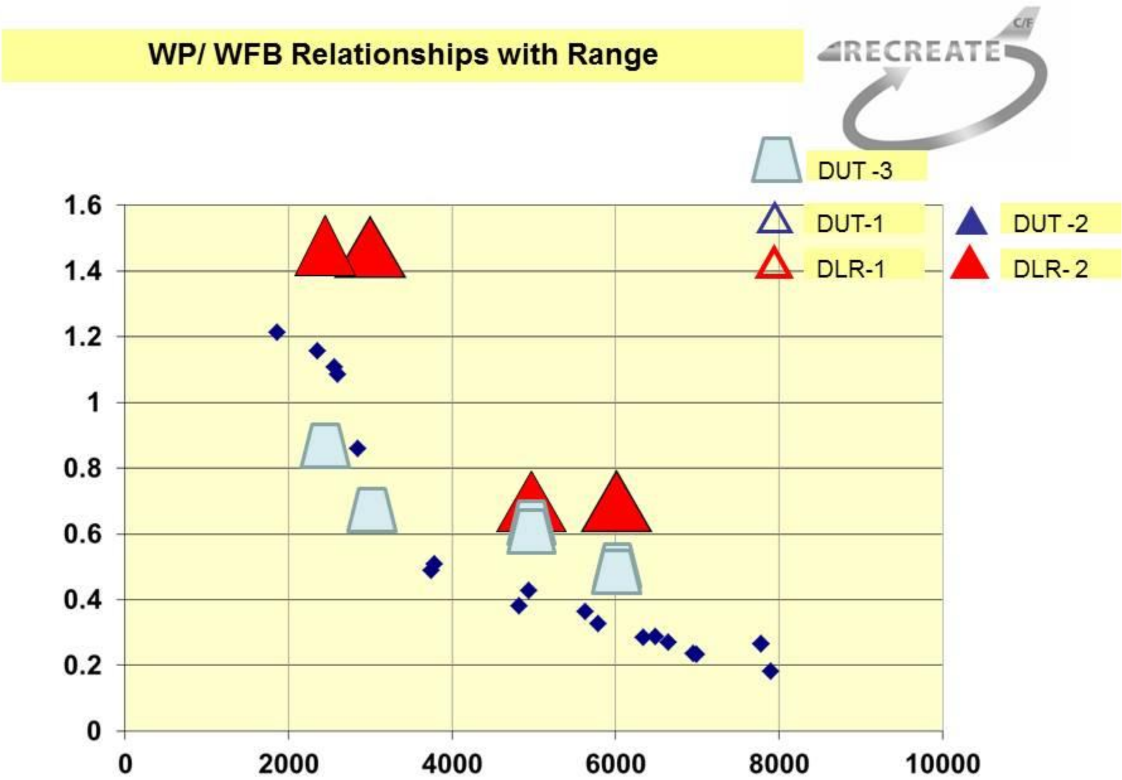
A321-Take-off run, Airbus book
1000 kg
1000 lb
Sea Level
3700m
10%
Difference
in TOW
TAKE-OFF WEIGHT
AIRPORT PRESSURE ALTITU
2
4
6
8
1000 ft
RUNWAY LENGTH
1000 m
Used too small Runway lengths –
Compromised Efficiency
62

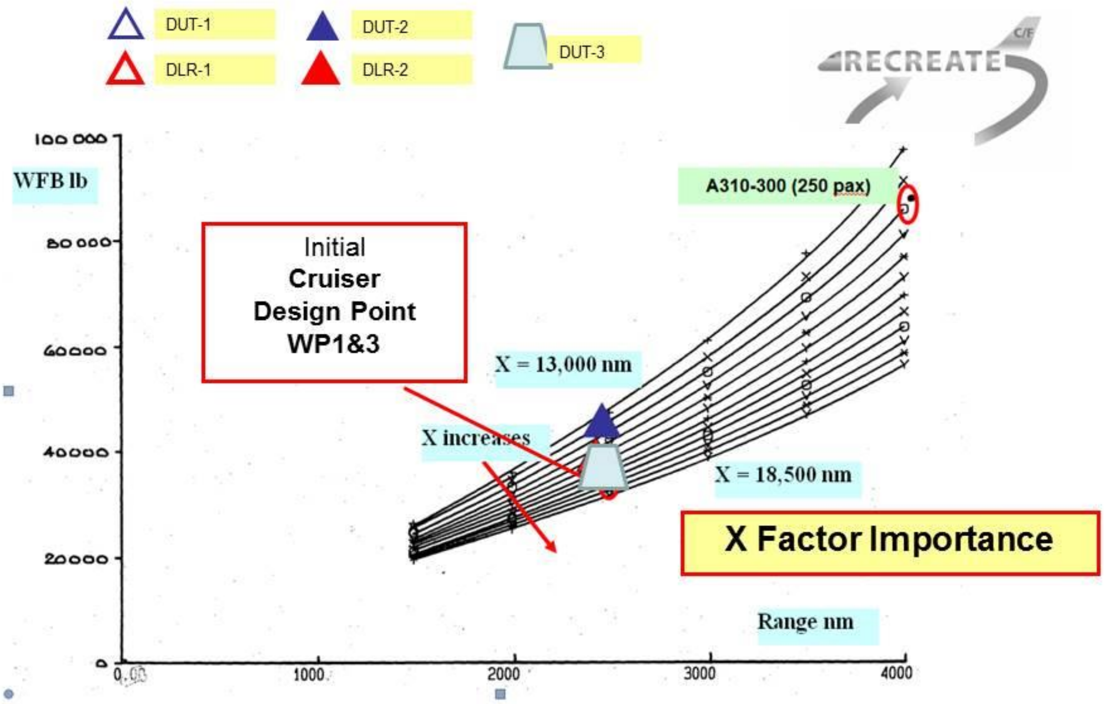


WP & WOE Structure Efficiency Relationships with Range

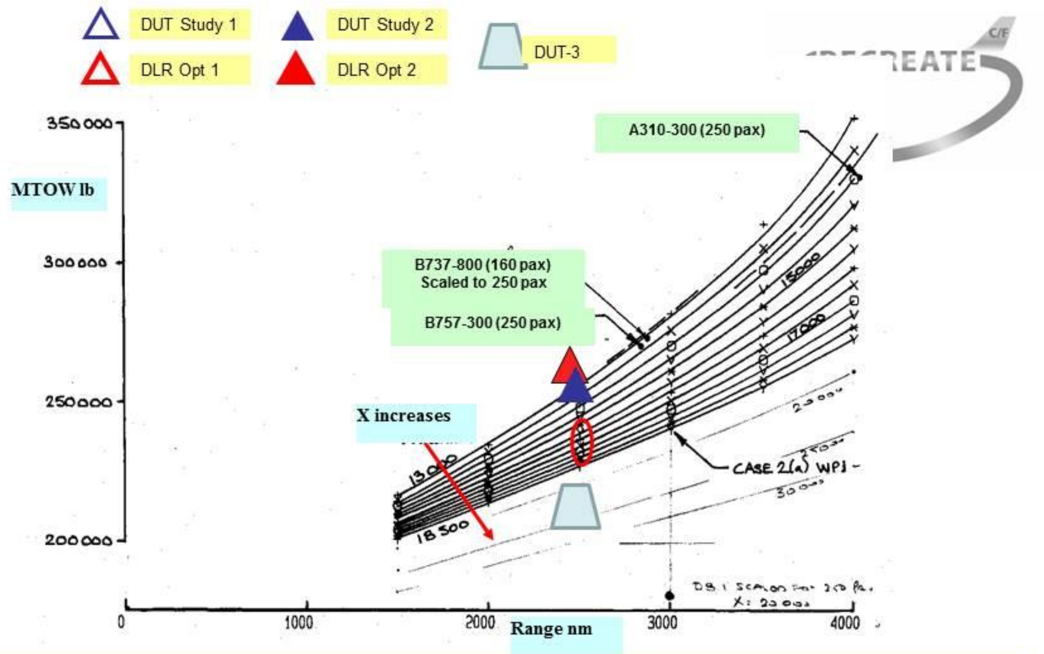


Structure Efficiency WOER/(1-WOER) Relationship with Range
DUT -3
DUT Study 1
DUT Study 2
DLR Opt 1
DLR Opt 2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2000
4000
6000
8000
10000


WP/ WFB Relationships with Range
DUT -3
DUT-1
DUT -2
DLR-1
DLR- 2
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
2000
4000
6000
8000
10000

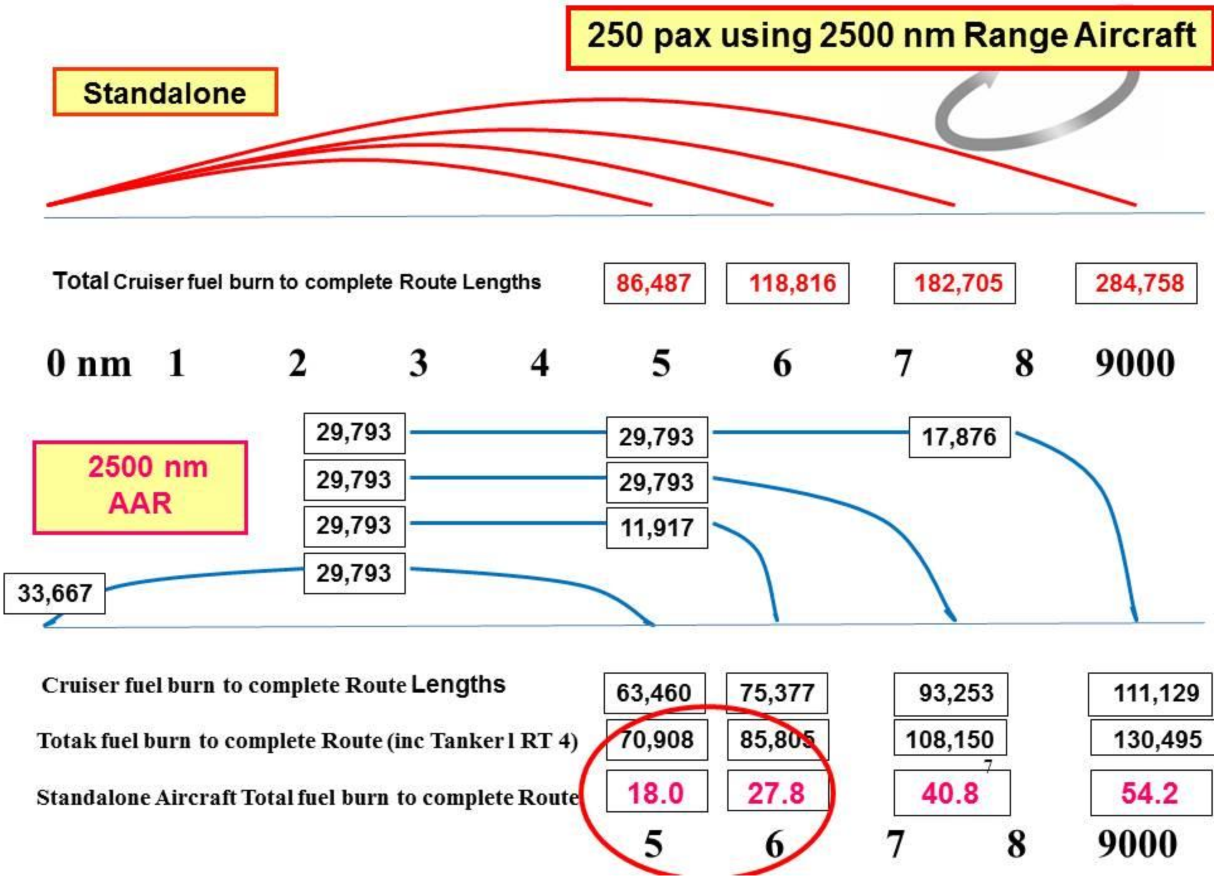


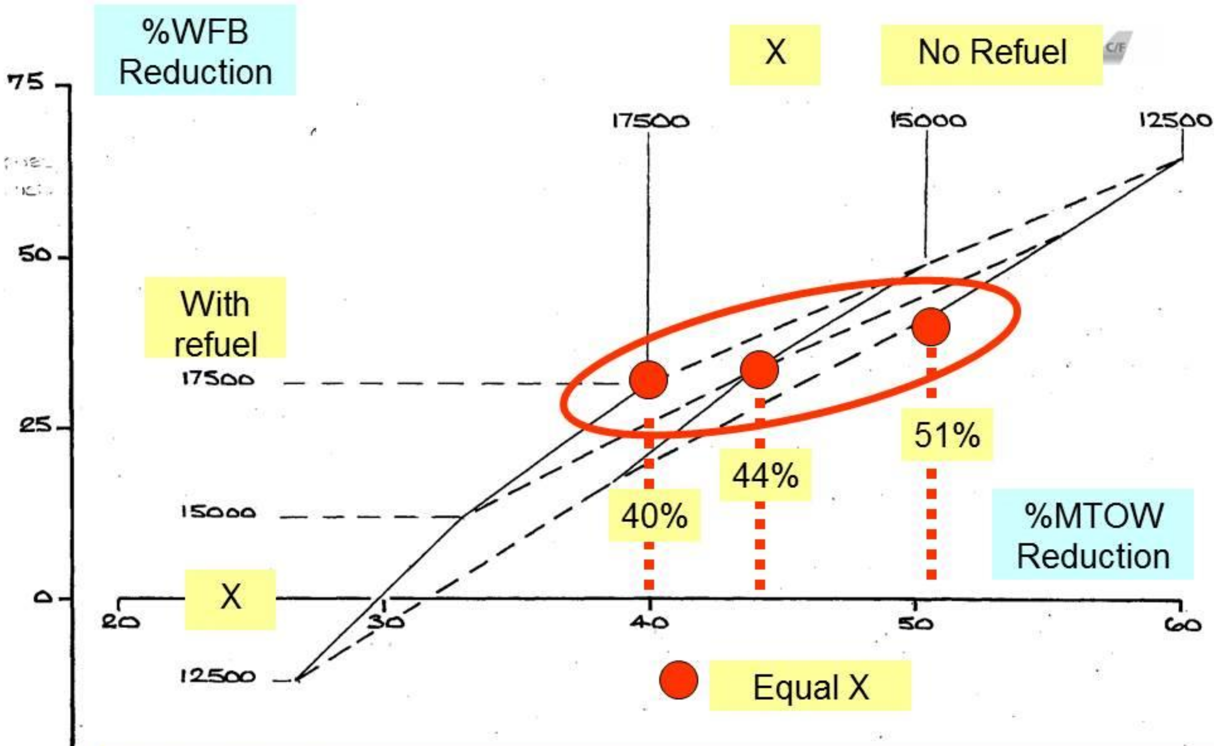
WFB (Block Fuel lb) ~ Range (nm)
250 pax Aircraft, X from 13,000 to 18,500 nm
Ranges 1,500 to 4,000 nm



MTOW (lb) v Range (nm)
Aircraft designed for 250 passengers, X from 13,000 nm to 18,500 nm
Ranges 1,500 nm to 4,000 nm

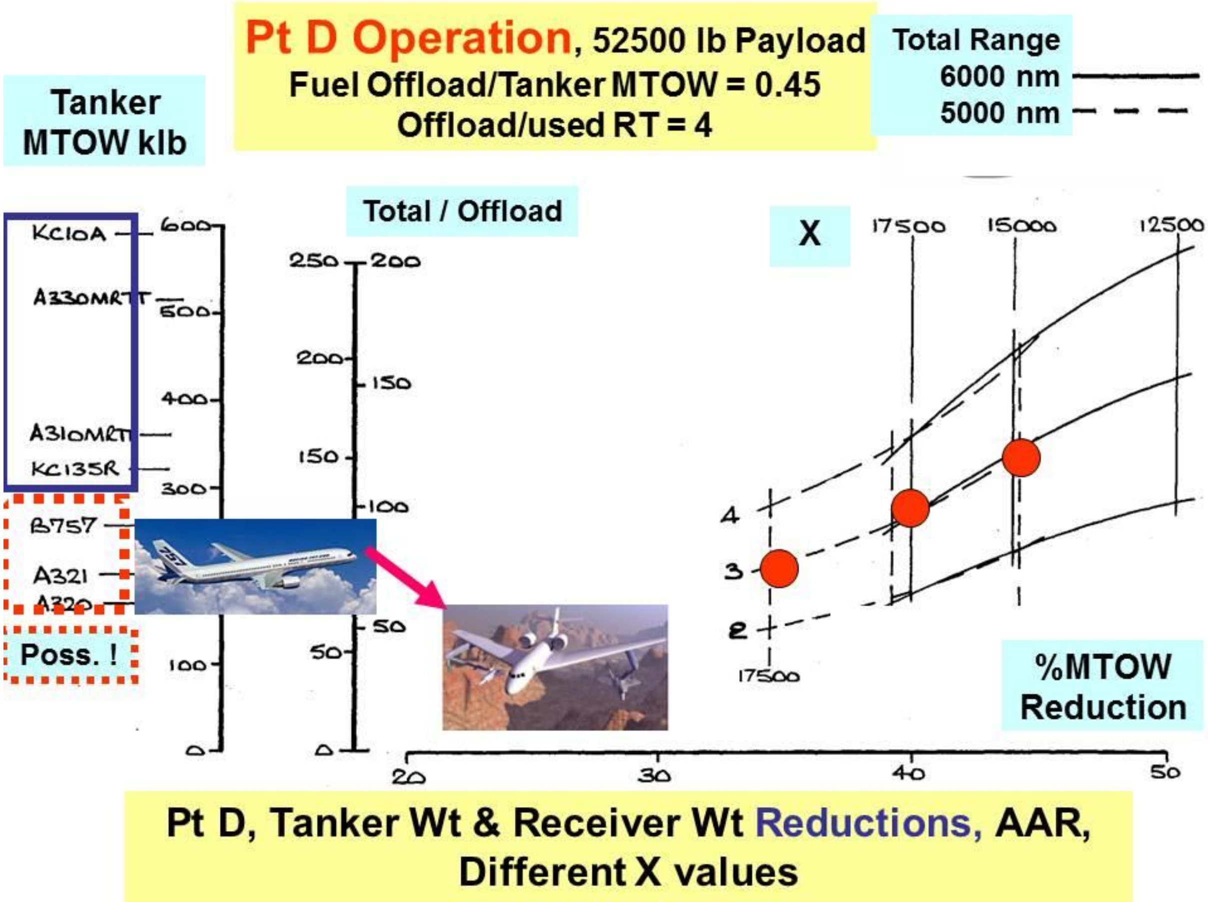
X Factor Importance


250 pax using 2500 nm Range Aircraft
Standalone
Total Cruiser fuel burn to complete Route Lengths
86,487
118,816
182,705
284,758
0 nm 1 2 3 4 5 6 7 8 9000
2500 nm AAR
29,793
29,793
29,793
29,793
33,667
29,793
29,793
11,917
17,876
Cruiser fuel burn to complete Route Lengths
63,460
75,377
93,253
111,129
Totak fuel burn to complete Route (inc Tanker l RT 4)
70,908
85,805
108,150
130,495
Standalone Aircraft Total fuel burn to complete Route
18.0
27.8
40.8
54.2
5 6 7 8 9000

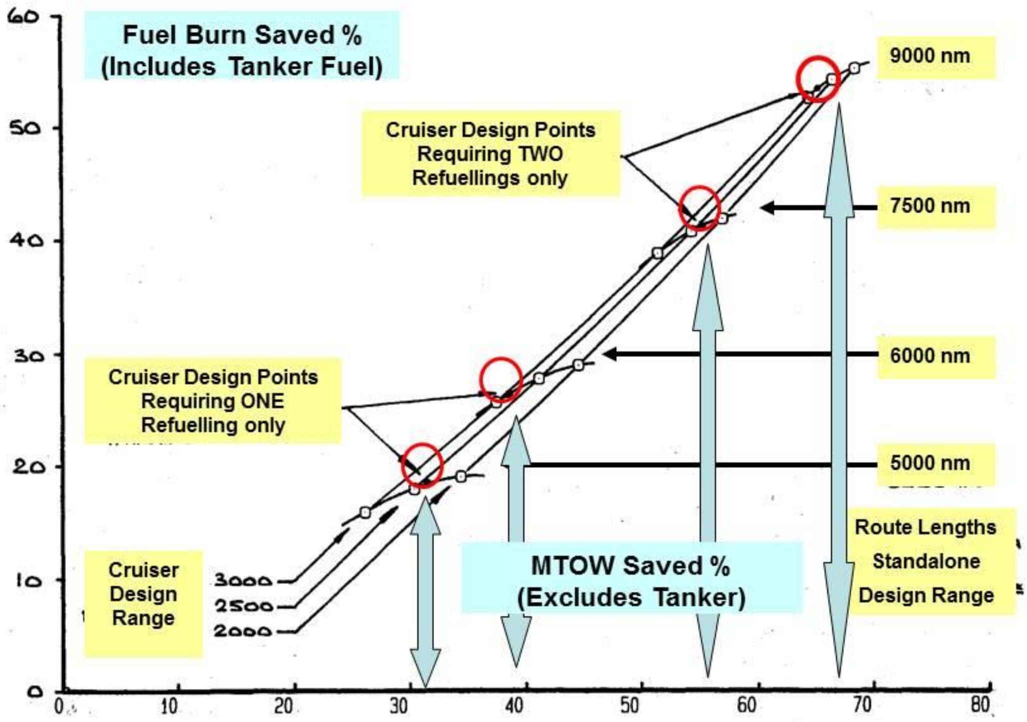


Pt D, WFB & TOW Advantages with AAR, 6000nm range, Relative X values

Less Metal in Air



Pt D Operation, 52500 lb Payload
Fuel Offload/Tanker MTOW = 0.45
Offload/used RT = 4
Total Range
6000 nm
5000 nm
Tanker MTOW klb
KC10A
A330MRTT
A310MRTT
KC135R
B757
A321
A320
Poss. !
600
500
400
300
100
0
Total / Offload
250
200
150
100
50
0
200
150
100
50
X
17500
15000
12500
4
3
2
17500
%MTOW Reduction
20
30
40
50
Pt D, Tanker Wt & Receiver Wt Reductions, AAR, Different X values

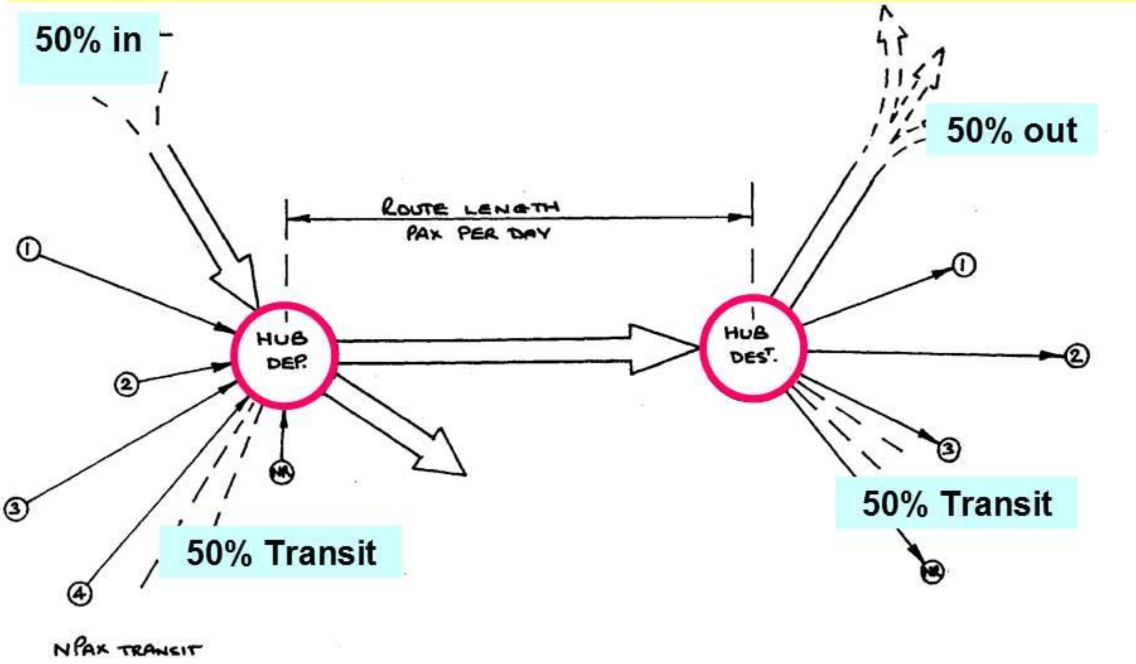


Fuel Burn and TOW Advantages Afforded by AAR, 3,000 Pax per Day
Cruiser Design of 2,000, 2,500 and 3,000 nm and 200, 250 and 300 Pax Capacity
Standalone Cruiser Design Ranges to match Service Route Lengths of 5,000, 6,000, 7,500 and 9,000 nm

AIRPORT & PLANNING
Hubs Implications Benefits

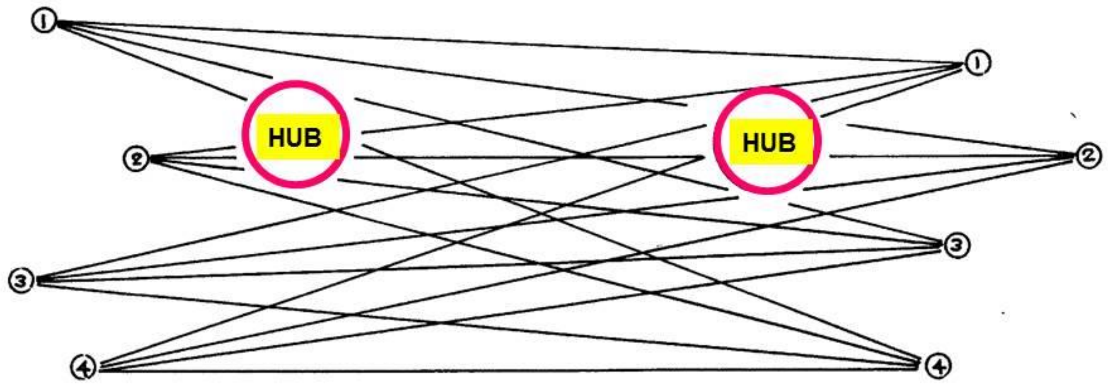
- Pt A to B offered with Smaller A/C
- Regional airports become truly “International”. Expansion where? Open question !
- Less noise - less night flying restrictions
  - MTOW near 250,000 lb
- Less congestion into airports. Cost Savings again!
  - Less terminals at hubs
- Less Fuel storage at airports 30-50% !
- Less ground tanker movements or pipes 30-40%
- ATC considerations - very difficult already

Start from Tankers, Work Outwards for Schedules



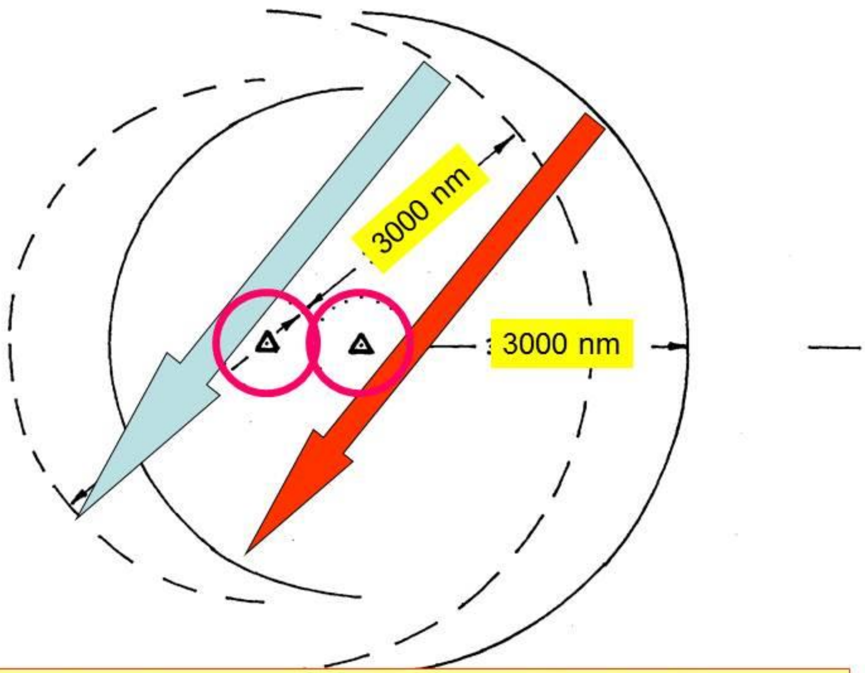
Hub & Feeder Network - 50% pax locally from Hub
Others in Transit via Feeders (4 say, Extra Fuel Burn)

- Pressure on Hubs RELEASED
- Close Formation Flying encouraged



City Pair Network using AAR- Hubs Avoided for Transit Pax (Fuel saved) Smaller Cruisers needed

Twin Tanker Bases about 1000 nm apart

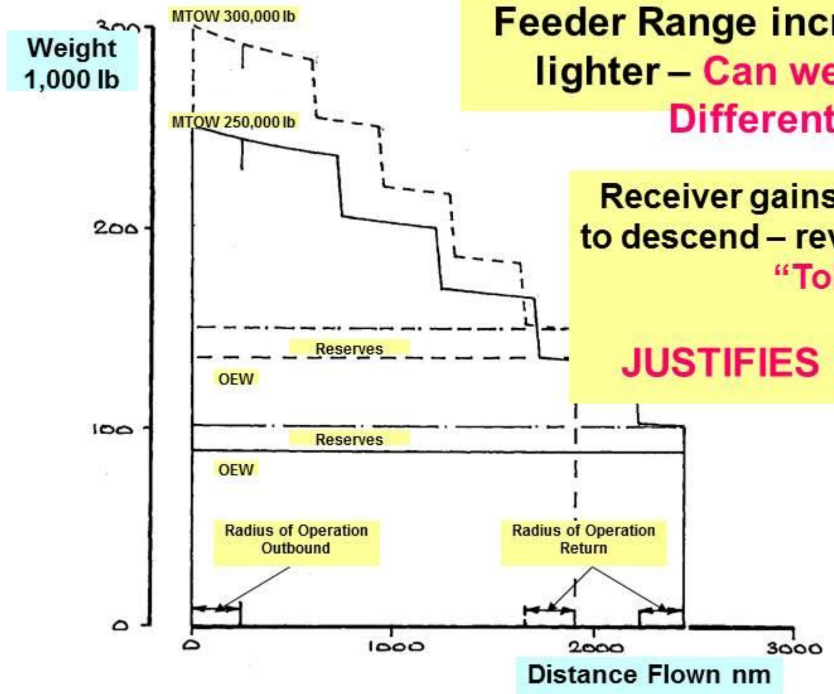


Showing Region Covered via Eastern Tanker Base
Formation Flying Feasible, more than 1 tanker

Feeder Range increases as it gets lighter – Can we exploit this ? Different OEWR

Receiver gains weight – May need to descend – reverse of cruise-climb "Toboggan"

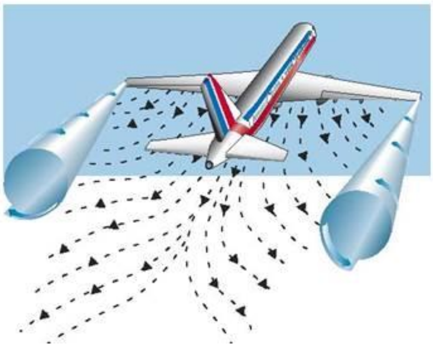
JUSTIFIES REAR TANKER

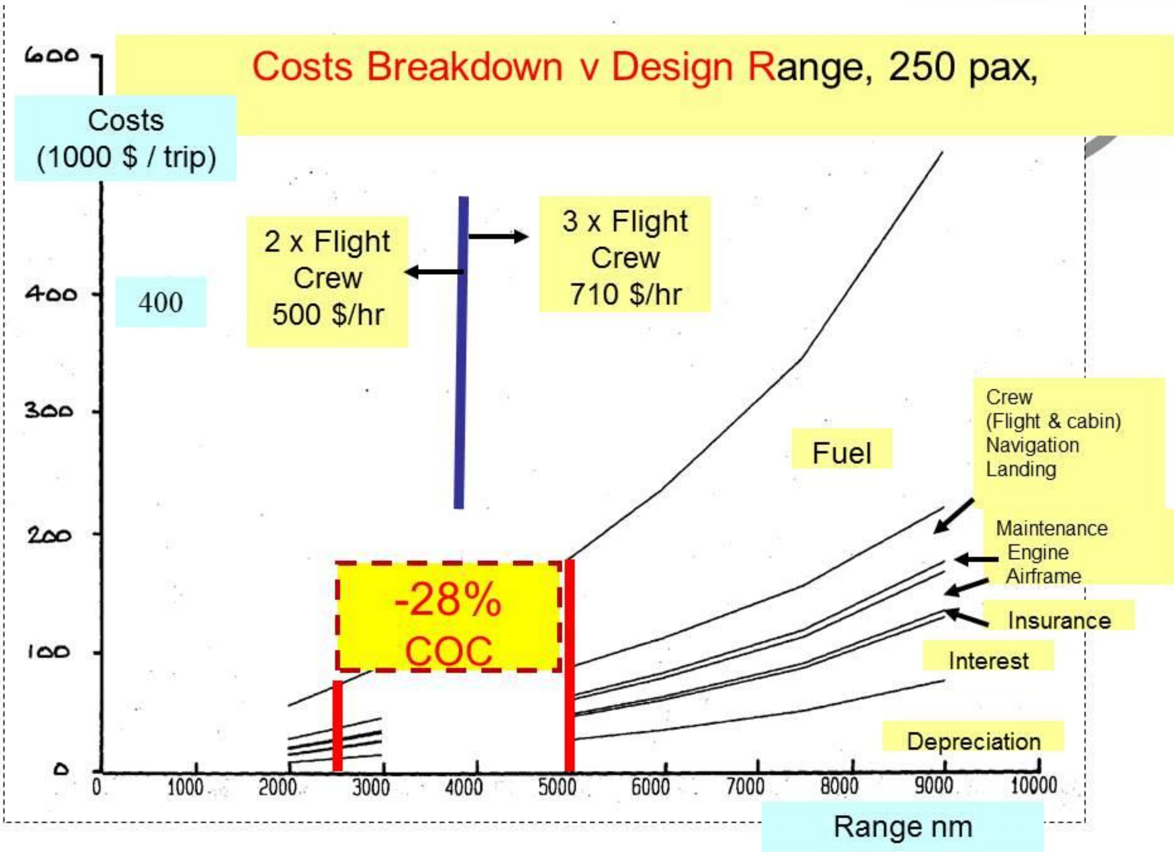


Feeder Weight Breakdown – Distance Flown, Four 30,000 lb Offloads, X 17,500 nm
MTOW 250,000 lb, OEWR 0.35, RT 4, Loiter 61 min
MTOW 300,000 lb, OEWR 0.45, RT 4, Loiter 42 min

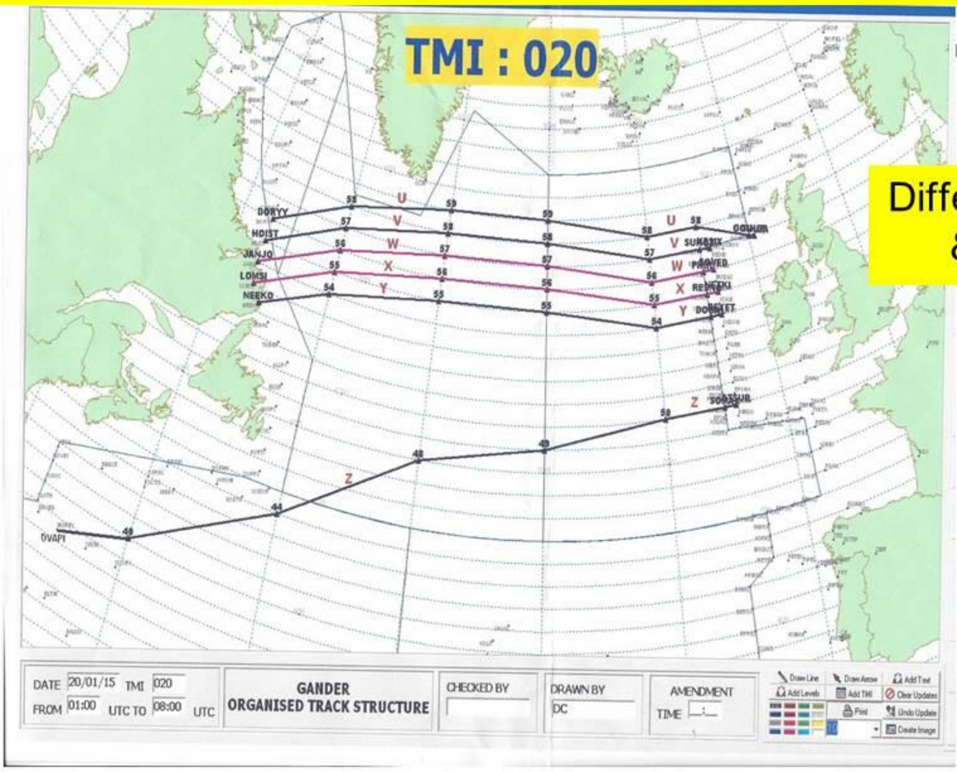
Handling Qualities & Flight Control Laws

- Civil certified
- Extra engine power 15 to 20% - induced drag
- 3% less engine power – bow wave effect on Tanker
- Direct lift kinematics & restored positive spiral stability, Cnv / Clv




Costs Breakdown v Design Range, 250 pax,
Costs
(1000 $ / trip)
600
400
300
200
100
0
400
2 x Flight
Crew
500 $/hr
3 x Flight
Crew
710 $/hr
Fuel
Crew
(Flight & cabin)
Navigation
Landing
Maintenance
Engine
Airframe
Insurance
Interest
Depreciation
-28%
COC
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Range nm

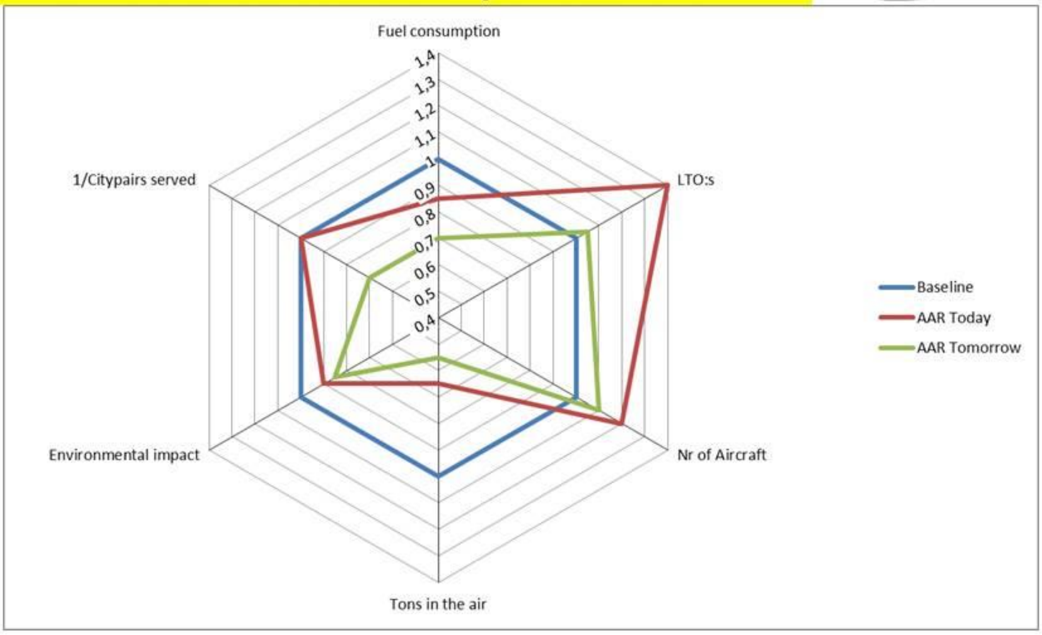
Planning a day at NATS 19 Jan 2015
Oceana Traffic in Tubes 60nm apart, Longitudinal Sep’n 10 mins



Different speeds & heights

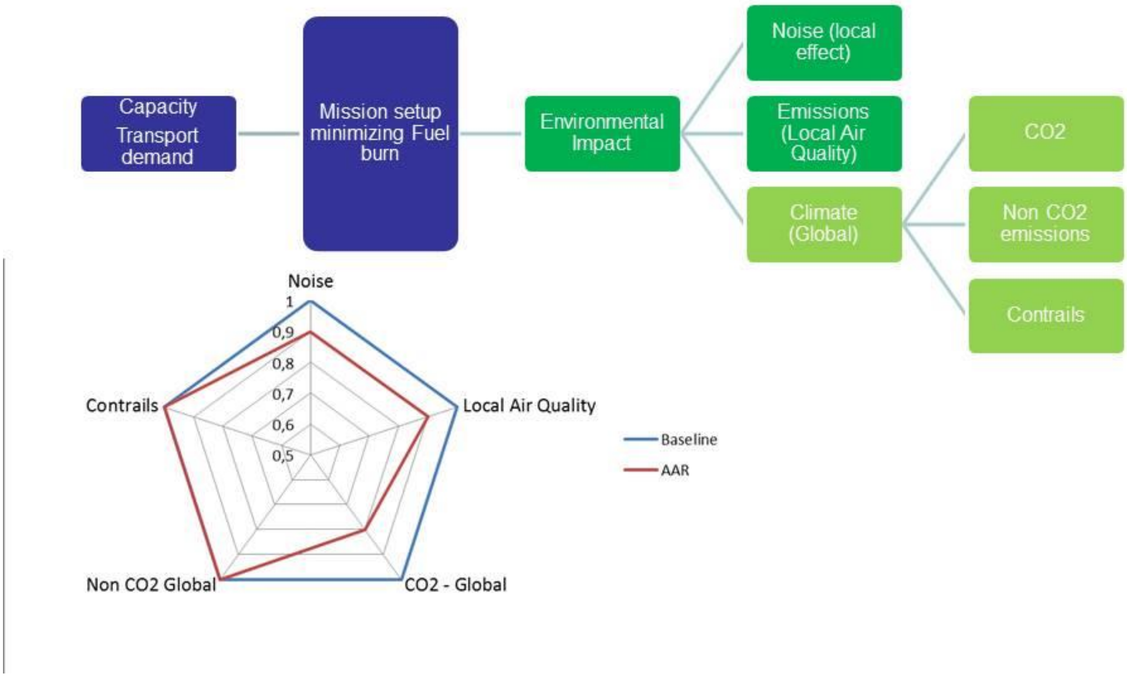
79

Expected improvements from cruiser/feeder operations

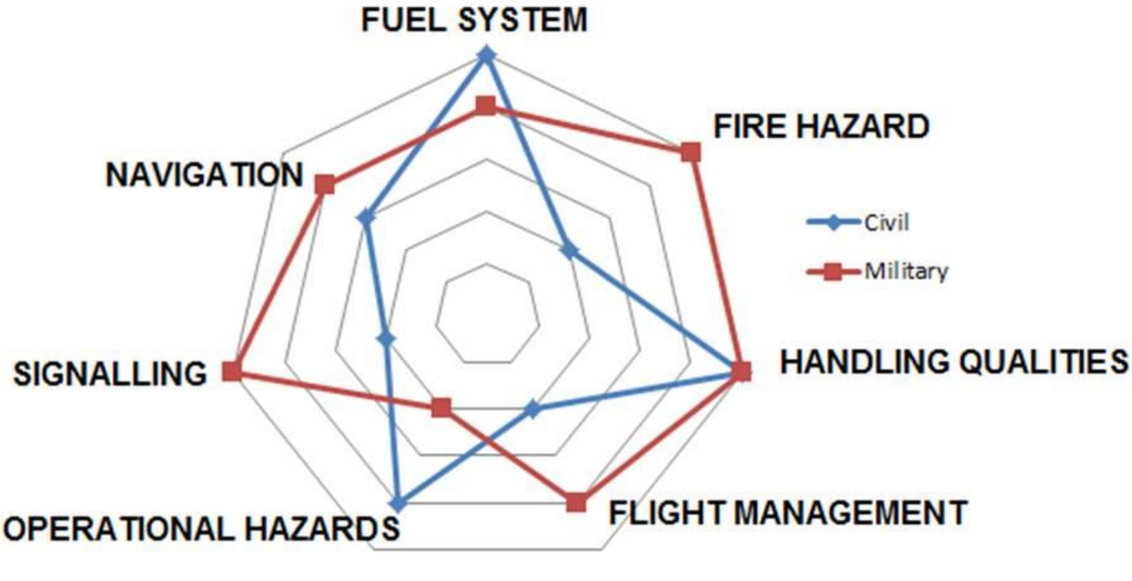


(for the same transport capacity per unit of time)

Environmental impact - AAR



Civil vs Military Certification (A400M Experience)

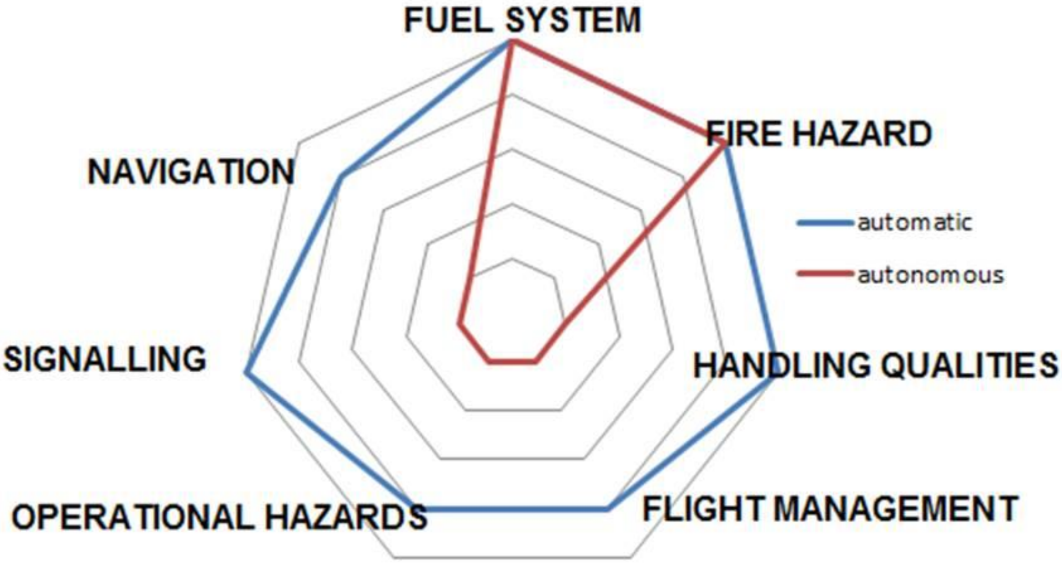


Automatic vs Autonomous

Automatic – *take the existing perimeter of civil & military certification enhanced with AAR specific Flight Management & Guidance Systems*

Autonomous – *one aircraft in the bracket controlled by either the other aircraft or a ground station*

Automatic vs Autonomous



Civil AAR Certifiaction Issues

- Autonomous AAR beyond the scope of current civil certification.
- Automatic civil certified AAR is viable.
- Automatic civil AAR will be highly dependent on developing specific high integrity Flight Management System functionality. Find a competent software house to develop the code.
- Handling Qualities, Flight Control Laws, Navigation and Hazard Analysis activities will be expanded beyond the civil perimeter, but it must follow as the consequence of introducing AAR as a civil flight phase.
- Treatment of fuel spillage and fire risks more involved than simply preventing fuel tank explosion
- Civil certification of other systems and airframe as today.
- Military standards for signalling & markings would be adopted.

Inferences

- Air **Traffic growing at 4.5%** annually. Feeder-cruiser, AAR operations – gradually introduced.
- Important to understand **Efficiency Parameters** for design
- Short-range (with AAR) & long range cruiser - **comparable X**
- Need for appropriate **Runway Lengths** in analyses
- Leading to **appropriate Cruisers,** pax. 200, 250, 350
- **Twin Tanker base** with nearly straight runs - **Remove hubs**
- **Tanker availability controls the schedules** – not the other way round (existing)
- Demonstrated **Fuel & MTOW savings** - depend on range
- Absolute value Predictions Vary – **Differences Reliable** & **very similar** to Originals
- **Small Tankers** needed
- **Cost savings + Noise, Airport & other benefits**

Work on Sizes & Ranges

- We need different sized aircraft for different ranges
- This inference is also in WP1
- Further work needed on Design incl Runway Effects

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REsearch on a
CRuiser Enabled Air
Transport Environment

WP3

Benefits analysis of the cruiser-feeder concept

The research leading to these results has received funding from the European Union Seventh Framework Programme (*FP7/2007-2013*) under *grant agreement* n° 284741.
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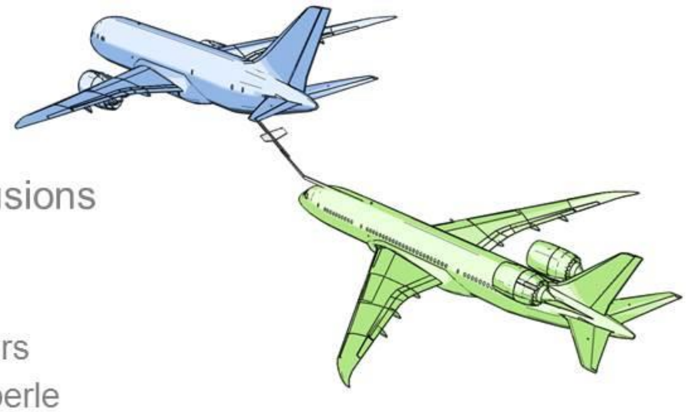
Appendix D Final results of WP4

RECREATE

WP 4 Design

Summary and Conclusions
January 2015



Contributions of all partners
presented by Martin Hepperle

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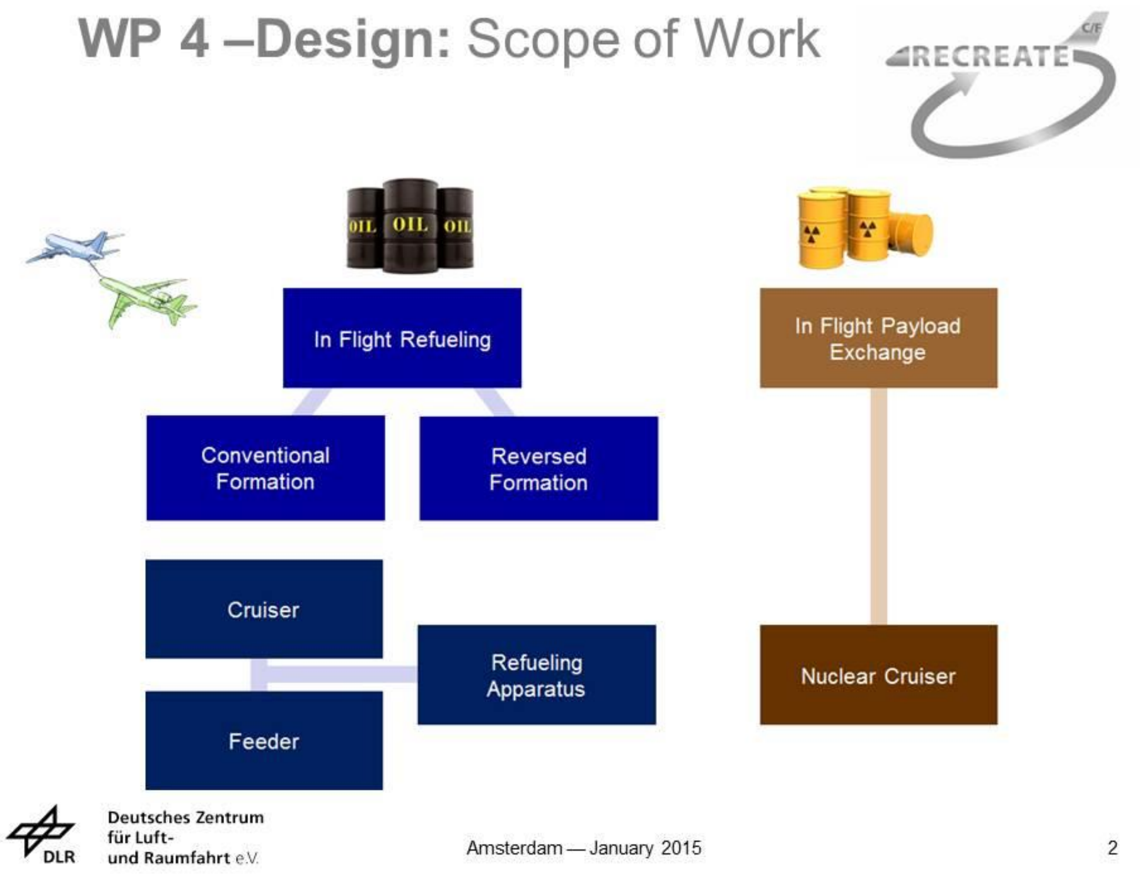
WP 4 –Design: Scope of Work
RECREATE
C/F
In Flight Refueling
Conventional Formation
Reversed Formation
Cruiser
Feeder
Refueling Apparatus
In Flight Payload Exchange
Nuclear Cruiser
Deutsches Zentrum für Luft- und Raumfahrt e.V.
DLR
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WP 4 – Design
Resources and Activities

The resources in this work package were split approximately 50/50:

- Aircraft design and assessment (cruiser, tanker, nuclear cruiser)
- Refueling boom design and assessment

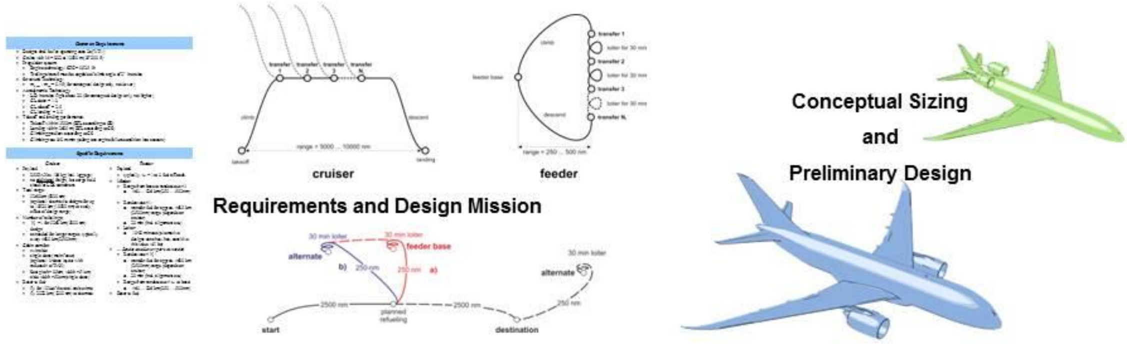
	Partner	Person Months	Main Work Topic	
1	RKN	9	Guidance and Assessment	63%
2	DLR	30	Aircraft Design	
3	DUT	24	Aircraft Design (+ Refueling Boom)	
4	NLR	4	Refueling Boom	37%
5	QUB	20	Refueling Boom	
6	ZHAW	13	Refueling Boom	
	TOTAL	100		

- Deliverable 4.1: “Initial Design of Cruiser Aircraft and Feeder Aircraft”
- Deliverable 4.2: “Updated Design of Cruiser and Feeder Aircraft”

WP 4 – Design
Objectives

1) Define mission and Top Level Aircraft Requirements.
2) Design and assess realistic aircraft for specific operation:
   - A "Cruiser" – a short range passenger aircraft flying long range,
   - A "Feeder" - a short range tanker aircraft,
   - An alternative Cruiser design using nuclear power sources,

3) Design a refueling boom and determine its aerodynamic properties.



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WP 4 – Design
Top Level Aircraft Requirements

The TLARS were based on the initial work in WP 1.

The main parameters defined in WP 1 were

- total range: 9260 km (5000 nm), refueled once or twice,
- transport capacity: 250 passengers

Note:

This represents relatively small aircraft (cf. A380, B747).

One reason for this selection was that refueling could also enable point-to point connections from smaller airports.

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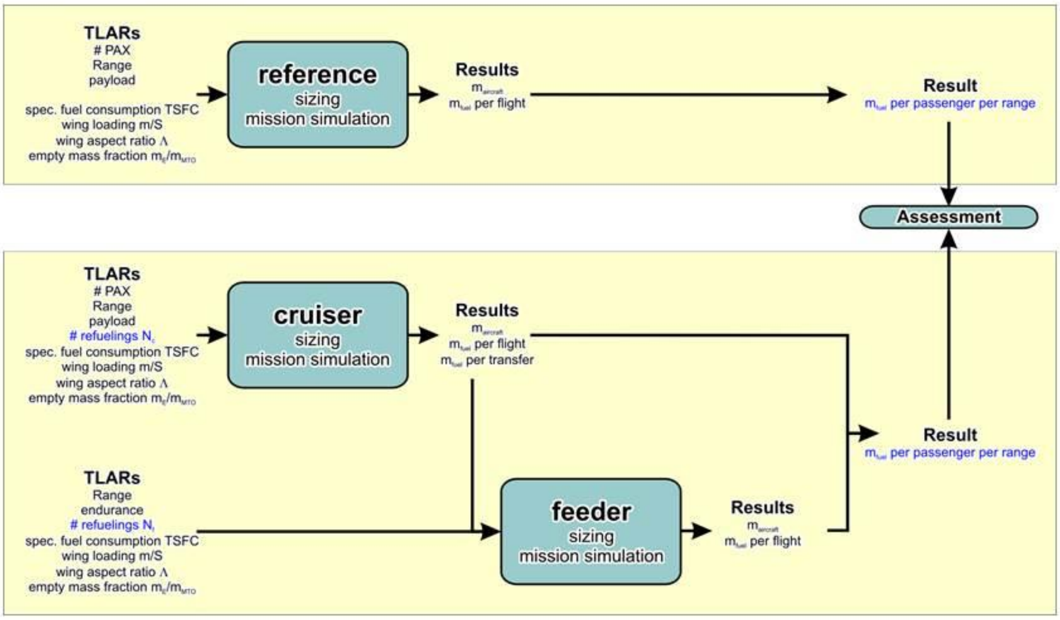
WP 4 – Design

Conceptual Design Process



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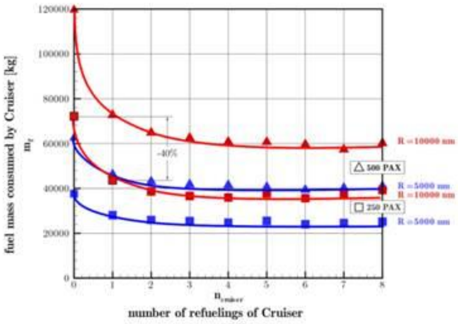
WP 4 – Design
Conceptual Design Results

A systematic design approach was started at the conceptual design/analysis level.

At this level some assumptions are made:

- aerodynamic efficiency (L/D ratio),
- structural efficiency (weight fractions),
- engine efficiency (TSFC),
- all assumptions
  - were based on efficient long range aircraft,
  - must be critically reviewed, especially when aircraft of unusual proportions are designed.



At this level gains of 30% were obtained (R=5000 nm, 40%@10’000 nm

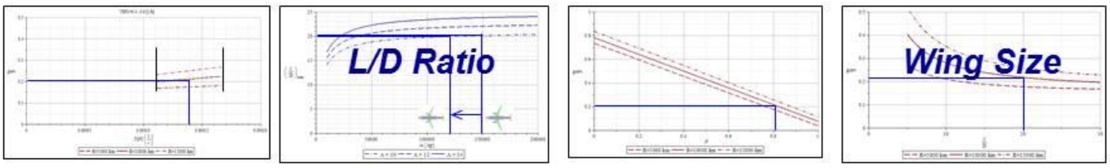
(results are for the cruiser only – subtract ~3-4% for tanker)

WP 4 – Design
Sensitivity Studies

Sensitivity Studies help to understand trends and dependencies.
Sensitivities have been determined with respect to 4 parameters:

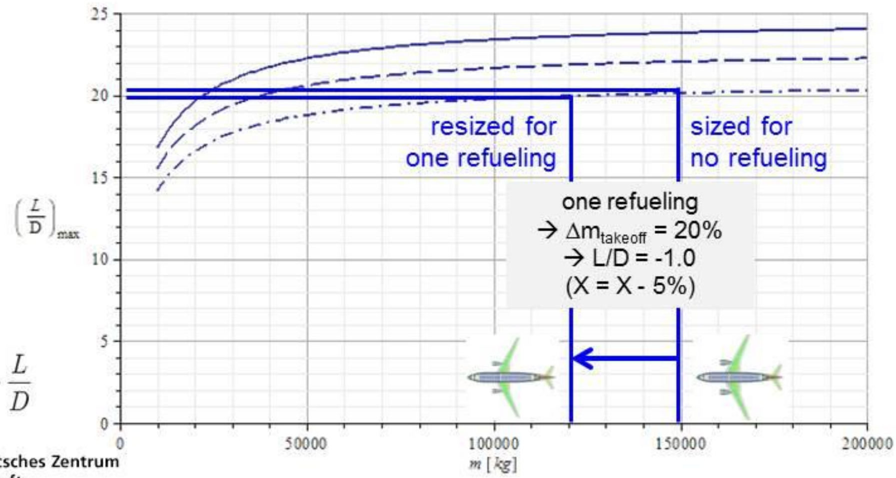
- aerodynamics: lift over drag L/D, fuselage wetted area rel. wing area,
- engine technology: thrust specific fuel consumption TSFC,
- structural technology: empty mass fraction m_E/m_{TO},
- operations: refueling altitude H.

Here only two sensitivities related to aerodynamics are presented.



WP 4 – Design
L/D for adapted Wing Size

- L/D (and therefore “X”) is reduced by wing design for refueling:
  → reduced mass → reduced wing area ← but fuselage size is the same.
- L/D Loss only partially recoverable by increasing span
  → “X” for refueled aircraft <u>must</u> be lower than for non-stop aircraft



$$X = \frac{v}{TSFC} \cdot \frac{L}{D}$$

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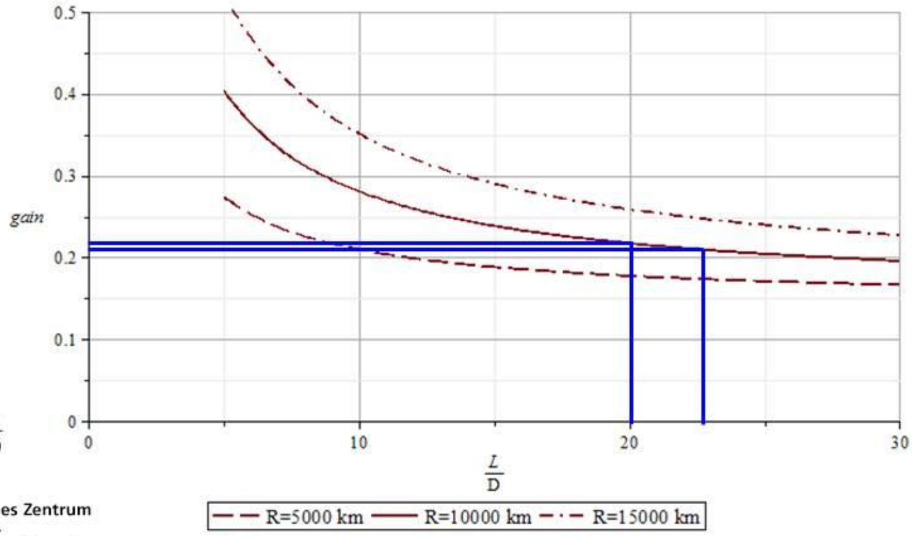
WP 4 – Design
Impact of L/D of Future Aircraft

How depends the benefit on given aerodynamic efficiency?

Improved aerodynamics → lower gain and weaker effect

$$1 - \frac{m_{f,\,refueled}}{m_{f,\,direct}}$$



$$X = \frac{v}{TSFC} \cdot \frac{L}{D}$$

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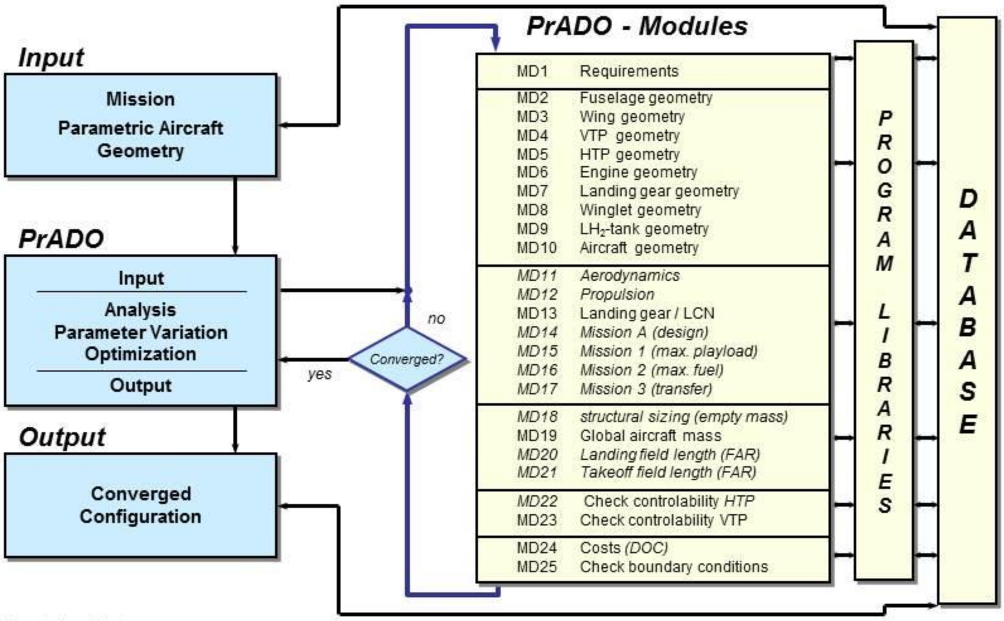
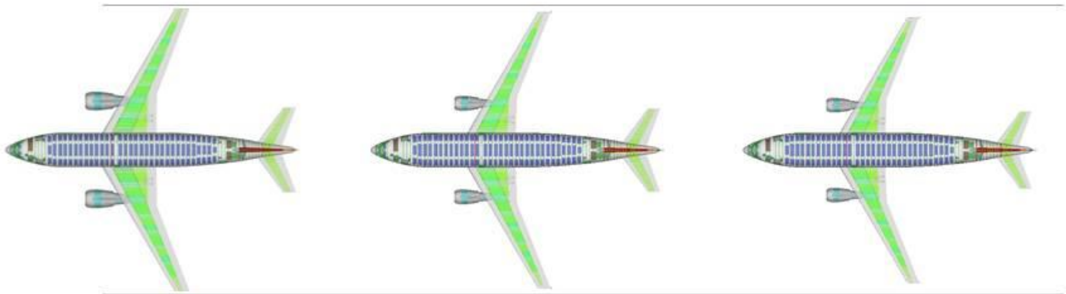
WP 4 – Design
Preliminary Design Tool



WP 4 – Design
Preliminary Design Results

In the next step medium fidelity preliminary design tools were used.
Numerical optimization was performed for 3 designs:

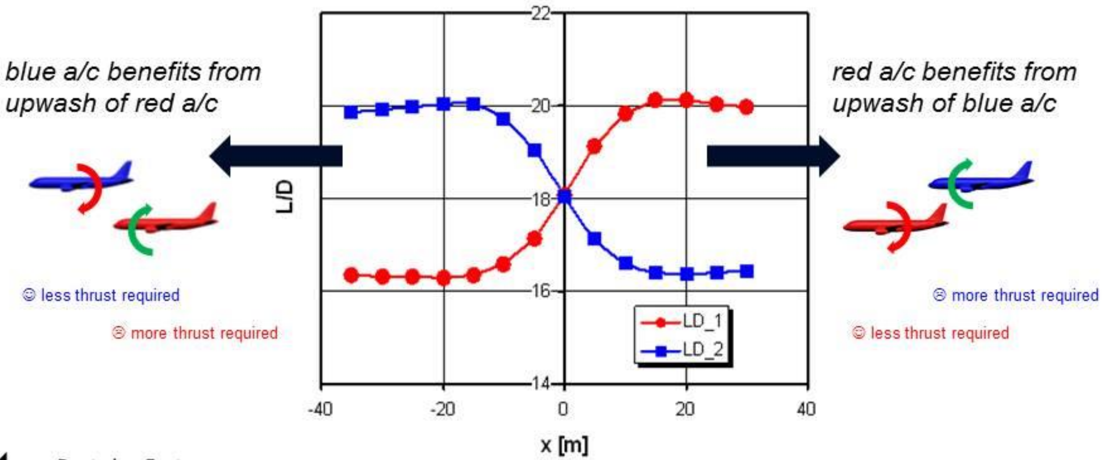
- wing size adapted to reduced weight,
- fuselage size was maintained.



	Reference L/D = 18.9	one refueling L/D = 17.9	two refuelings L/D = 17.5
Cruiser only		Δm_f = 20.6%	Δm_f = 24.9%
Cruiser+Tanker (m_f given/used = 5/1)		**Δm_f = 13.2%**	**Δm_f = 15.5%**

WP 4 – Design
Formation Flight

Blue aircraft passing over red aircraft (separation Δz = 15 m).
Both aircraft trimmed to maintain lift → angle of attack changes.



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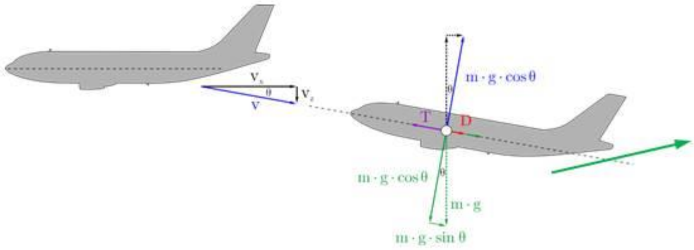
WP 4 – Design
Formation Flight

Flight Physics:

- In Formation flight the trailing aircraft needs <u>additional thrust</u>.



$$T = q \cdot S \cdot C_{D,0} + \frac{k}{\pi \cdot q} \cdot \left(\frac{m \cdot g \cdot \cos\theta}{b} \right)^2 + m \cdot g \cdot \sin\theta$$

$$\frac{L}{D} = \frac{m \cdot g}{T}$$

$$T = \frac{m \cdot g}{L/D}$$

$$\Delta T = m \cdot g \cdot \sin\theta$$

$$\frac{\Delta T}{T} = \frac{L}{D} \cdot \sin\theta$$

θ = 0.5° → ΔT/T ≈ 18%

θ = 1.0° → ΔT/T ≈ 35%

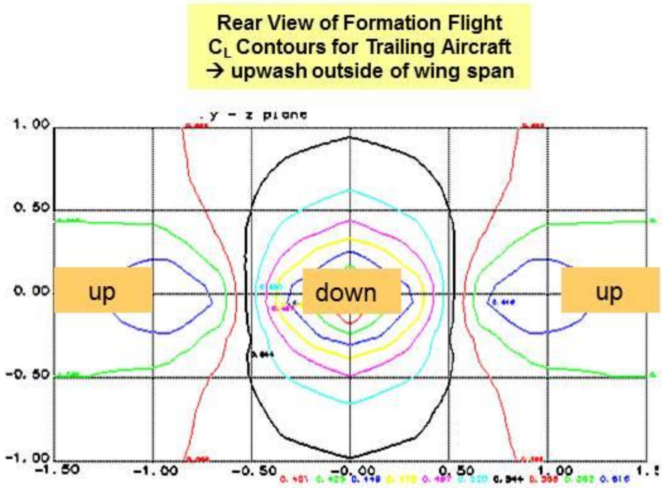
The conventional formation is "Cruiser behind Feeder".

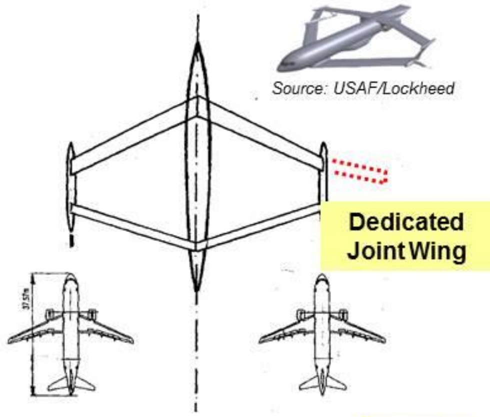
An innovative formation could be "Feeder behind Cruiser" (see TUD).

Then only the feeder has to be designed for a higher thrust reserve.

WP 4 – Design
Formation Flight

Benefits due to spanwise staggering – not fully studied in RECREATE.





Source: USAF/Lockheed

Source: USAF-KC-BWB

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WP 4 – Design
Low Altitude Refueling

<u>Stability and Control favor refueling at lower altitude</u>

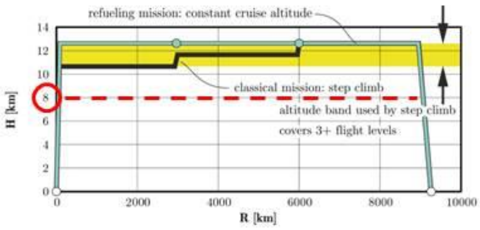
- aircraft cruises at optimum cruising altitude (H=10…11 km),
- aircraft descends, refuels at H=8 km, climbs back to cruise altitude.

<u>Drawbacks</u>

- This operation leads to an increased fuel consumption in the order of 450 kg (≈1% of the cruise) <u>per refueling operation</u>,
- Reduced passenger comfort.

<u>Benefits</u>

- Improved maneuverability,
- Higher thrust reserves for both aircraft.



WP 4 – Design
Conclusions from DLR Results

1 - Conceptual Design: **1 refueling: gains of about 30%.**

Note: some initial assumptions proved optimistic (L/D, mass fractions)

2 - Preliminary Design: **1 refueling: gains of up to 15%.**

Note: tanker (5/1) eats about 7% of the benefits

3 - Future Aircraft:

circa 2030 EIS → technology +10% L/D and -10% structural mass

1 refueling: gains of about 10%.

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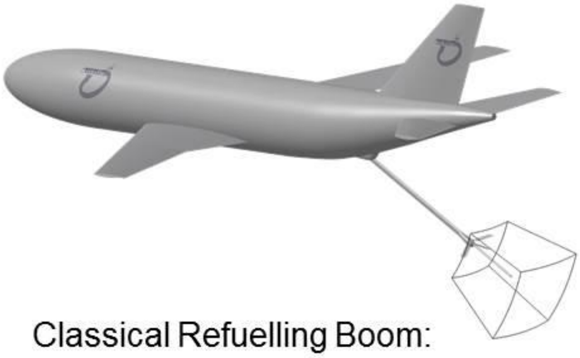
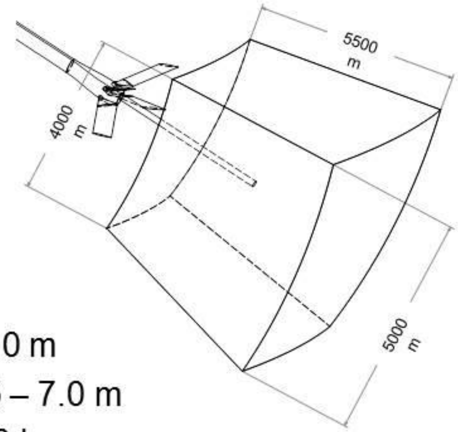
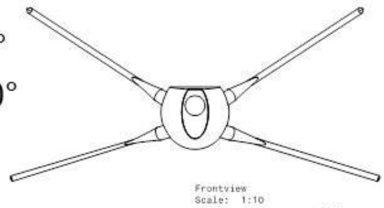
WP 4 – Design
Design of Refueling Boom



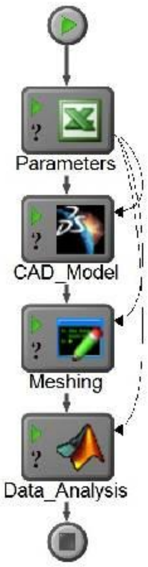


Classical Refuelling Boom:

• fixed part length		11.0 m
• extension length		0.5 – 7.0 m
• Estimated mass		730 kg
• Lateral boom angle	θ	15° – 45°
• Longitudinal boom angle	Ψ	-20° – 20°
• Ruddervator deflection angle	δ	+/- 15°
• 4 control surfaces for redundancy		



WP 4 – Design
Design of Refueling Boom



Automatic simulation Loop in ModelCenter

1. Selection of parameters in excel

2. Geometry change in the CAD program → .igs file

3. Meshing; discretization of the geometry for the CFD simulation

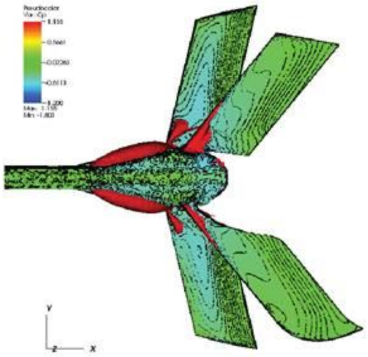
4. Aerodynamic calculation with VSAERO

5. Assemble of the results with Matlab

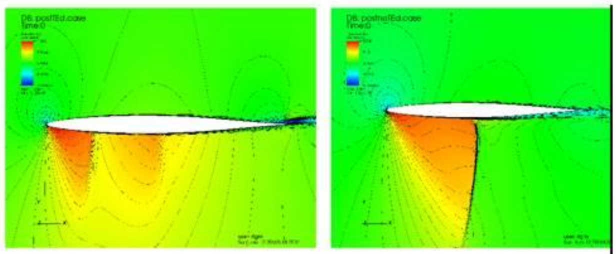
→ 4min per run

WP 4 – Design
Some Results

Some potential for shape optimization identified.



Option to use a TE-device to reduce buffet Mach number.



Same airfoil (ruddevators) at approximately the same c_l.

WP 4 –Design
Summary of Boom Design Work

- Geometry has been generated based on Requirements,
- Design/analysis loop has been implemented,
- ~ 800 calculations with CFD-Simulation loop performed,
- Aero-Database for boom simulation established and delivered to WP5.

- Additional validation and refinement conducted:
  - confirmation of aero-database by high-fidelity CFD results,
  - some studies towards control surface design,
  - test of some ideas for improvements by e.g. trailing edge devices.

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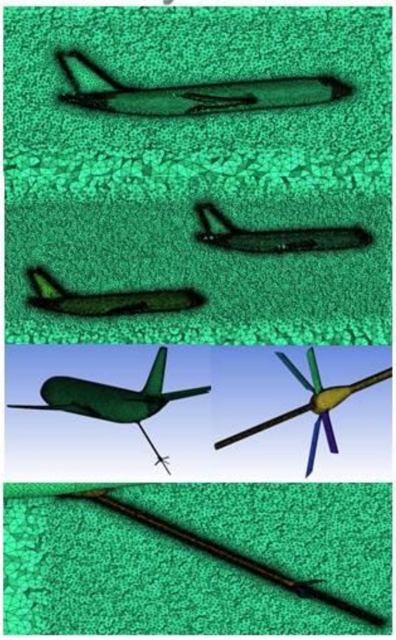
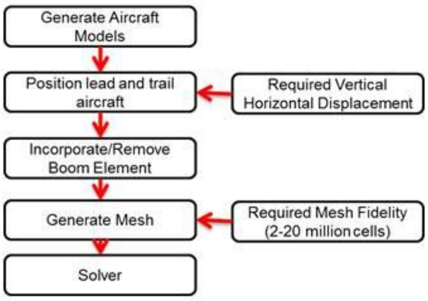
WP 4 – Design

Analysis of Interference Effects



The introduction of the secondary aircraft raises problems for stability of the following aircraft which is operating in the wake of the lead aircraft

This further is further exasperated by the presence of the boom which is required for the refuelling operation itself.

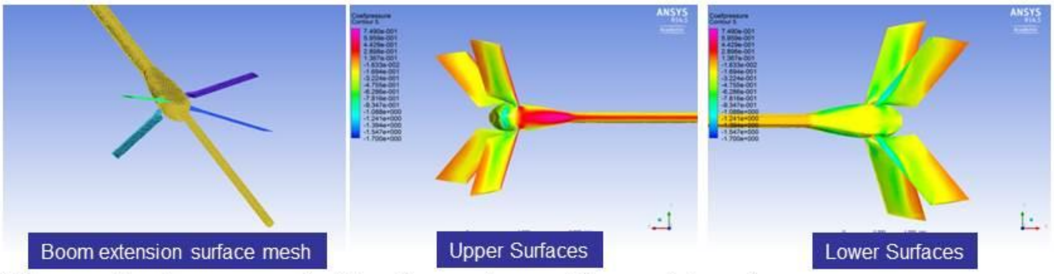


Model Generation, positioning, meshing and solver (Fluent) integrated and automated using a Matlab wrapper

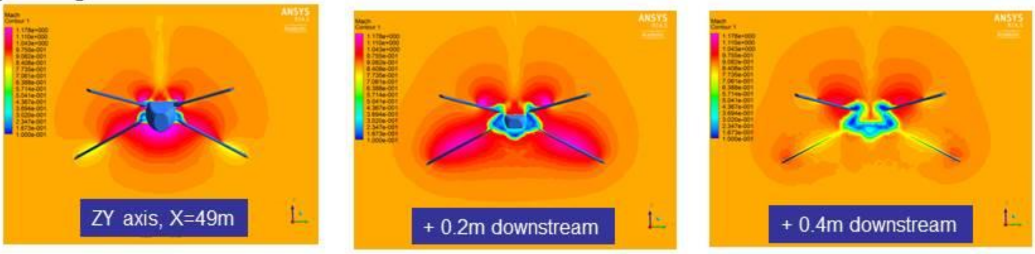
A number of initial trials were completed to ensure functionality of the automation wrapper

WP 4 – Analysis of Interference

Integration of boom (isolated)



Strong shocks generated leading edges of the ruddervators.
Cut planes clearly indicate flow dissymmetry between upper and lower ruddervator pairings



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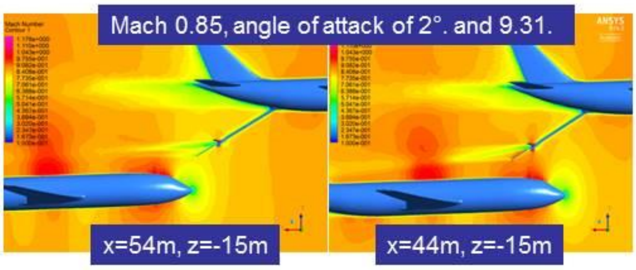
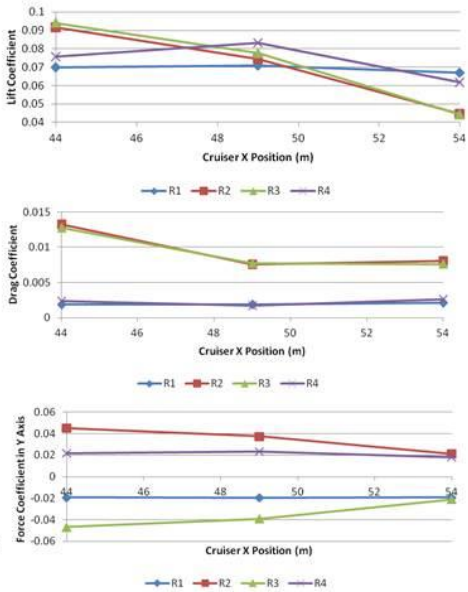
WP 4 – Analysis of Interference
Integration of boom (Cruiser-Feeder)



As the boom is moved closer to the cruiser aircraft, there is significant flow acceleration around the ruddervators as the boom protrudes into the shock generated by the cruiser aircraft.

Significant increase in drag on the boom induced by the start of the interaction with the shockwave.

Moving closer to cruiser still has a more significant effect on lower rather than upper ruddervators



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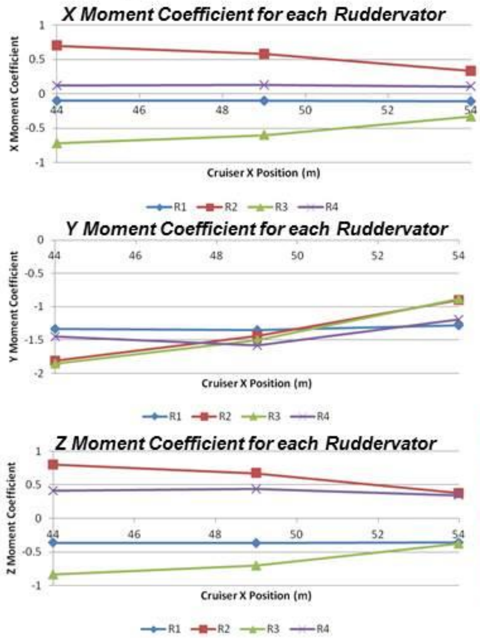
WP 4 – Design
Impact on Ruddervator Moments

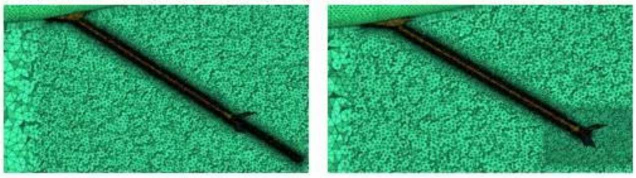


All moments for the upper ruddervators largely independent of the cruiser position

All lower ruddervators moments reduce with increasing distance from cruiser.

Pronounced negative moment in the y-plane - acts to push the boom and the ruddervators up and away from the cruiser towards the storage position.

Likely to have undesirable aeroelastic effects and impact on the control.



Boom extension needs to be removed to evaluate closer to surface

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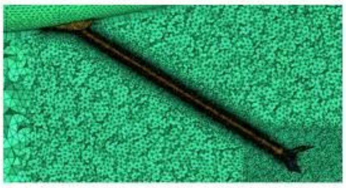
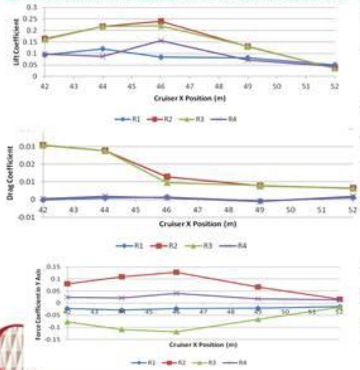
WP 4 – Analysis of Interference
Boom in Close Proximity to Cruiser (extension removed)

With the extension removed, the z displacement reduced to 10 metres (12.5 metres) to account for curvature



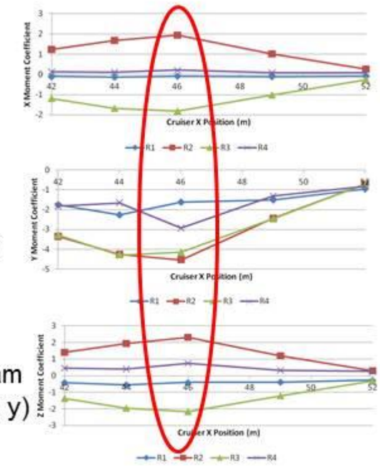
Position	P1	P2	P3	P4	P5
X (m)	52	49	46	44	42
Z(m)	-10	-10	-12.5	-12.5	12.5



As boom passes into shock, significant drag increases accompanied by pronounced increase in –ve y moment.

Some asymmetry on upper surfaces present at this point, maybe indicative of transient flow at this point.

Shock induced moments rapidly reduce with increasing downstream distance (most prevalent in x and y)



WP 4 – Design
Analysis of Interference Effects

Conclusions

- Interference effects at transonic speeds are less critical than feared,
- Interference affects control surface derivatives, but is manageable,
- Aerodynamic interference is no showstopper.

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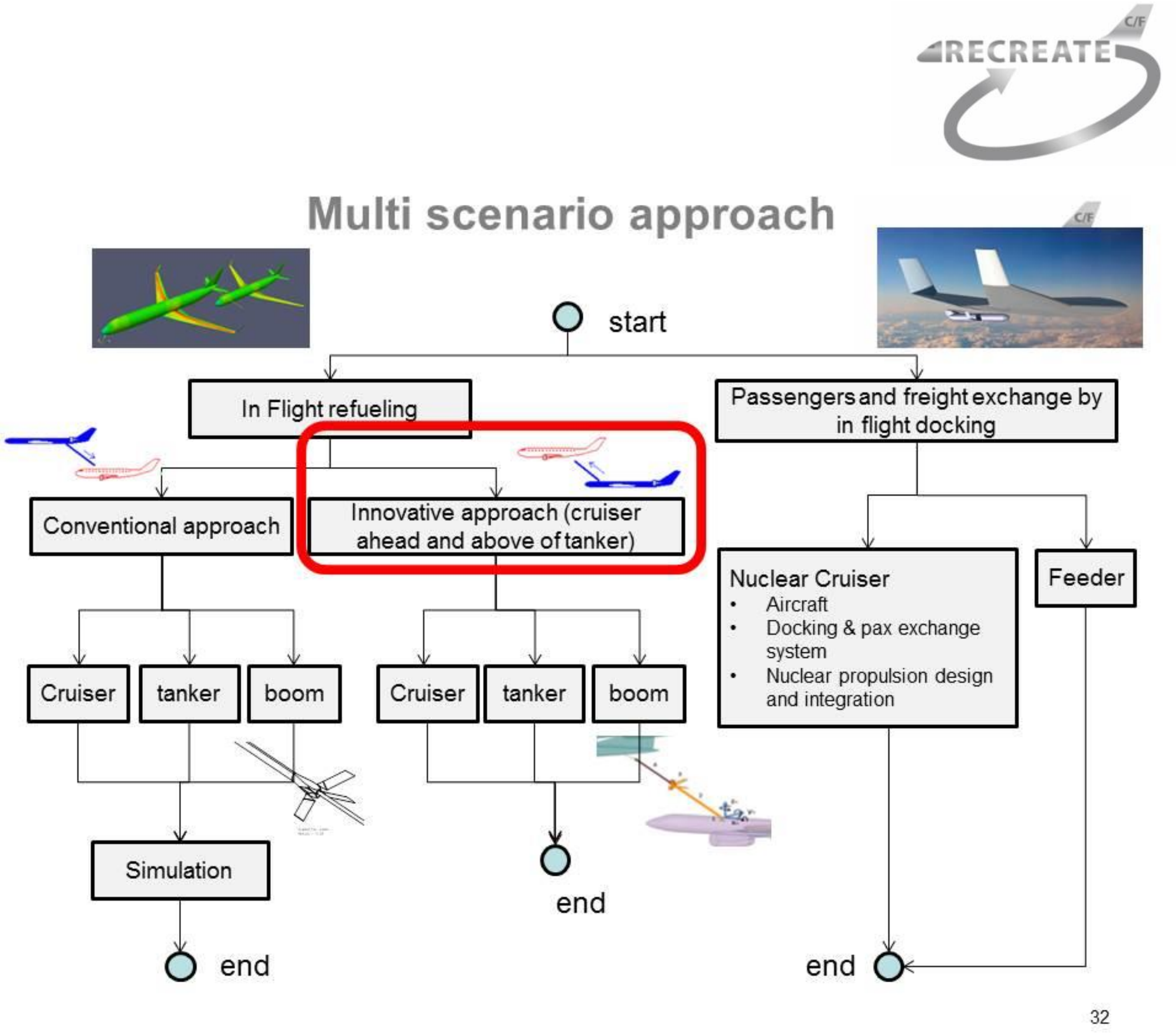
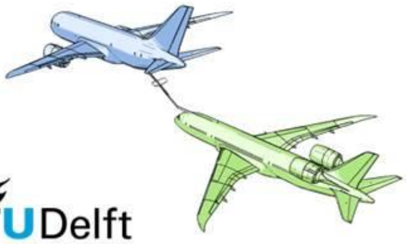
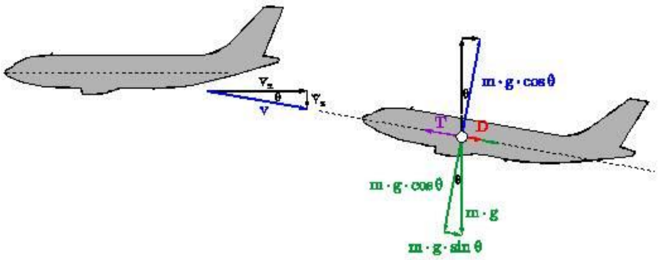

RECREATE
Multi scenario approach
start
In Flight refueling
Passengers and freight exchange by in flight docking
Conventional approach
Innovative approach (cruiser ahead and above of tanker)
Nuclear Cruiser
• Aircraft
• Docking & pax exchange system
• Nuclear propulsion design and integration
Feeder
Cruiser
tanker
boom
Cruiser
tanker
boom
Simulation
end
end
end
32

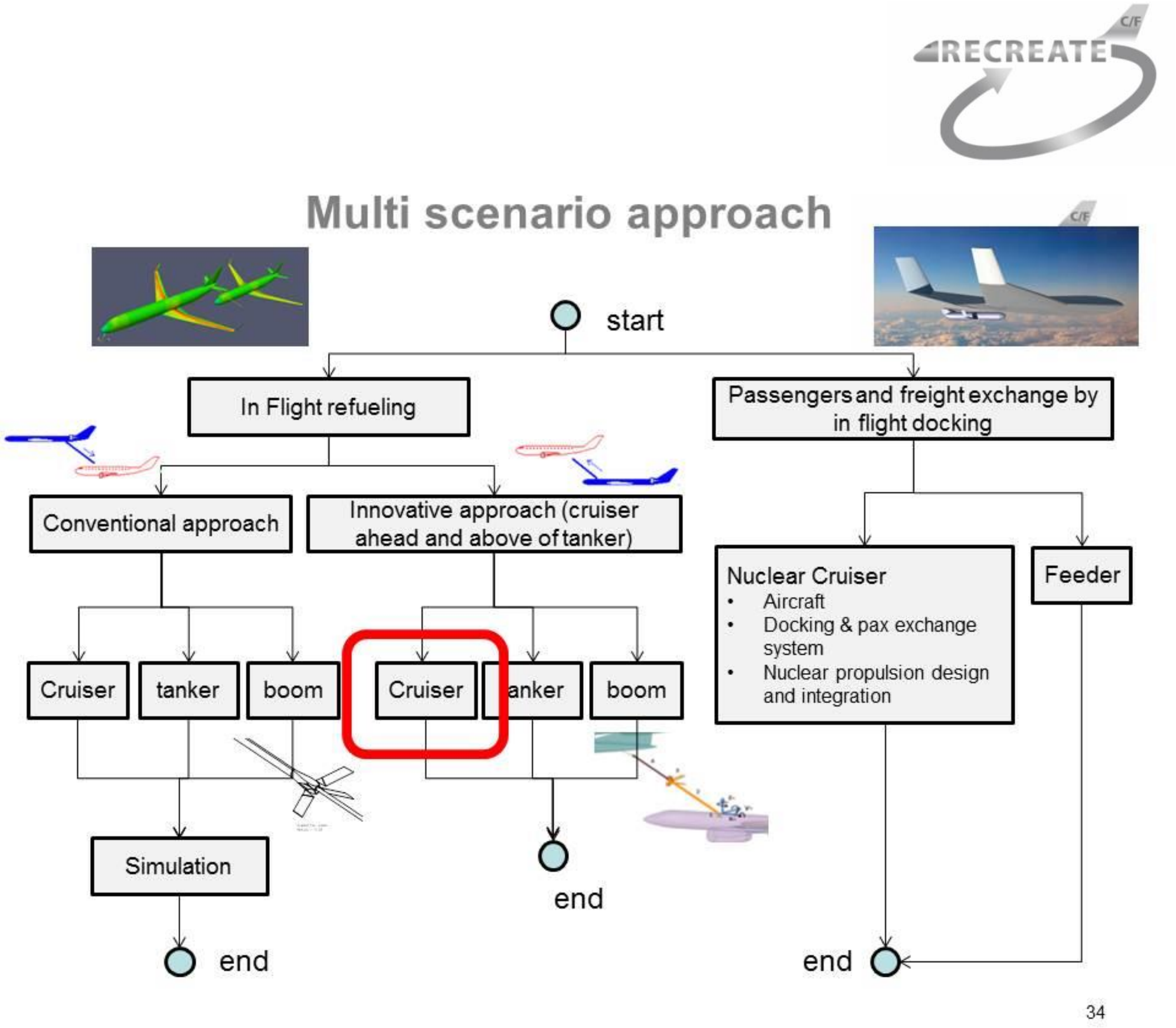
Unconventional AAR approach Benefits

Main advantages

- No hazard of collision with parts detaching from the tanker
- Cruiser pilots are not required to perform the approach maneuver
- Passengers not subjected to maneuvering acceleration
- No extra thrust requirement for passenger aircraft during refueling
- Cruiser's architecture and payload volume minimally affected by the presence of the refueling system (boom on tanker).







RECREATE
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Feeder
Cruiser
tanker
boom
Cruiser
anker
boom
Simulation
end
end
end
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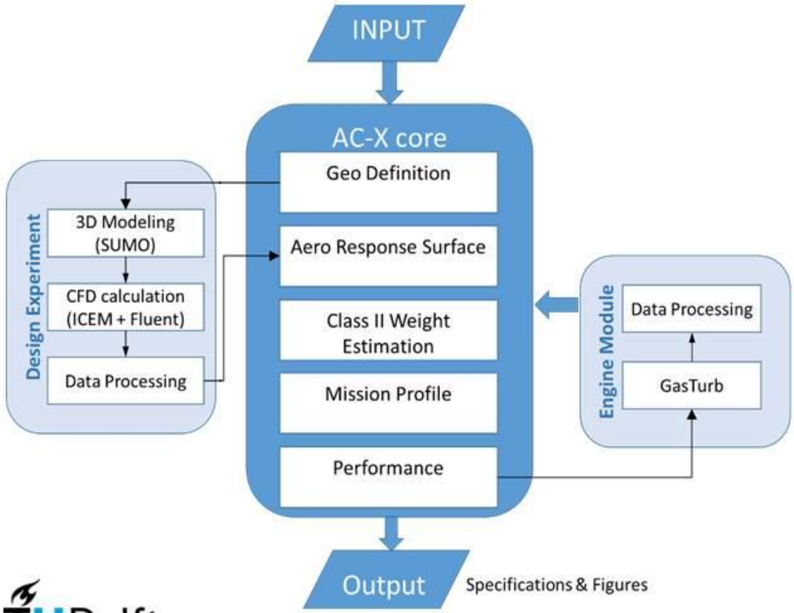
Cruiser Design
TU Delft Conceptual design tool



_AC-X_ main features

- Largely Excel based
- Usable for both Cruiser and Tanker
- Allows complex missions definition
- Aerodynamic analysis based of response surfaces from CFD analysis (FLUENT)
- Allows engine design (GASTURB)
- Allows plenty of user interaction

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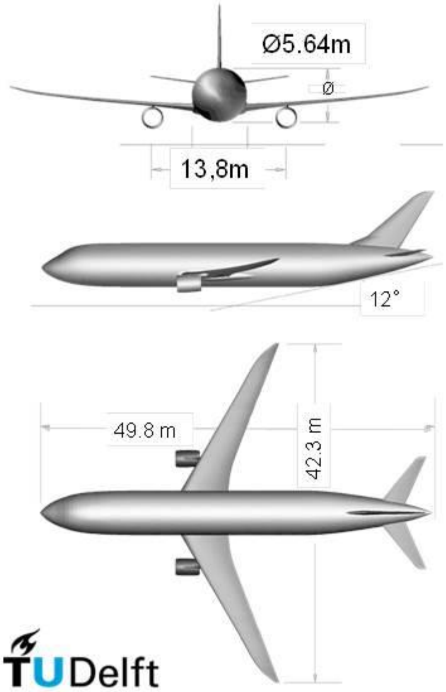
Cruiser Design

Design results from AC-X

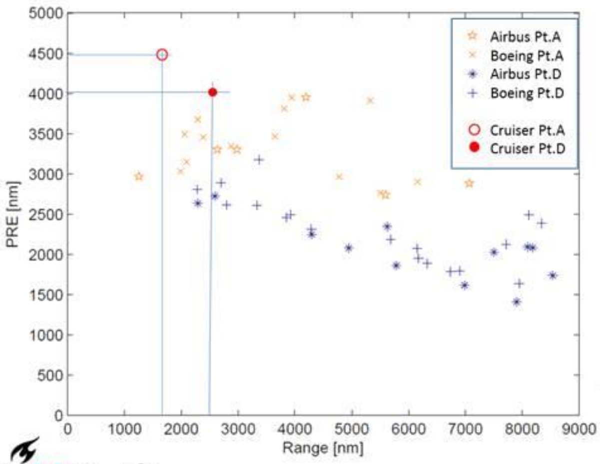


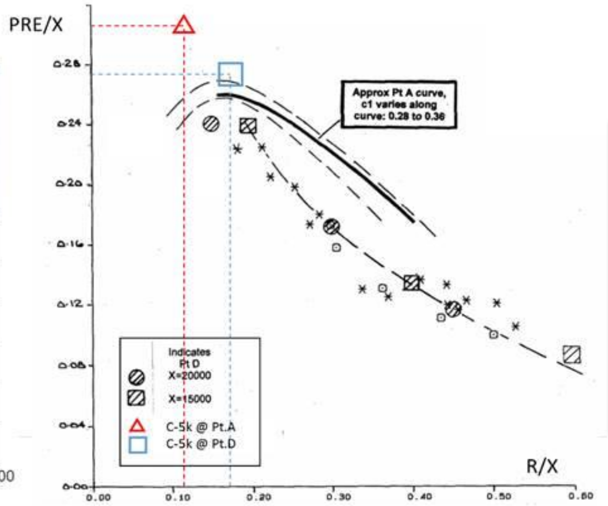
OEW [kg]	52,589
MTOW [kg]	100,865
OEW / MTOW	0.52
Total mission fuel weight [kg]	32,929
Fuel received via AAR [kg]	14,505
Fuel reservation [kg] (250nm diversion+30 minutes loitering+5%	3,352
T/MTOW	0.3
Wing Area [m²]	164
Span [m]	42.4
Aspect Ratio	11
Cruise L/D	16.2
PRE [nm]	4,024
X [nm]	14,409
PRE/X	0,279

Cruiser Design
Design results from AC-X

$$PRE[m] = \frac{WP[kg] \cdot R[m]}{WFB[kg]}$$

$$X[m] = \frac{V[m/s] \cdot L/D[-]}{SFC[1/s]}$$





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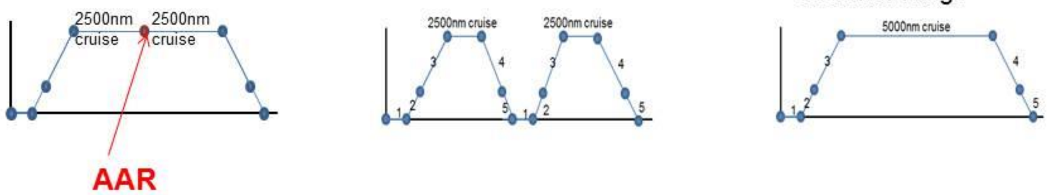
Cruiser Design

Comparison of AAR with Staging and Direct flight

AAR cruiser ***C-5k***
5000nm with AAR

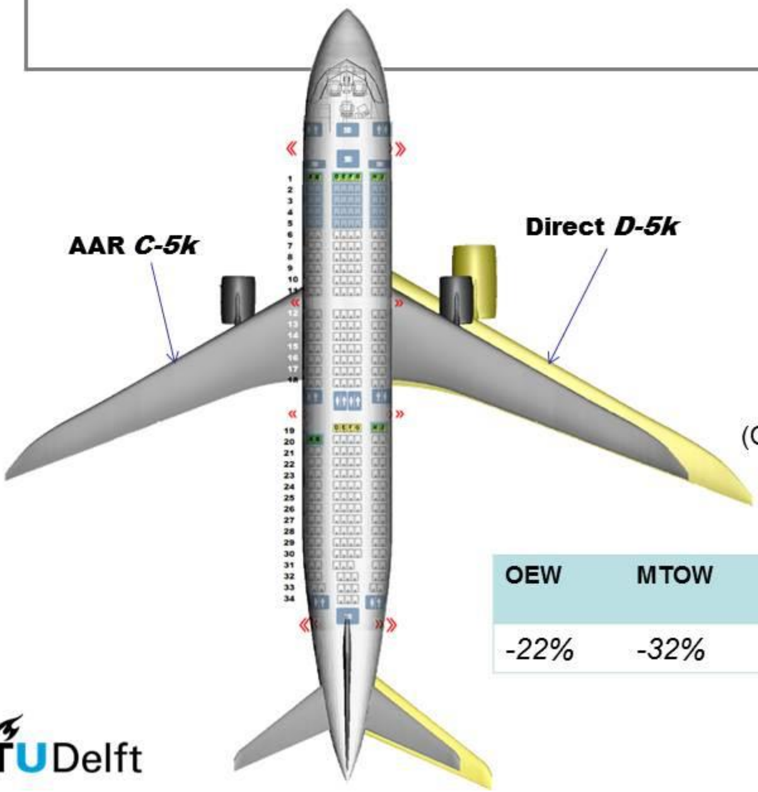
I-2.5k
Intermediate stops
2500nm range

D-5k
Direct flight variant
5000nm range



All aircraft designed with same tool

Cruiser Design
Comparison of AAR with Direct flight



AAR vs Direct Flight
(Cruiser only, excluding the tanker)

OEW	MTOW	Mission Fuel	Engine Thrust	Wing Area
-22%	*-32%*	***-20%***	*-32%*	*-31%*

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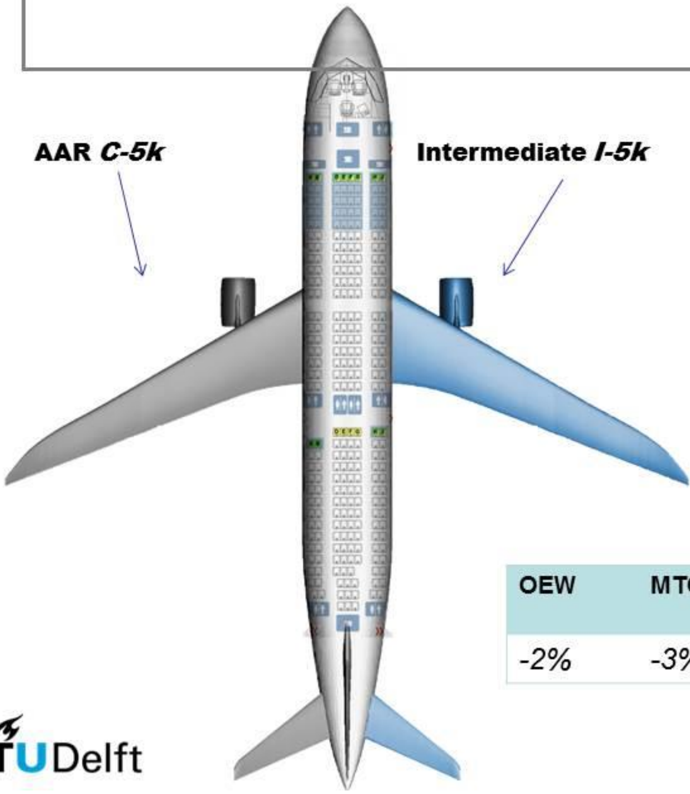
Cruiser Design

Comparison of AAR with Staging flight



AAR vs Staging Flight

(Cruiser only, excluding the tanker)

OEW	MTOW	Mission Fuel	Engine Thrust	Wing Area
-2%	-3%	**-7%**	-4%	-4%

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Cruiser Design

AAR cruiser vs. existing aircraft for same AAR operations

Cruiser C-5k vs B737-800 & B767-300 (same **5,000nm AAR** mission)

	Cruiser	B737-800*	Δ	B767-300**	Δ
MTOW [kg]	100,865	75,477	-25.1%	147,985	46.7%
OEW [kg]	52,589	38,624	-26.5%	79,028	50.3%
Payload [kg]	26,500	18,587	-29.9%	25,017	-5.6%
Pax	250	186	-25.6%	260	4.0%
Seat Pitch [m]	.85	.76	-10.4%	.80	-5.9%
Mission fuel [kg]	32,929	28,201	-14.3%	51,140	55.3%
PRE [nm]	4,024	3,297	**-18.1%**	2,446	**-39.2%**
PRE/X	0,279	0,267	**-4,2%**	0,187	**-33%**

*B737-800 similar design range **B767-300 similar pax capacity

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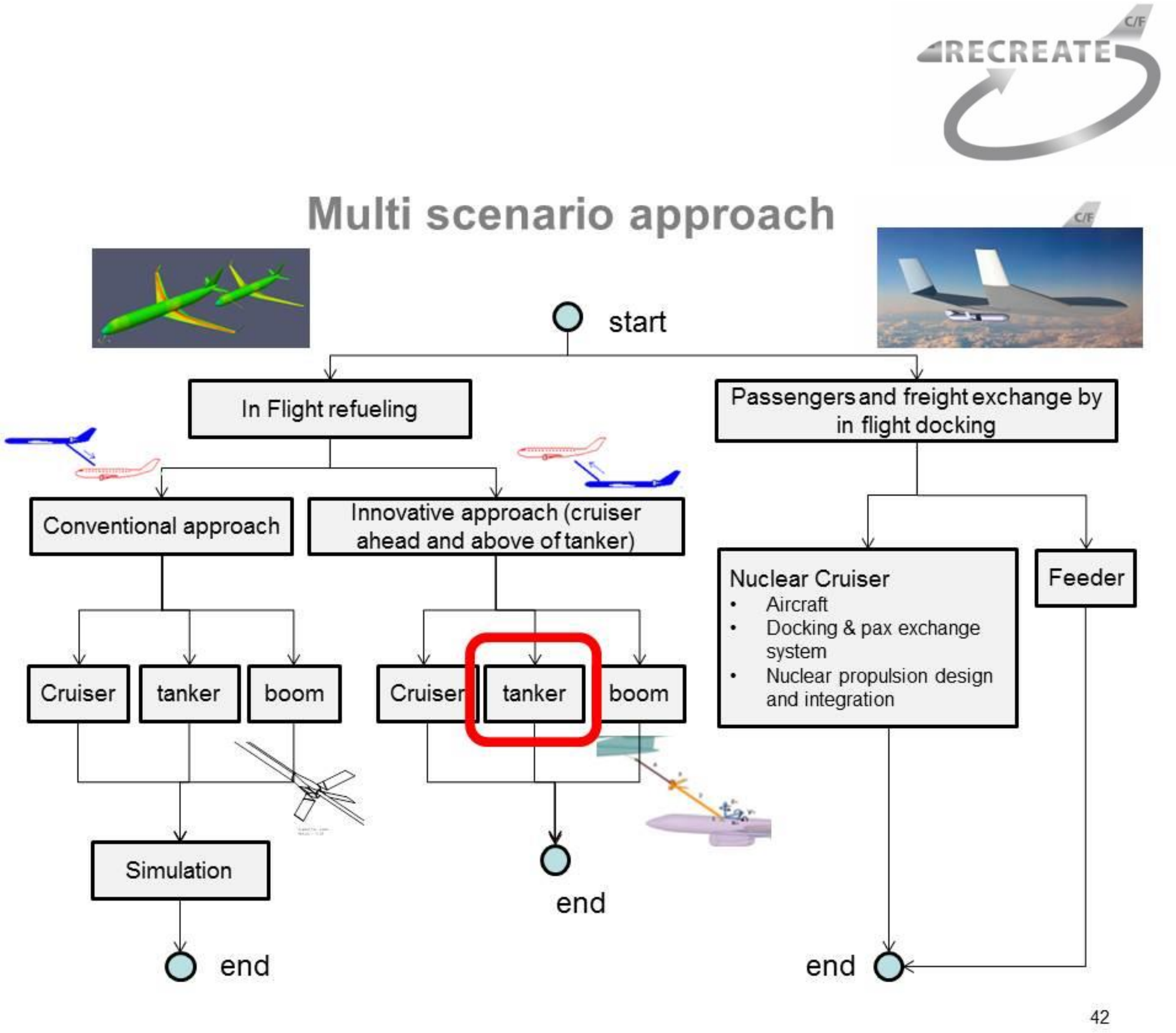

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Cruiser
tanker
boom
Cruiser
tanker
boom
Simulation
end
end
end
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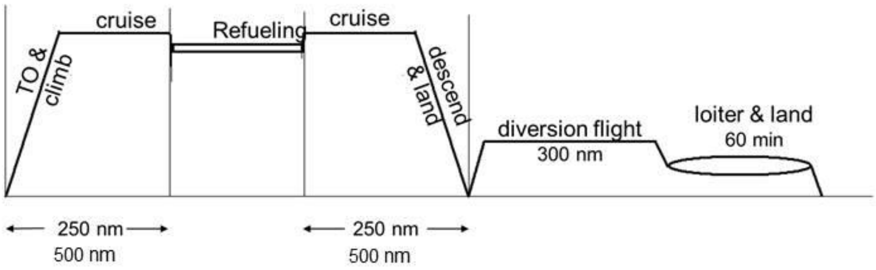
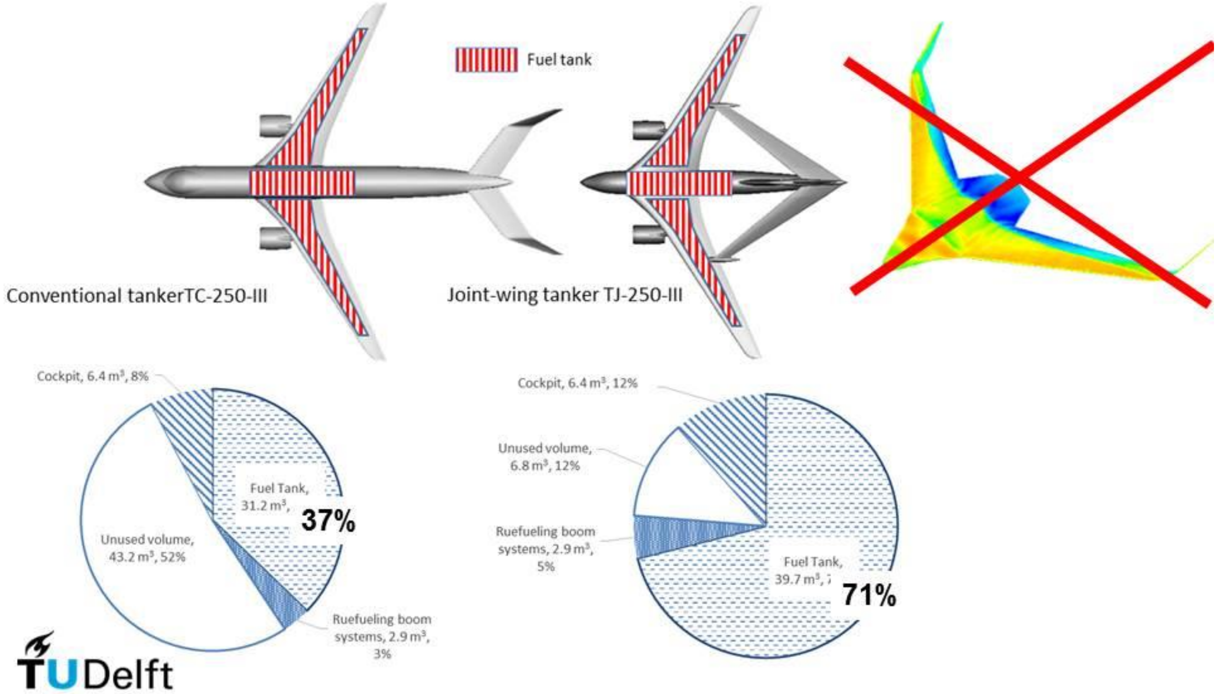
Tanker Design
Configuration Study



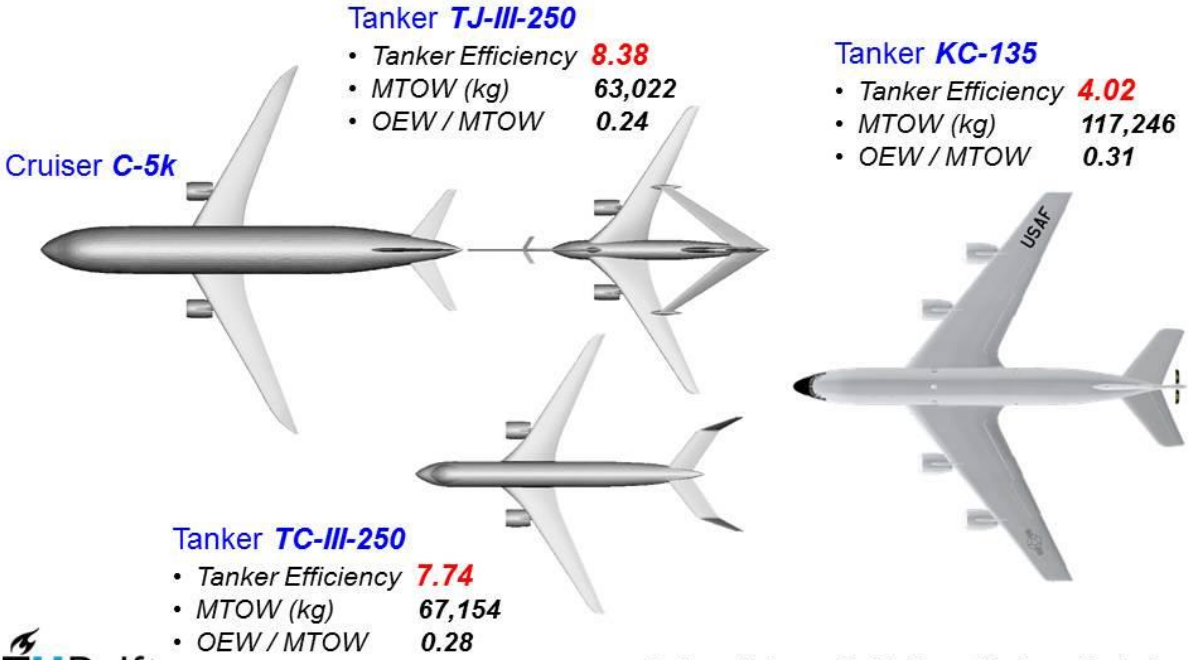
Fuel offload per tanker [kg]	14,505
Number of refueled cruisers per mission	**1-5**
Refueling radius [nm]	**250-500**
Contact time during refueling [min]	20
Waiting time between refueling [min]	20
Mach @ cruise	0.82
TO&L field Length at sea level [m]	2500

Tanker Design

Configuration Study



Tanker Design
Comparison



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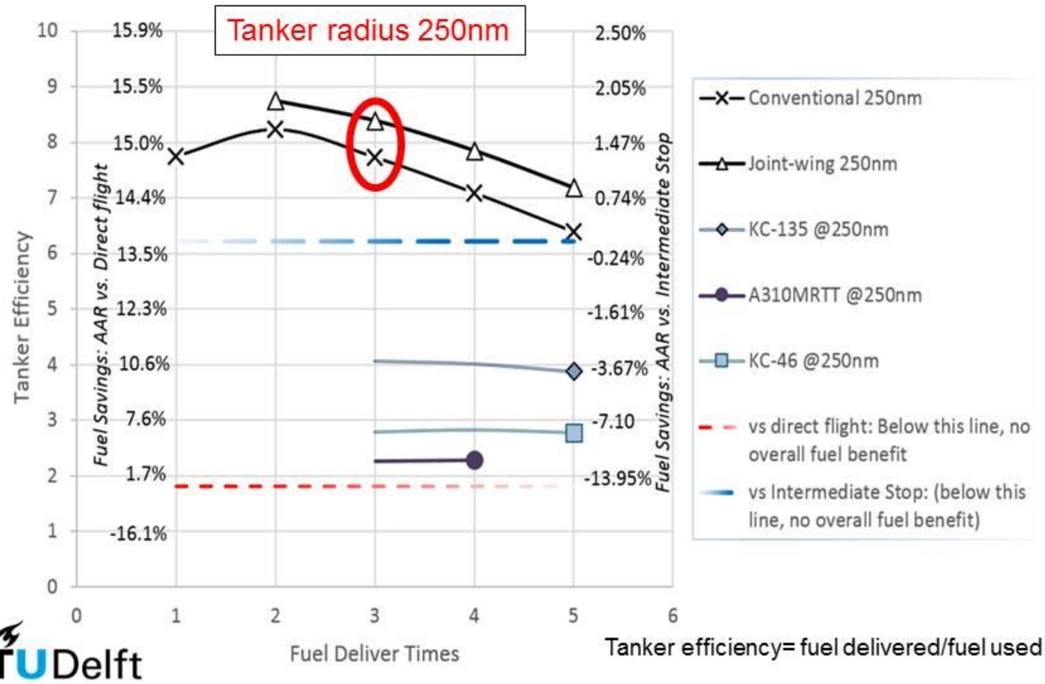
Tanker efficiency= fuel delivered/fuel used by tanker

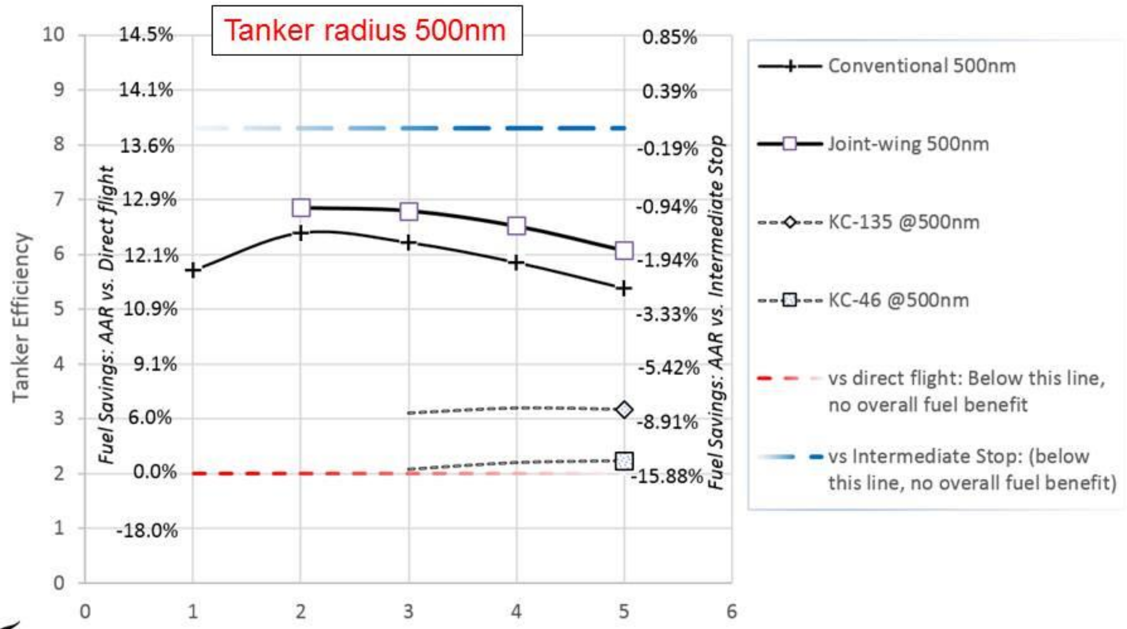
Cruiser-Tanker Design

Benefit analysis



Tanker efficiency= fuel delivered/fuel used by tanker

Cruiser-Tanker Design
Benefit analysis



Tanker efficiency= fuel delivered/fuel used by tanker

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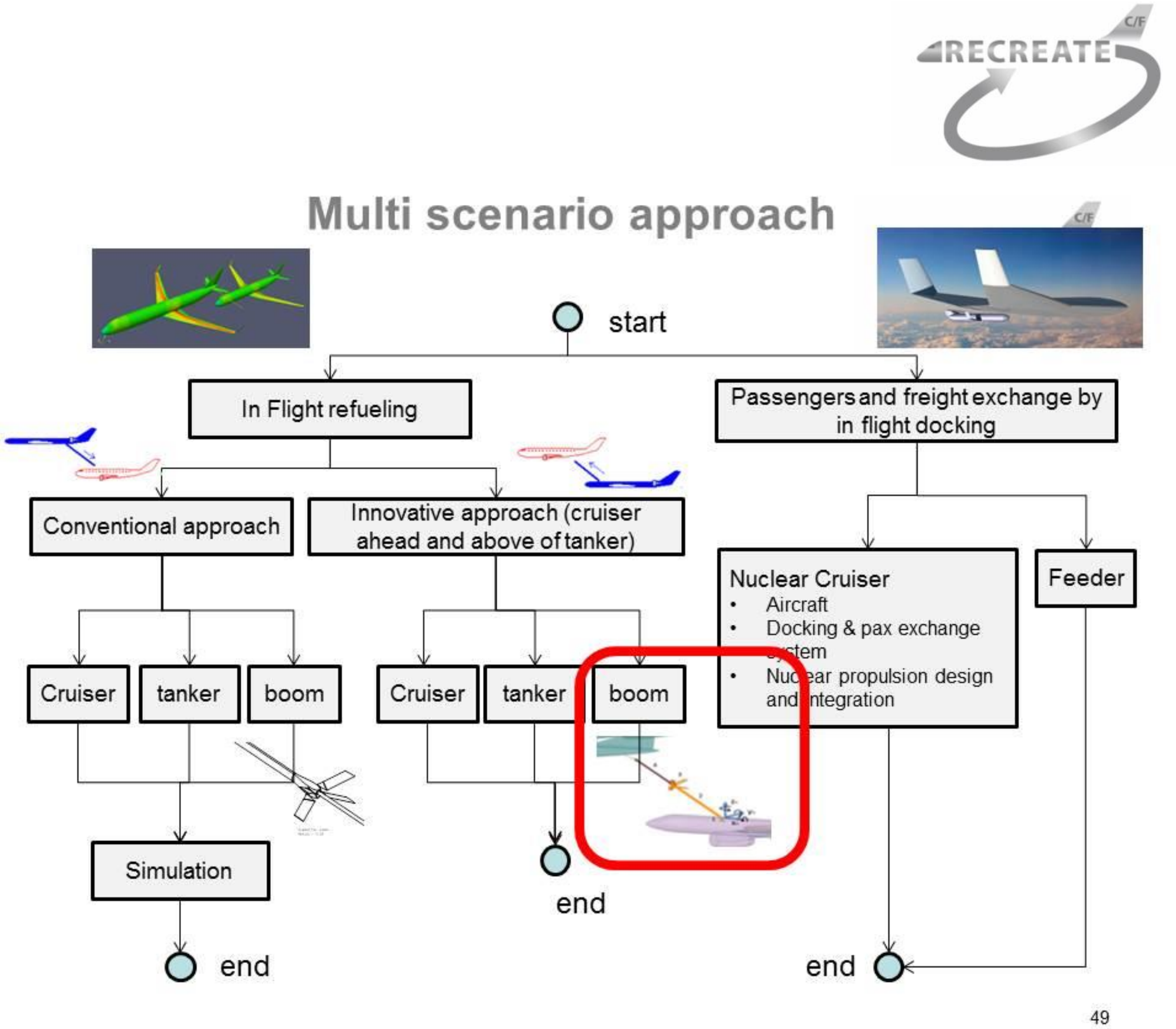
Cruiser-Tanker design
AAR fuel benefit estimation

Fuel savings	with Joint Wing tanker Radius: 250nm N. of served cruisers: 3	with Conventional Tanker Radius: 250nm No. of served cruisers: 3	with best existing tanker
AAR vs direct	**15.2%**	**14.8%**	**10%**
AAR vs Staging	**1.7%**	**1.3%**	**-3.7%**

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end
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end
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Forward extending boom design

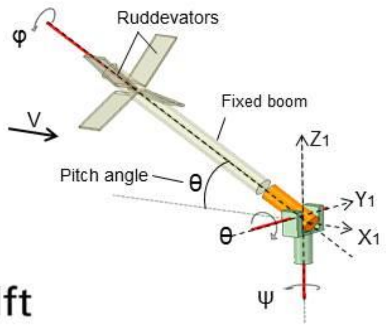
Kinematic options

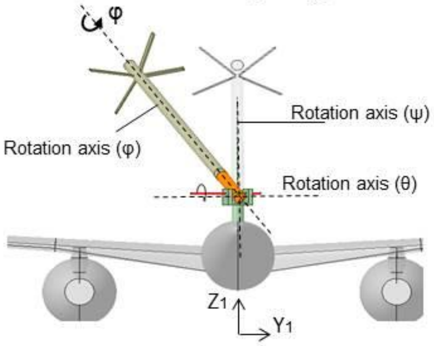
Challenge : Design a boom which is **fully controllable** and free of **aeroelastic instabilities**.

Considered kinematic options:

1.Lateral actuated boom (plus variant with self-aligning fairing for drag reduction);
2.Rolling boom;
3.Roll actuated kinematic relation

- Rotation around Z1 axis (Yaw movement, angle: ψ)
- Rotation around Y1 axis (Pitch movement, angle: θ)
- Rotation around Boom (Boom longitudinal axis, actuated angle: φ)





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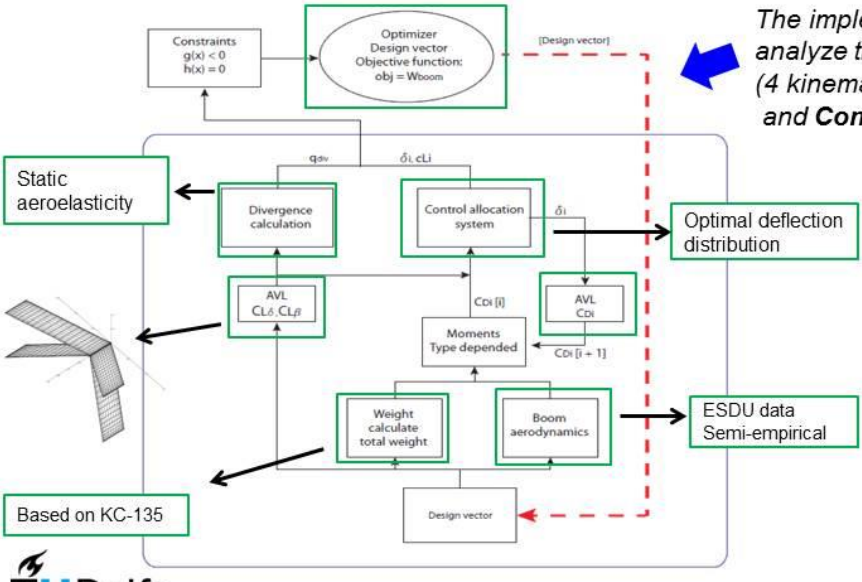
Forward extending boom design

MDO sizing framework

Part 1: Downselection of **feasible designs** based on **controllability** and static aeroelastic instability (**divergence**).

The implemented MDO framework to analyze the 8 boom variants (4 kinematic relations with ***Aluminum*** *and* ***Composite*** *material)*



Design variables:

- Length Fixed Boom
- Ellipse chord length
- Ellipse chord width
- Inner house diameter
- Wall thickness
- Ruddevator span
- Ruddevator aspect ratio

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Forward extending boom design
Dynamic aeroelastic design

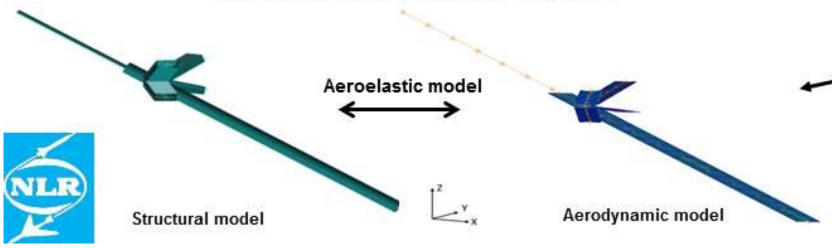
Part 2 : Aeroelastic instability investigation (flutter) for the feasible designs
Goal : Prevent flutter in the entire operating envelope as defined by regulations

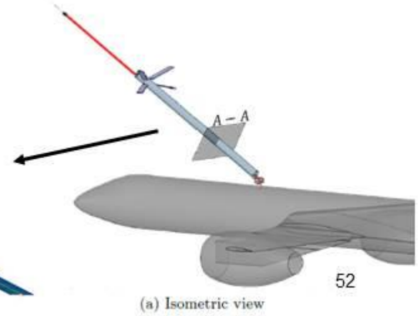
CS – 25 Regulations as guideline for analyses:

- All combinations of normal speed (+15%) and altitude conditions

- Selected Failure cases (up to Vd/Md):
  - Ruddevator actuator failure;
  - Dual hydraulic system failure;
  - Ruddevator structural failure.

- Most significant design variables:
  - Ruddevator actuator stiffness
  - Extending boom bending stiffness





(a) Isometric view

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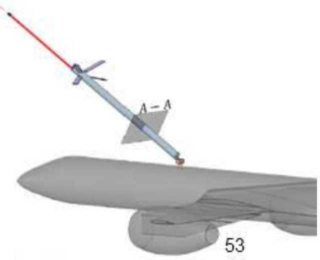
Forward extending boom design
Conclusions

- There is a feasible design space for the entire operating envelope in which the boom is controllable and aeroelastically stable (free from flutter and divergence).
- Roll actuated kinematic relation is selected which composite material to increase the bending stiffness of the boom
- Failure cases are not a show stopper:
  - Ruddevator actuator failure: Lock system, positive aeroelastic effect
  - Dual Hydraulic System failure: Dampers not possible, should be considered extremely improbable

Boom Property	KC-135 boom	FW Ext boom Composite	%
Length Fixed boom [m]	8.4	11	+30%
Length Extending boom [m]	8.2	9.9	+21%
Slenderness ratio, b/c [-]	0.5	0.7	+40%
Mass [kg]	607	516	-15%



(a) Isometric view

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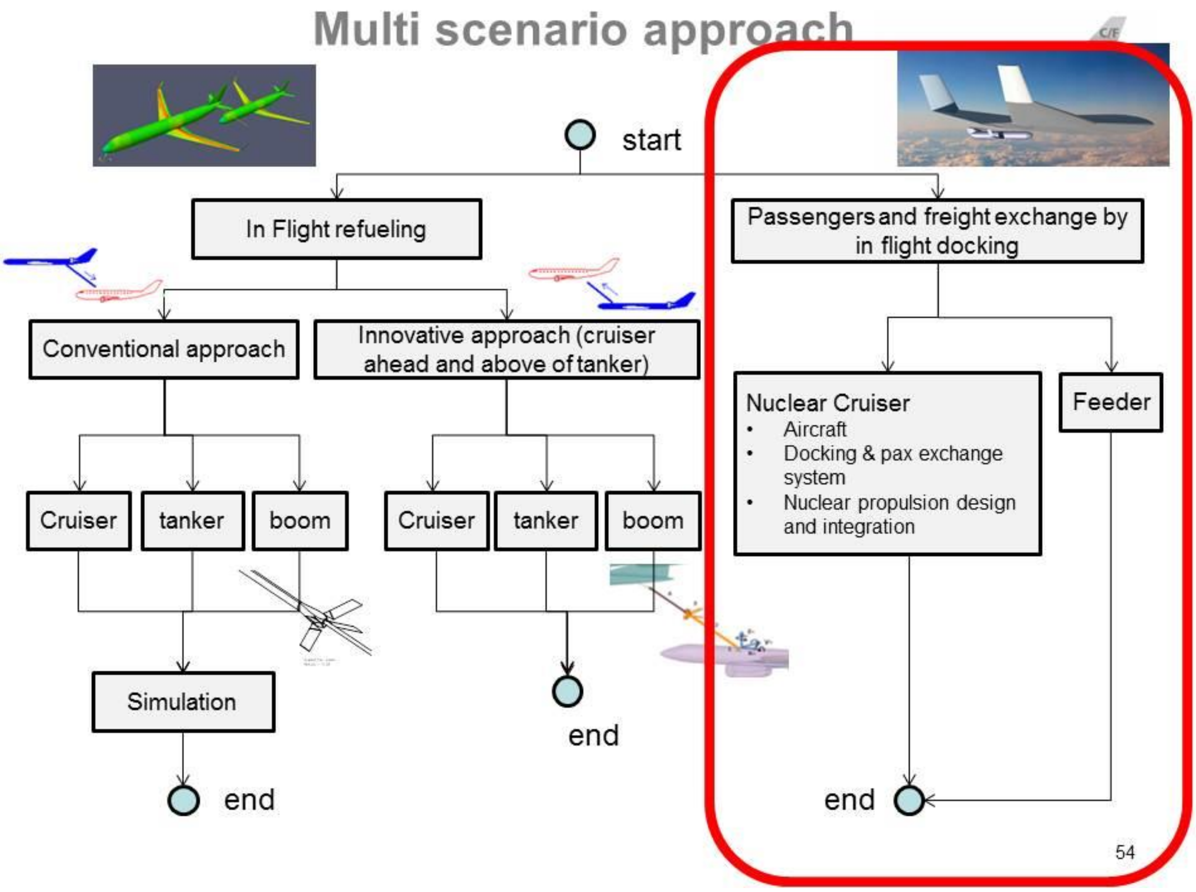

Multi scenario approach
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Nuclear Cruiser
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Feeder
end
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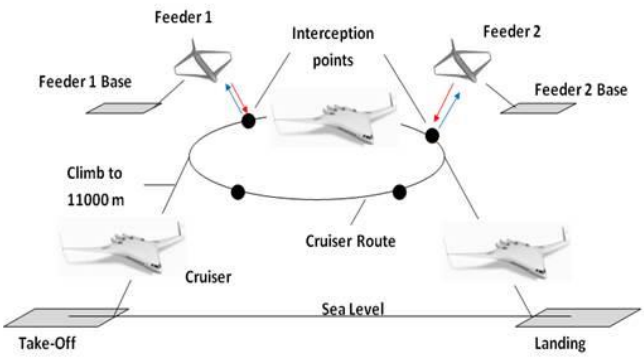
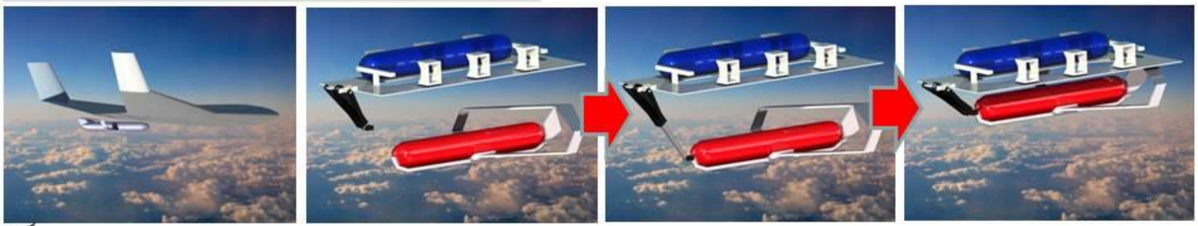
Nuclear cruiser

Nuclear cruiser requirements and docking approach

Pax capacity	1000 PAX
MTOW	$900 \cdot 10^3$ kg
Range	$112 \cdot 10^3$ km 1 week endurance
Cruise speed	M = 0.8
Docking Speed	M = 0.7
L/D	>20
Cruise altitude	$h_{cruise} > 11000$ m
Fuel	Uranium 235/ jet fuel
Pax Transfer Concept	Single container station concept (100 pax each)





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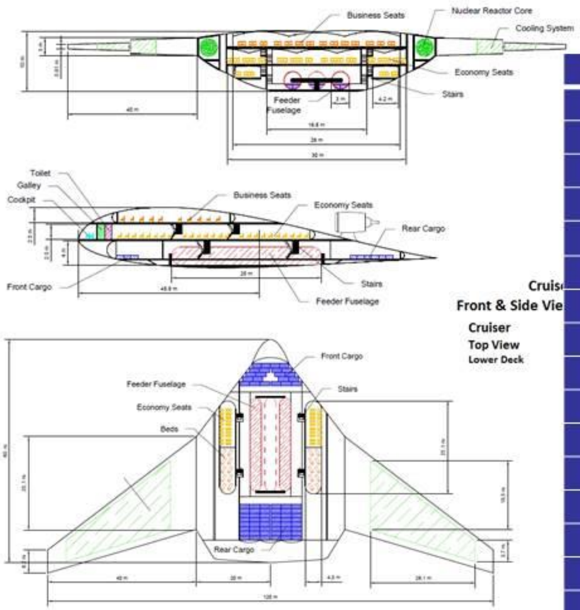
Nuclear cruiser
Conceptual design (Iteration 2)



	Symbol	Value	Units
Root thickness	t_{root}	10	m
Span	b	122	m
Wing Surface	S	2469	m^2
Aspect Ratio	A	6	-
Aerodynamic Efficiency	L/D	22	-
Take-Off Weight	W_{TO}	894	10^3 kg
Max Operating weight	W_{MO}	1000	10^3 kg
Operative Empty Weight	W_{OE}	367	10^3 kg
Payload Weight	W_{PL}	106	10^3 kg
Power Plant Weight	W_P	482	10^3 kg
Wing loading	W/S	360	kg/m^2
Fuel for takeoff & landing	W_{F-TOL}	31.4	10^3 kg
Fuel reservation	W_{F-R}	34.3	10^3 kg
Static thrust	T	1743	kN
Takeoff distance	L_{TO}	6,402	m
Landing distance	L_{LND}	2,546	m

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Nuclear cruiser
Conceptual design (Iteration 2)

Overall Sizing

•Max Operating weight (1000 ton) is a design input (≠ MTOW)

•Wing geometry based on first design iteration (D4.1), and here resized for the updated TO weight.

Weight estimation

•Operative empty weight estimated using a class II weight estimation method then corrected by 5% to account for future technology for weight reduction

•Weight of passenger transfer system estimated 2.5%MTOW

Propulsion system

•4 turbofan engines (sized by means of GasTurb)

•Nuclear propulsion system sized for cruise condition only.

•TO&LND performed with jet fuel.

•Diversion flight (in case one reactor / cycle fail): 44% of the overall propulsion power provided by chemical fuel.

Field performance

•The cruiser takes off with no payload onboard, and one empty pax container.
•TO distance calculated based on available TO thrust (not an input).
•OEI case considered.

Nuclear cruiser
propulsion design

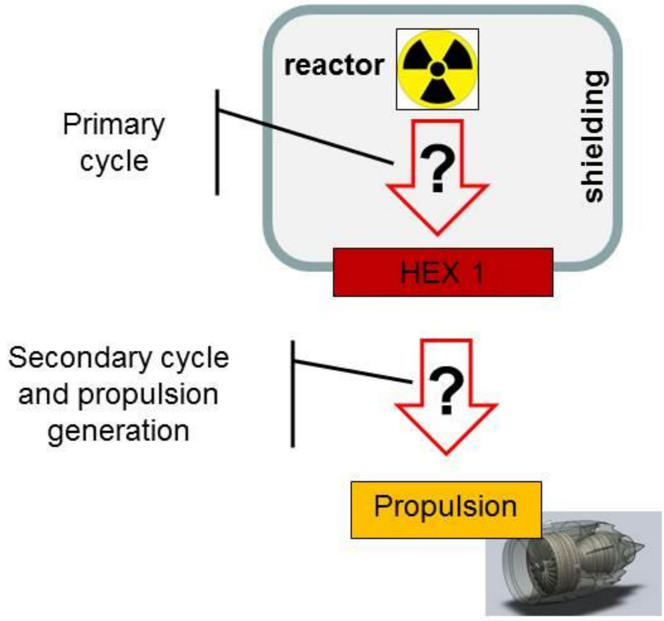
Double cycle concept:

Primary cycle (reactor coolant):

- Inside shielding
- Transfer heat from reactor core
- Liquid lead-bismuth eutectic (LBE)

Secondary cycle:

- Outside shielding
- Transforms heat into propulsive power using thermodynamic processes



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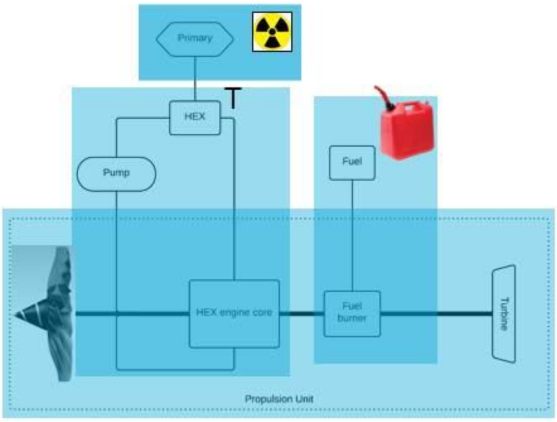
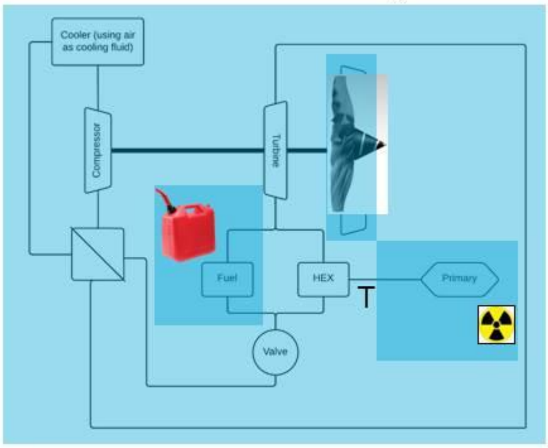
Nuclear cruiser

propulsion system options

Open Cycle



Closed Cycle



[illegible] exhausts

[illegible]

Nuclear cruiser
propulsion system options

- An optimization framework was developed to size the components of the two propulsion systems, **along with** the thermodynamic state of each cycle option (operating pressure and temperature).

- **Objective**: minimize propulsion system weight, while retaining safety.

- The computed weight and overall size of the **selected** propulsion system are used for the **cruiser second design iteration**

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Nuclear cruiser
propulsion system options

Preliminary results (cycle optimisations are still running)

Cycle option	Approximate weight (kg)
Open	120,000 (excluding primary HEX)
Simple Closed (regenerative)	200,000
More Complex Closed (recompression)	230,000*

* The recompression cycle can achieve higher efficiencies, saving reactor power and shielding weight

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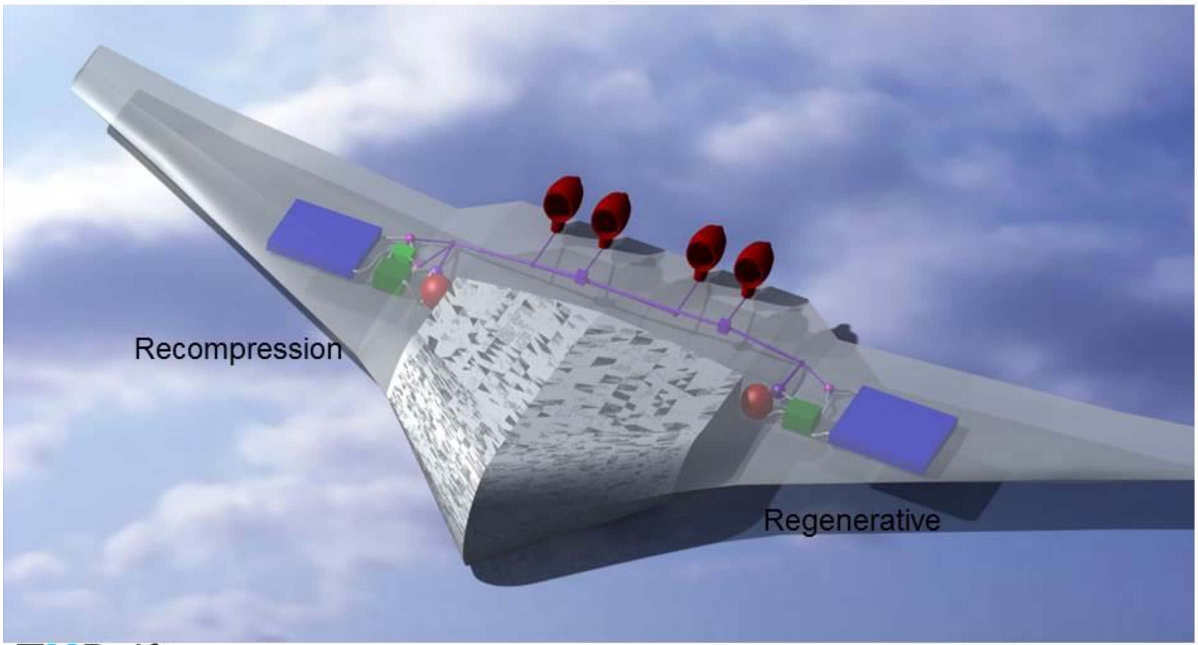
Nuclear cruiser
Conceptual design (Iteration 2)



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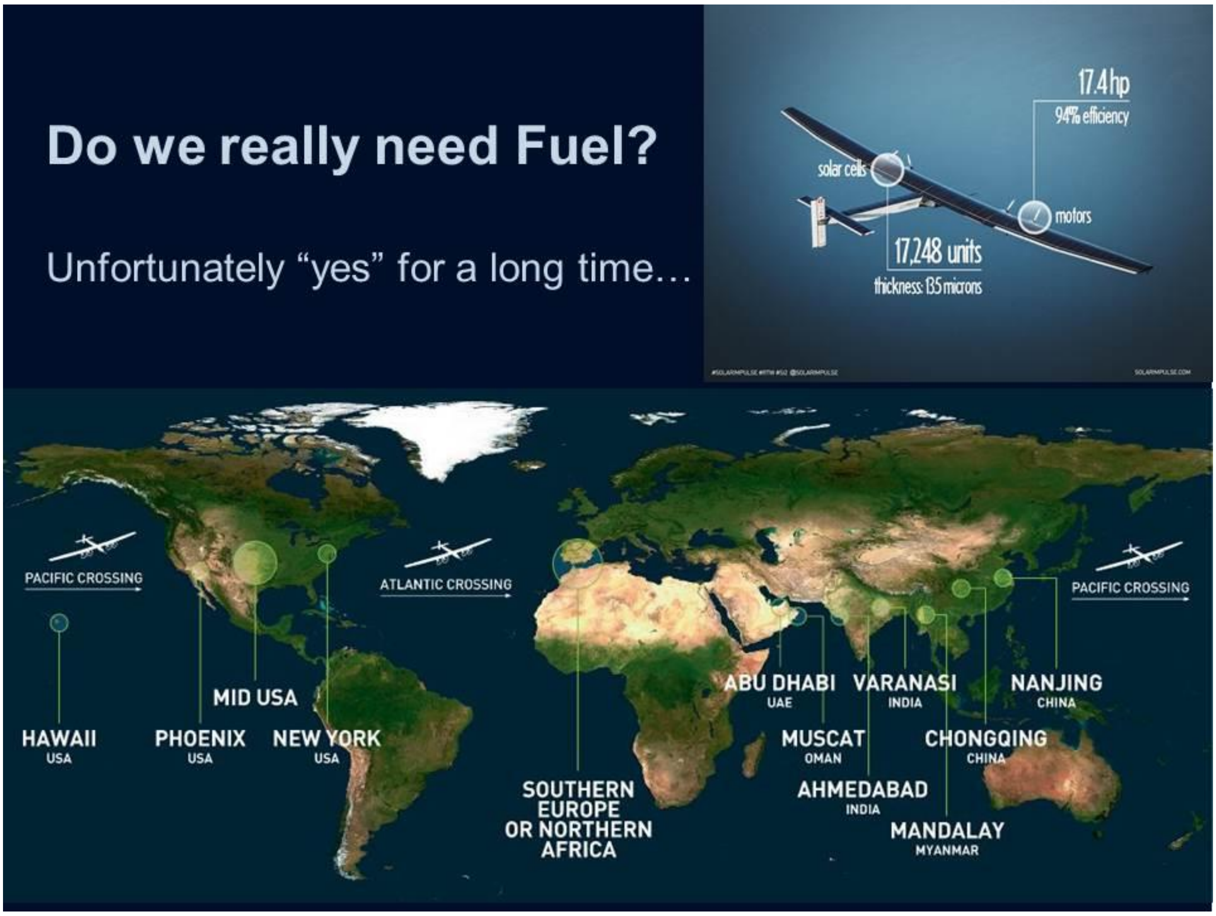
Dr. R. K. Nangia
Nangia Aero Research
Associates


Do we really need Fuel?
Unfortunately “yes” for a long time…
17.4 hp
94% efficiency
solar cells
motors
17,248 units
thickness: 135 microns
PACIFIC CROSSING
ATLANTIC CROSSING
PACIFIC CROSSING
HAWAII
USA
PHOENIX
USA
MID USA
NEW YORK
USA
SOUTHERN
EUROPE
OR NORTHERN
AFRICA
ABU DHABI
UAE
MUSCAT
OMAN
VARANASI
INDIA
AHMEDABAD
INDIA
MANDALAY
MYANMAR
CHONGQING
CHINA
NANJING
CHINA

Amsterdam — January 2015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Appendix E Final results of WP5

REsearch on a CRuiser Enabled Air Transport Environment

WP5: Automation

Final Meeting in Amsterdam
29 January, 2015

The 42-month RECREATE project research receives funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 284741.
This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.

Overview

- Objectives
- Transfer Process and Maneuver Design
- Cruiser, Feeder and Boom Guidance and Control
- Sensors, Data Fusion & Navigation
- Mode Selection, Supervision and Performance Monitor
- Automatic Flight Control Development and Simulation Environment
- Closed-Loop Simulation Results
- Safety Simulations

2

Objectives (1/2)

To demonstrate on a preliminary design level that the cruiser/feeder concept can be shown to ever comply with airworthiness requirements for civil aircraft.

⇨ Automatic control system for A/C relative position and boom control

- Maneuver design
- Control algorithms
- Sensors & Measurement data fusion

- Prove of safety by simulation
  - Events with very small probability of occurrence
  - To support safety assessment
  - And subsequently demonstrate technical feasibility for civil applications

3

Objectives (2/2)

- What for?
  - Simulation assessment of feasibility of automated cruiser-feeder operations
    - Design of components
    - Development and test of algorithms

- F

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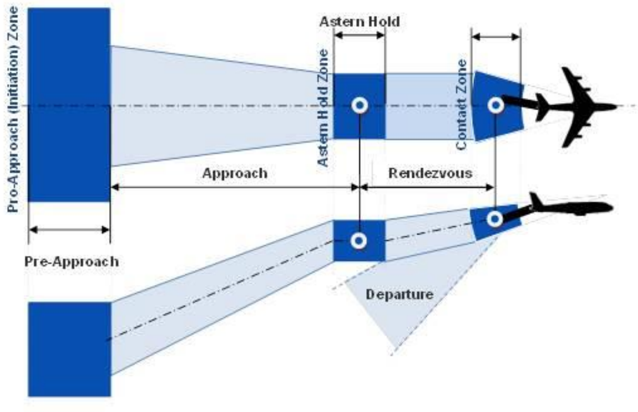
4

Transfer Process and Maneuver Design (1/2)

- Consideration of complete maneuver
- Starting at minimum separation for independently controlled flight
- Different Phases for / with different Objectives
  - Pre-Approach
  - Approach
  - Astern Hold
  - Rendezvous
  - Contact / Station Keeping
  - Departure



- Maneuver defined with respect to:
  - Receptacle Position
  - Refueling Reference Point

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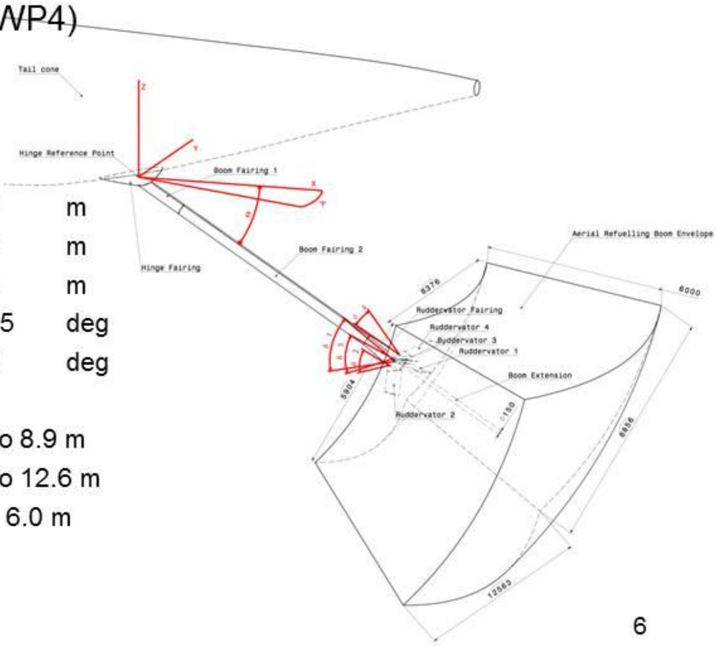
Transfer Process and Maneuver Design (2/2)

- Station Keeping Phase (WP4)



– Length of fixed part	11.0	m
– Total length extended	18.0	m
– Total length retracted	11.5	m
– Boom pitch angle	15-45	deg
– Boom yaw angle	± 20	deg

- – Vertical displacement 5.7 to 8.9 m
- – Lateral displacement 8.0 to 12.6 m
- – Longitudinal displacement 6.0 m

6

Cruiser, Feeder and Boom Autopilots (1/4)

- Both involved aircraft are large with slow dynamics
- A separation of dynamical aspects relevant for control matters
- Layered autopilot structure with decoupled controllers with time scale separation between layers
  - Tanker autopilot: keep tanker speed and orientation, straight and level
  - Cruiser autopilot: control distance from boom hinge point to receptacle
  - Boom controller: distance from boom tip to receptacle

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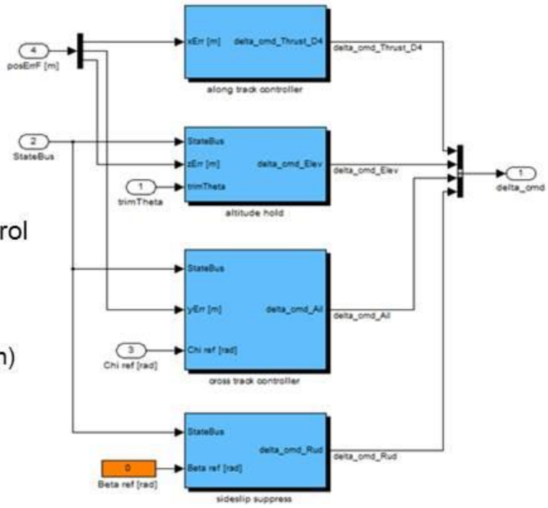
Cruiser, Feeder and Boom Autopilots (2/4)

- Design Objectives Cruiser
  - Approach
    - bring the cruiser to its nominal refueling point behind the feeder
    - In a timely manner
    - Performance indicators: Tracking properties and sufficient disturbance rejection
  - Station keeping
    - Disturbance rejection is of primary concern
- Design Objectives Boom
  - Good tracking properties and disturbance rejection properties
  - Compensation of disturbances from fast vertical motion of boom hinge

8

Cruiser, Feeder and Boom Autopilots (3/4)

- Cruiser and Feeder Controller
  - Same basic controller architecture
  - Different parameter settings Cruiser and Feeder
  - Parameter constant over phases
  - PID concept
  - Decoupled loops for yaw and pitch control
  - Tuning done using
    - Step response criteria (stability, speed)
    - Statistical analysis (disturbance rejection) of performance in turbulent conditions



9

Cruiser, Feeder and Boom Autopilots (4/4)

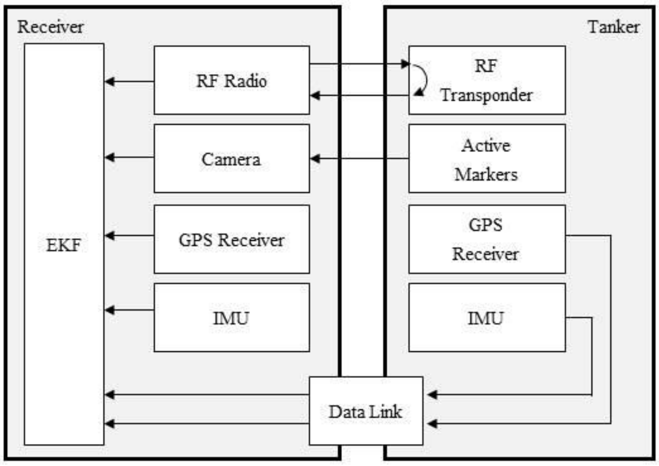
- Boom Controller
  - Based on (analytic) exact linearization of the equations of motion for the constrained boom system
  - Outer control loop designed using pole placement and loop shaping
  - Actuated variables: Hinge angles for the boom control surfaces

10

Sensors, Data Fusion & Navigation (1/10)

Sensors

- Estimation of relative position between the aircraft:
  - Four independent measurement technologies



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Sensors, Data Fusion & Navigation (2/10)
Sensors

- Inertial measurements
  - Used to propagate reference trajectory
- GPS
  - Loosely coupled → Consideration of resultant GPS position (instead of pseudoranges directly)
  - Compensation of measurement time delays and GPS antenna lever arms
  - “Pseudo-differential GPS”
    - Both GPS receiver suffer the same external disturbances (with slow dynamics), e.g.
      - Ephemeris error
      - Satellite clock error
      - Ionosphere and troposphere error
    - Relative GPS position is (much) more accurate than absolute GPS position measurement

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Sensors, Data Fusion & Navigation (3/10)
Sensors

- Electro-optical measurements
  - Bearings from camera to marker positions are measured
  - Closely-coupled – each measurement is considered independently
    → No minimum number of visible markers required
  - Modified gain extended Kalman filter
    → No linearization of measurement equations required
    → Higher performance and accuracy

- Transponder Measurements
  - Closely-coupled
  - Linearized measurement equation
  - High accuracy of longitudinal relative position
  - Lower accuracy of vertical relative position

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Sensors, Data Fusion & Navigation (4/10)

Data Fusion

- High number of measurements
  ⇨ Merging measurements using an Extended Kalman Filter

- Multivehicle Error Propagation

$$\delta\dot{x}_{Feeder} = A_{Feeder}\delta x_{Feeder} + B_{Feeder}u_{Feeder}$$
$$\delta\dot{x}_{Cruiser} = A_{Cruiser}\delta x_{Cruiser} + B_{Cruiser}u_{Cruiser}$$

$$\begin{bmatrix}\delta\dot{x}_{Feeder}\\ \delta\Delta\dot{x}_{CF}\end{bmatrix} = \begin{bmatrix}A_{Feeder} & 0\\ A_{Feeder}-A_{Cruiser} & A_{Cruiser}\end{bmatrix}\begin{bmatrix}\delta x_{Feeder}\\ \delta\Delta x_{CF}\end{bmatrix} + \begin{bmatrix}B_{Feeder} & 0\\ B_{Feeder} & B_{Cruiser}\end{bmatrix}\begin{bmatrix}u_{Feeder}\\ u_{Cruiser}\end{bmatrix}$$

→ High benefits for relative position estimation

Löbl, D., Holzapfel, F., “Simulation Analysis of a Sensor Data Fusion for Close Formation Flight”, AIAA Guidance, Navigation, and Control Conference 2014, National Harbor, MD, January 2014.

14

Sensors, Data Fusion & Navigation (5/10)

Navigation

- Sensor errors modeled according to typical error behavior
  - Noise
  - Bias
  - Discretization
  - Quantization
  - Latency
- Sensor faults
  - Outage
  - Gradual build-up of error
- High number of available measurements

⇨ Fault detection and exclusion

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Sensors, Data Fusion & Navigation (6/10)
Navigation

- Two-tiered approach:
  - "Warning level": Sensor measurement first time out of bound
  - "Error level": Sensor measurement out of bound for a certain period of time
    ⇨ Exclusion
- Error bounds adapted dependent on current
  - Sensor accuracy
  - Estimation accuracy
- Implementation by a finite state space machine

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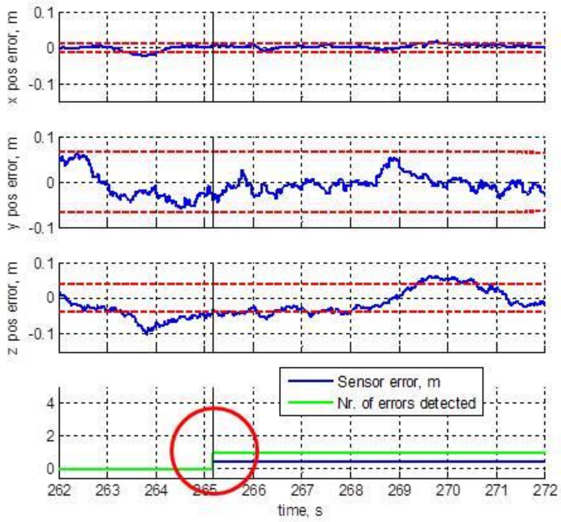
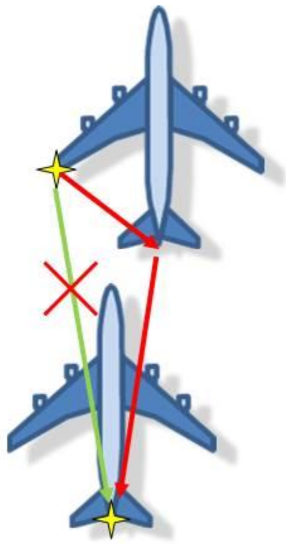
Sensors, Data Fusion & Navigation (7/10)
Navigation

- Example 1: 0.5m stepwise error of one transponder range measurement
- Sensor error detected within one time step / no impact on estimation





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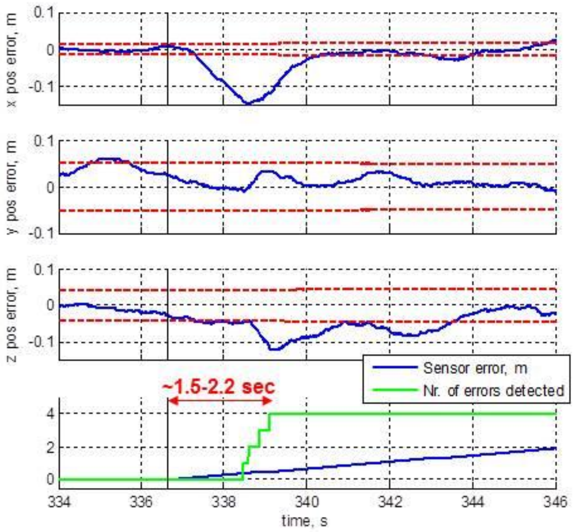
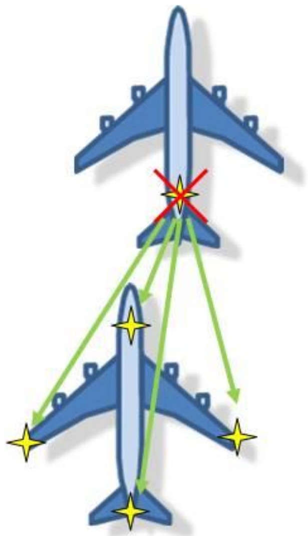
Sensors, Data Fusion & Navigation (8/10)

Navigation

- Example 2: Slow ramp error (0.2 m/s) of one transponder
- Error detected within ~2sec / Recognizable error of estimation





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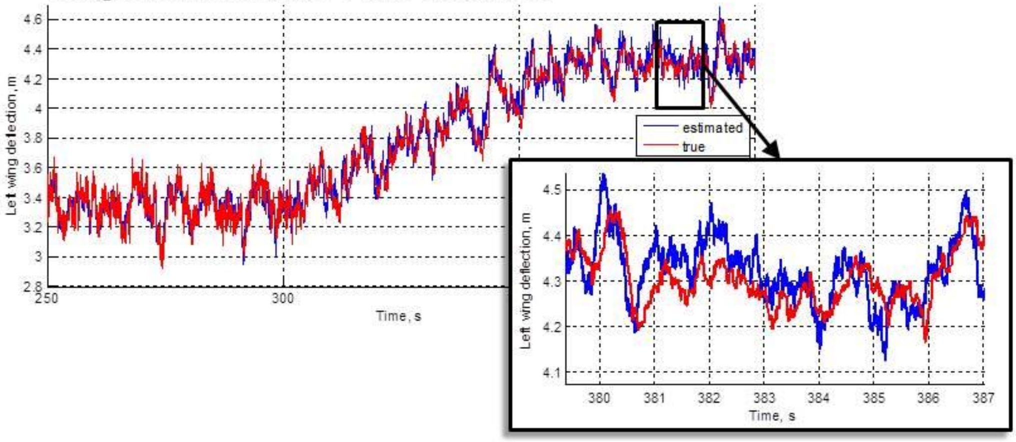
Sensors, Data Fusion & Navigation (9/10)

Navigation

- Markers and transponders fixed to wing tips
- Wing deflection due to
  - Turbulences
  - Changes in aircraft weight
- Generic deflection model dependent on aircraft weight and load factor
- Wing deflection can be well estimated



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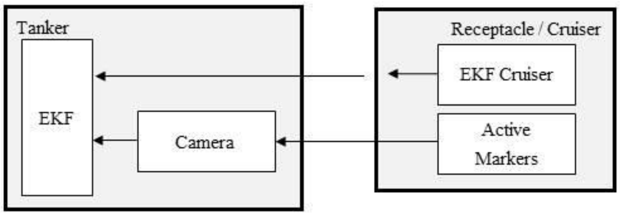
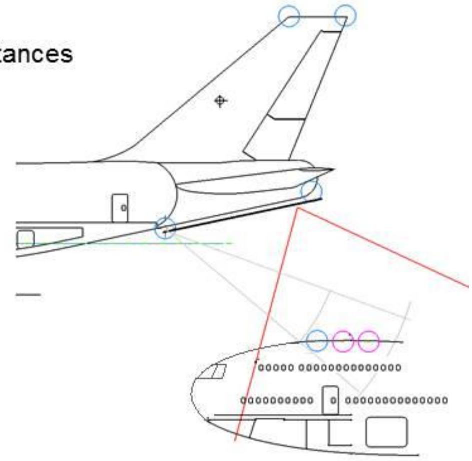
Sensors, Data Fusion & Navigation (10/10)

Navigation

- Estimation of relative position between boom tip and receptacle
  - "Reutilize" relative aircraft position estimation
  - Enhanced by optical sensor system at close distances





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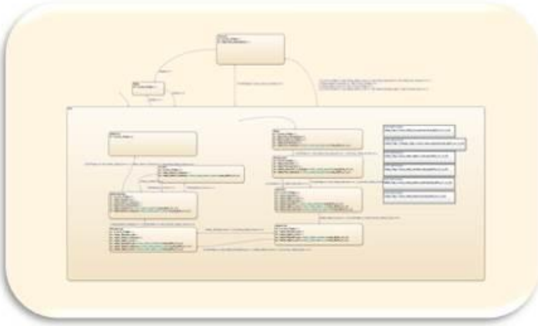
Mode Selection, Supervision and Performance Monitor (1/6)
Mode Selection Logics

- Different phases with different control objectives (Task 5.1)
  → Switch logics required
- Geometry-based detection of maneuver phases
- Automatic abort initiation if the probability that the defined maneuver is left is higher than a predefined border
- Implemented as finite state machine
  (using Matlab/ Stateflow)
  - Criteria / Functions for
    - Entry
    - Exit / Transitions
    - Abort



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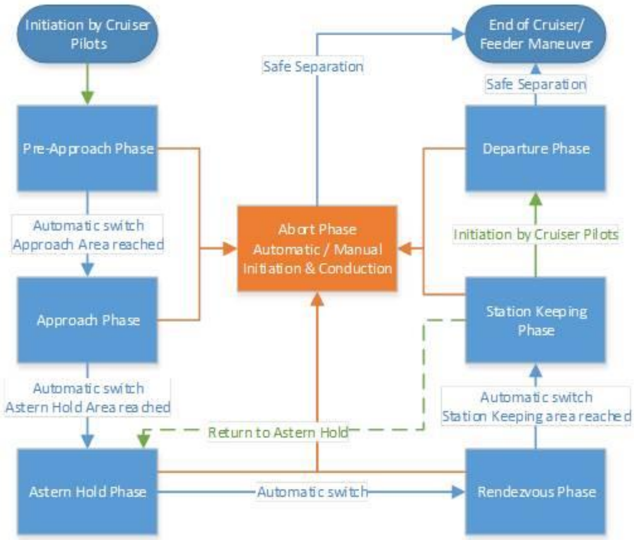
Mode Selection, Supervision and Performance Monitor (2/6)

Mode Selection Logics

- Modes and Transitions for Cruiser Operation
  - Keep pilots in the loop
  - Automatic phase transitions where possible
  - Automatic / manual abort



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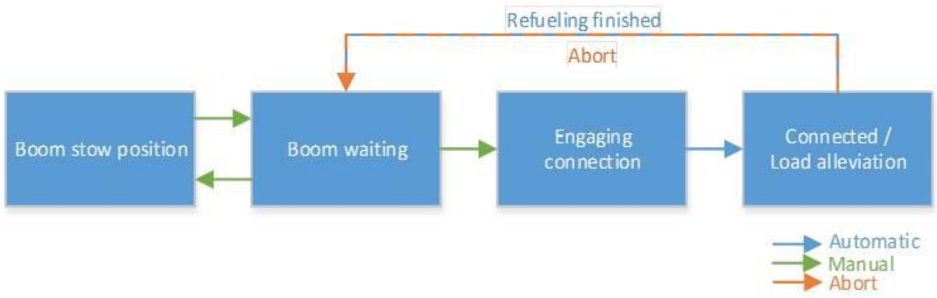
Mode Selection, Supervision and Performance Monitor (3/6)

Mode Selection Logics

- Modes and Transitions for Boom Operation



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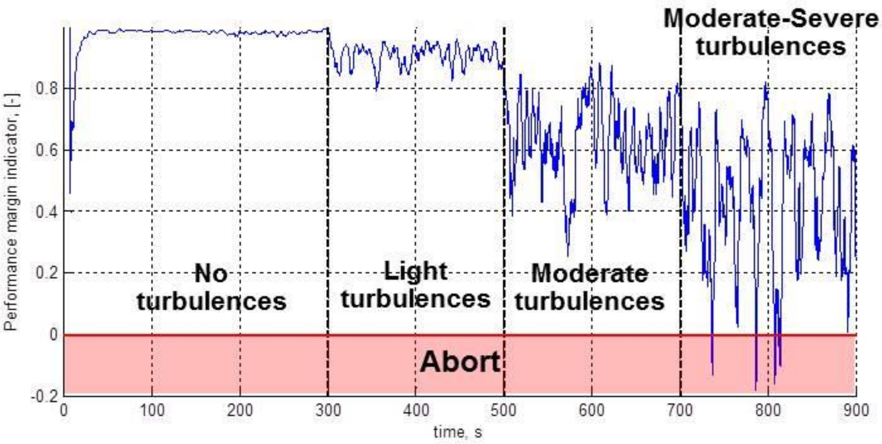
Mode Selection, Supervision and Performance Monitor (4/6)

Performance Margin Indicator

- Performance Margin Indicator
  - Feedback on current system performance for pilots, comprising
    - Current turbulence intensity
    - Control and navigation errors
  - Generate awareness for possible aborts



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Mode Selection, Supervision and Performance Monitor (5/6)

Human Machine Interface

- Human Machine Interface
- Complete maneuver is conducted automatically
- It is important to keep the pilots in the loop

  ⇨ Design of a Human Machine Interface
- To provide outputs to the pilots that are necessary to keep situational awareness
- Provide necessary inputs options to the automation system
- Developed interfaces:
  - Maneuver Progress Display (Cruiser and Feeder)
  - Boom Status and Control Display (Feeder)

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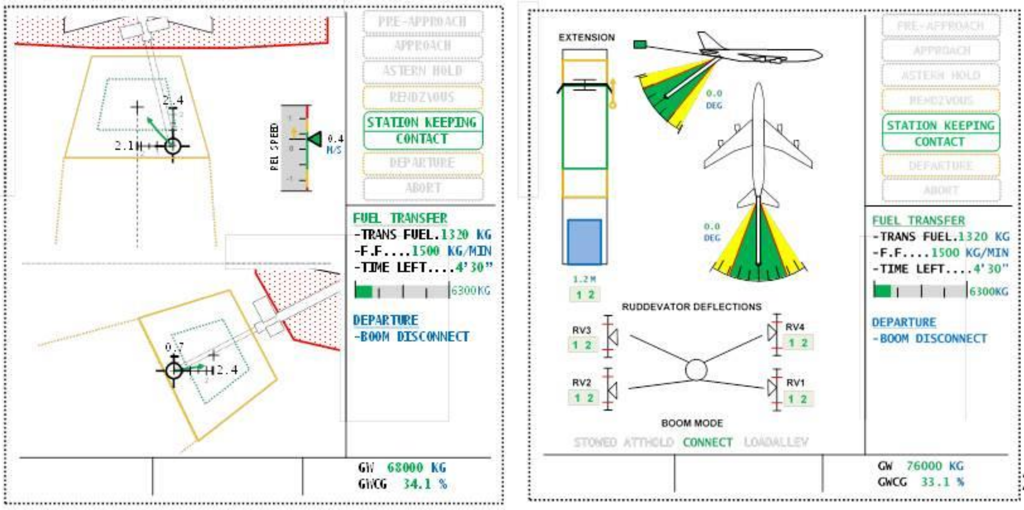
Mode Selection, Supervision and Performance Monitor (6/6)

Human Machine Interface

- Designed in the scope of work package 5 in collaboration with NLR / WP6
- Implemented by NLR / WP6 (⇨ more details there)



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Automatic Flight Control Development and Simulation Environment (1/3)

Overview

- Simulation environment required for
  - Control, navigation, and supervision algorithm development
  - Tuning
  - Testing
- Simulation Environment Components
  - Two high-fidelity aircraft simulation models of a generic large transport aircraft
  - Multi-body boom simulation model according to RECREATE design
  - Aerodynamic Interaction models
    - Downwash of leading aircraft
    - Correlated wind turbulence field based on Dryden turbulence model

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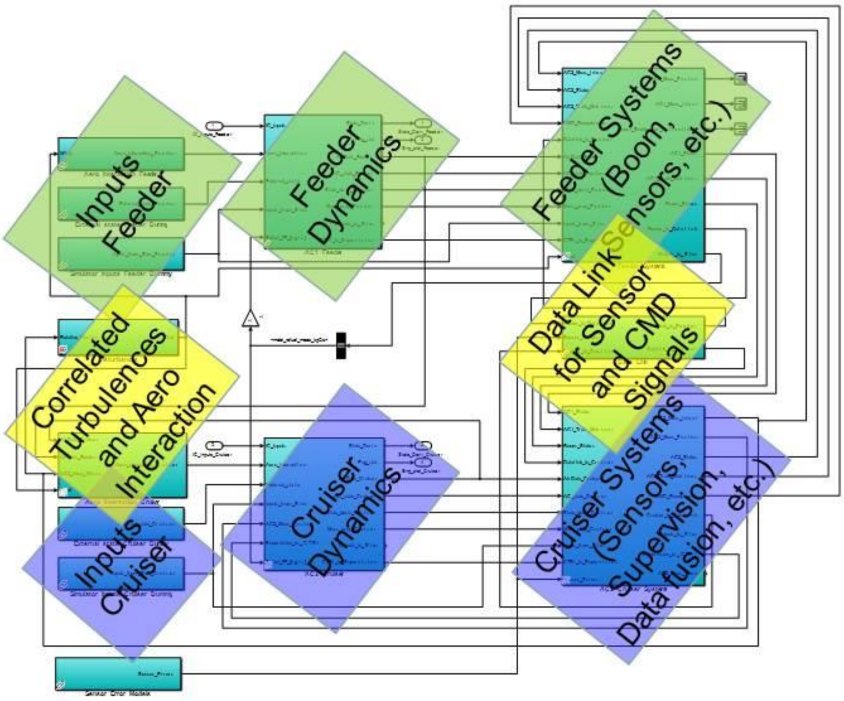
Automatic Flight Control Development and Simulation Environment (2/3)

Top Level Simulation Model



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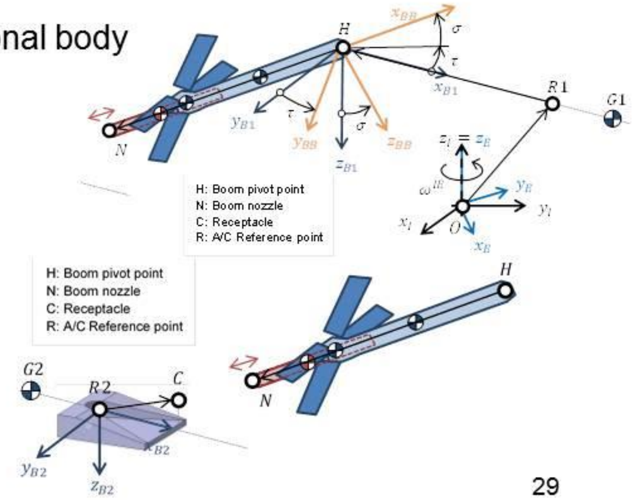
Automatic Flight Control Development and Simulation Environment (3/3)

Boom and Receptacle Simulation Model

- Multi-body simulation model
- Aerodynamic control forces by ZHAW
- Receptacle modeled as additional body
  ⇨Reaction forces measurable



Löbl, D., Holzapfel, F., "High Fidelity Simulation Model of an Aerial Refueling Boom and Receptacle", Deutscher Luft- und Raumfahrtkongress 2013, Stuttgart, Germany, September 2013.

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Automatic Flight Control Development and Simulation Environment (Supplementary)

Cruiser and Tanker aircraft	
Four-engined transport aircraft, conventional low wing aircraft configuration	
Maximum take-off weight	378.000kg
Thrust/MTOW Ratio	0.25 (at sea level)
Actuator & engine dynamics similar to today's aircraft	
Sample time of aircraft dynamics: 240Hz	
Boom	
Multi-body simulation model with individual bodies for boom rigid pipe, extension and control surfaces (according to boom design specified in D4.1 [4]). Aerodynamic model based on VSaero panel calculations.	
Total weight	773kg
Total length (fully extended)	18m
First order actuator dynamics with time constant T = 0.1sec	
Sample time of boom dynamics: 240 Hz	

Receptacle	
Modeling of receptacle slipway and boundaries as additional bodies, allowing for determination of impact forces [8]	
Sensors and Sensor data fusion of cruiser and receiver	
Sample times:	
Inertial measurements	120Hz
GPS measurements	2 Hz
EO measurements	24 Hz
RF ranging measurements	60 Hz
Kalman filter of cruiser and receiver	120 Hz
Data link	120 Hz
Data link latency: 42ms	
Additional latency of signal communication between sensors and flight control and navigation computers: > 8 ms	

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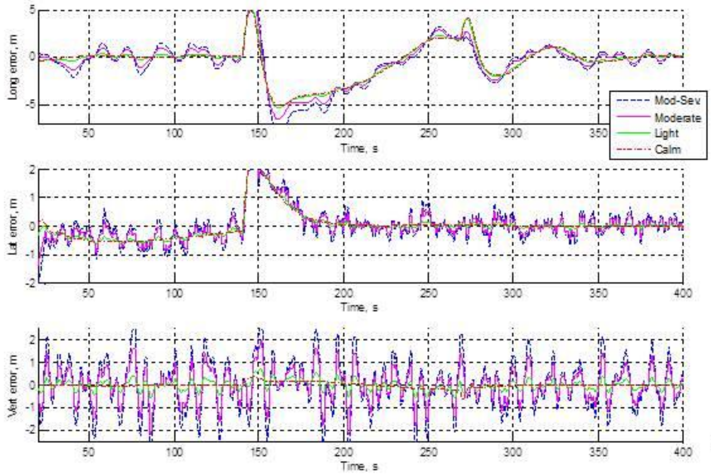
Closed Loop Simulation Results (1/11)

Ideal Control Performance

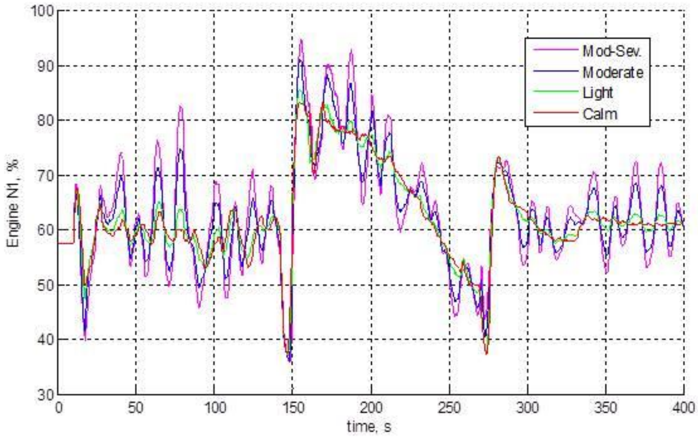
- Relative position control performance with state feedback (i.e. no measurement errors) in turbulent air
- Longitudinal control error < 2m, up to 5m during phase transitions
- Lat. error < 1m
- Vert. error < 2.5m



Closed Loop Simulation Results (2/11)

Ideal Control Performance

- Engine control signal from approach to station keeping
- High requirements on longitudinal tracking / disturbance rejection performance causes oscillating engine control signals of the approaching aircraft



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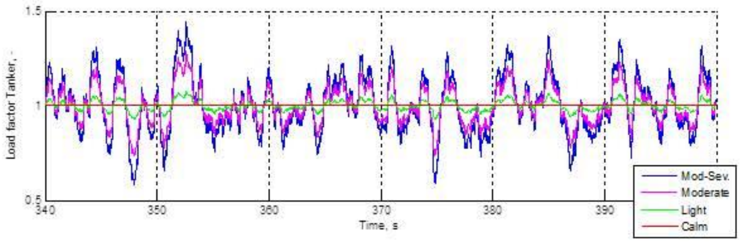
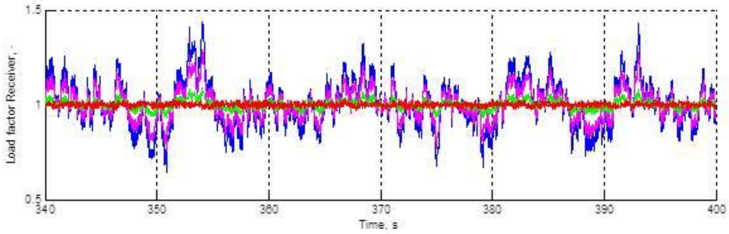
Closed Loop Simulation Results (3/11)
Ideal Control Performance

- Load factors at cockpit position for leading and trailing aircraft
- Only minor differences ⇨ No influence on passenger comfort with respect to aircraft load factors

Leading aircraft



Trailing aircraft



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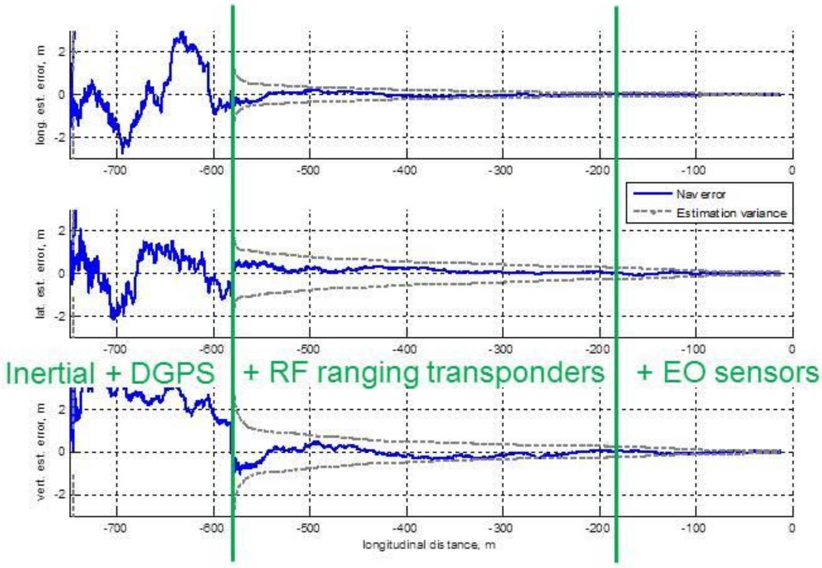
Closed Loop Simulation Results (4/11)
Navigation Performance

- Navigation performance increases with decreasing distance between the aircraft



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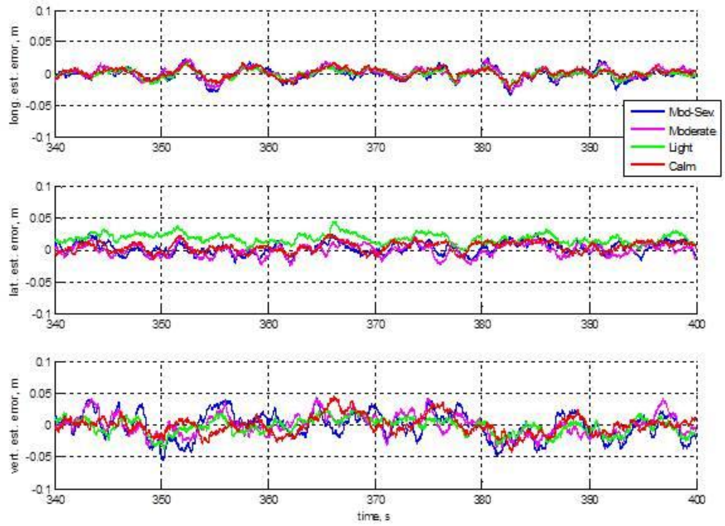
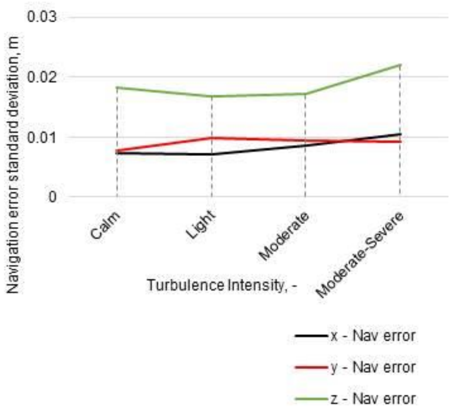
Closed Loop Simulation Results (5/11)
Navigation Performance

- Navigation performance during close formation flight
- Almost no influence of turbulence intensity on estimation accuracy





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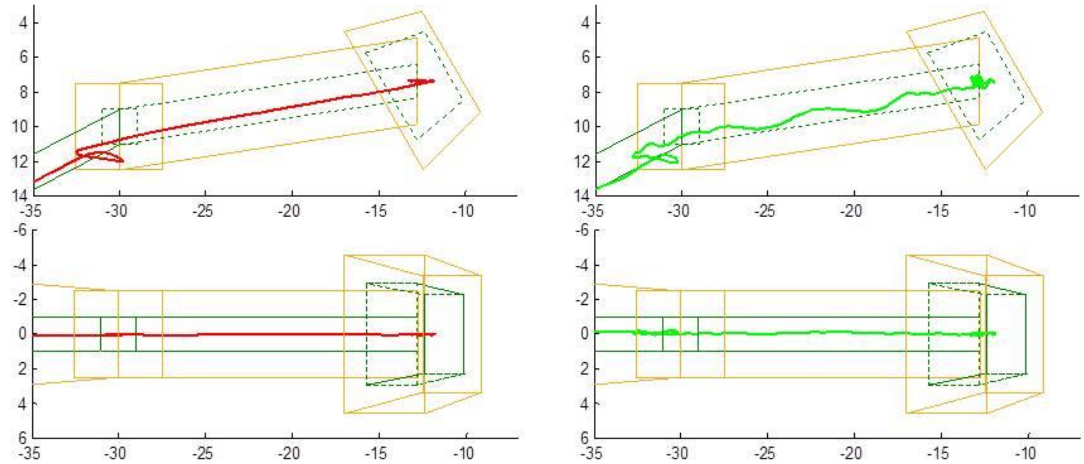
Closed Loop Simulation Results (6/11)

Close Formation Flight Performance

- Total performance including navigation and control performance
- Excellent performance in lateral plane
- Adverse behavior in longitudinal direction due to slow thrust dynamics



No turbulences

Light turbulences

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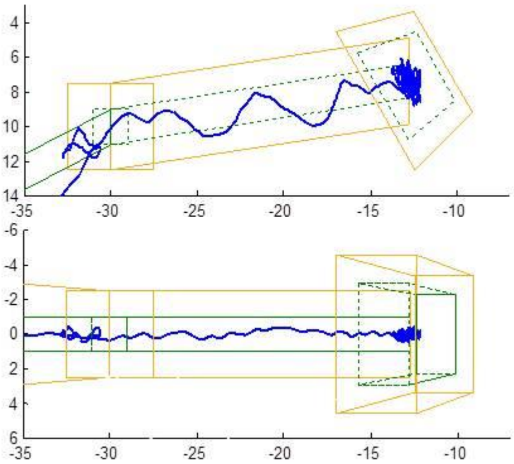
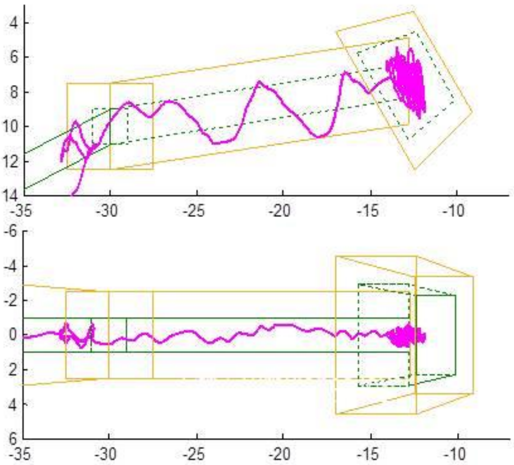
Closed Loop Simulation Results (7/11)

Close Formation Flight Performance

- Total performance including navigation and control performance
- Excellent performance in lateral plane
- Adverse behavior in longitudinal direction due to slow thrust dynamics



Moderate turbulences



Moderate-severe turbulences

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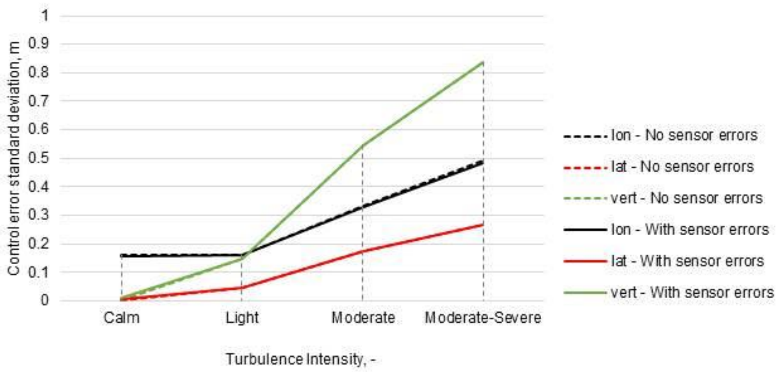
Closed Loop Simulation Results (8/11)
Close Formation Flight Performance

- Control error increases with turbulence intensity
- Almost no impact of navigation performance on control performance during close formation flight



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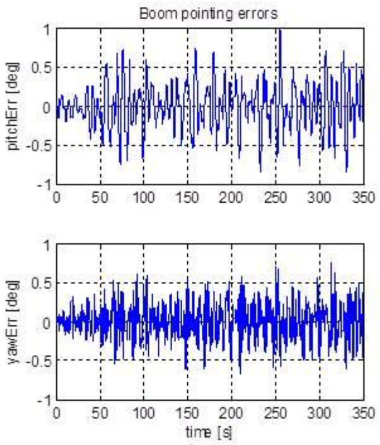
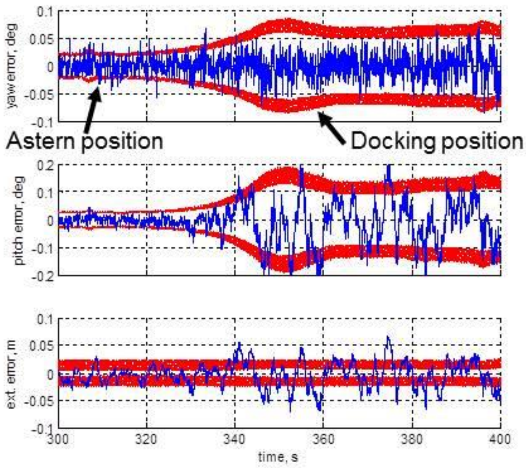
Closed Loop Simulation Results (9/11)
Boom Control and Measurement Performance

- Station Keeping Phase – Sensor Performance

Control Error



Navigation Error



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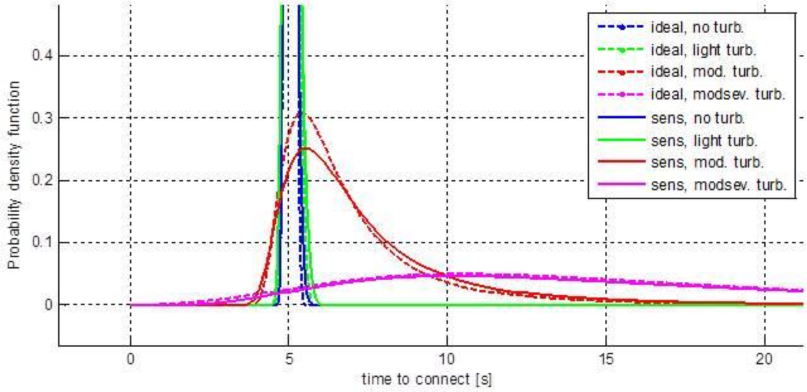
Closed Loop Simulation Results (10/11)
Boom Connection Performance

- Average boom time to connect: 5-6 seconds
- Minor influence of navigation performance on time to connect
- Good results up to moderate turbulences



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Closed Loop Simulation Results (11/11)

Boom Connection Performance

- Average number of control attempts until successful connection
- Successful connection at first attempt for calm and light turbulent air

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Safety Simulations (1/11)
Requirements

- Top-Level Requirements from WP2 (Safety)
- Major catastrophic events:
  - The probability of **a collision between the cruiser and the tanker** due to insufficient control authority of the cruiser and tanker, if **wind shear and turbulence levels remain within certain limits**, must be $<10^{-9}$ in order to meet the safety requirement.
  - The probability of a **collision between the cruiser and the tanker** due to insufficient control authority during an abort, if **wind shear or turbulence levels are outside certain limits** (but still inside certain upper limits which correspond with the ultimate load on the aircraft structure), must be $<10^{-9}$ in order to meet the safety requirement.
  - The probability of a **collision between the cruiser and the tanker** due to insufficient control authority during an abort, in the **presence of engine failures**, must be $< 10^{-9}$ in order to meet the safety requirement.

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Safety Simulations (2/11)
Simulation of Low Probabilities

- Classical Monte Carlo Simulation (MCS)

$$p_F \approx \overline{p}_{F,MC} = \frac{1}{N}\sum_{i=1}^{N} I_F(\underline{\theta^i}) \qquad k \sim \frac{1}{p_F}$$

⇨ High number of samples required for adequately high level of confidence

- Idea of Subset Simulation:
  Calculate the probability of a rare event by a chain of more probable events:

$$p_F = \prod_{j=1}^{m} P\left(F_j \middle| F_{j-1}\right) = \prod_{j=1}^{m} p_j$$

Löbl, D., Holzapfel, F., "Subset Simulation for Estimating Small Failure Probabilities of an Aerial System Subject to Atmospheric Turbulences", AIAA Atmospheric Flight Mechanics Conference, Kissimmee, FL, January 2015

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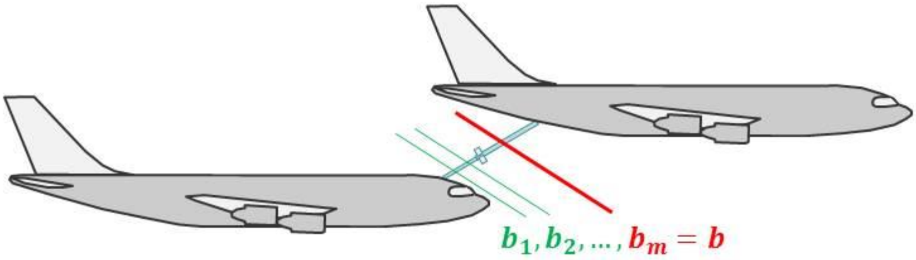
Safety Simulations (3/11)

Performance Function

⇨ What is the probability that a certain critical threshold is violated?

- Subset Simulation: Use intermediate thresholds!



- Intermediate Questions:
  "What is the probability that we exceed a certain threshold b_n if we are already beyond the threshold b_{n-1}?"

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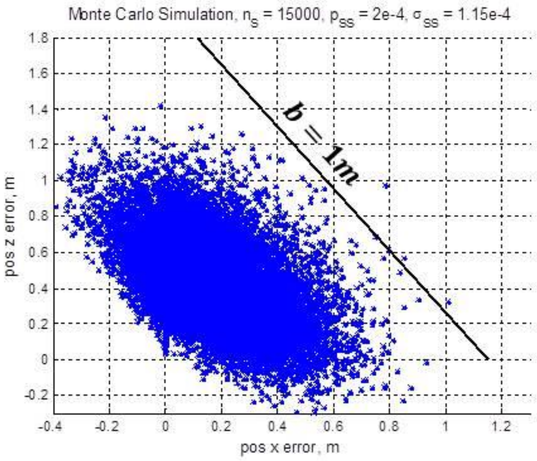
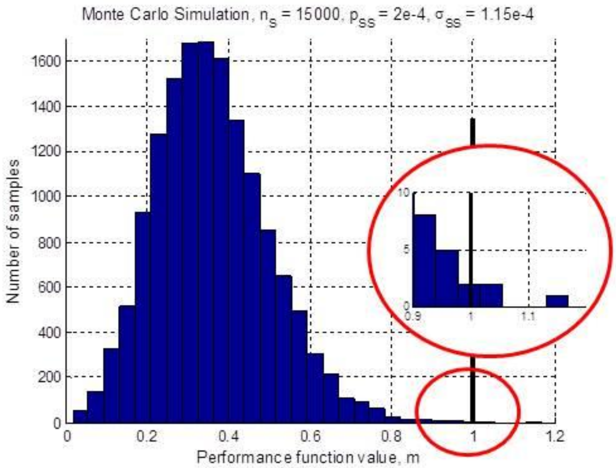
Safety Simulations (4/11)
Subset Simulation - Example

- Classical Monte Carlo Simulations





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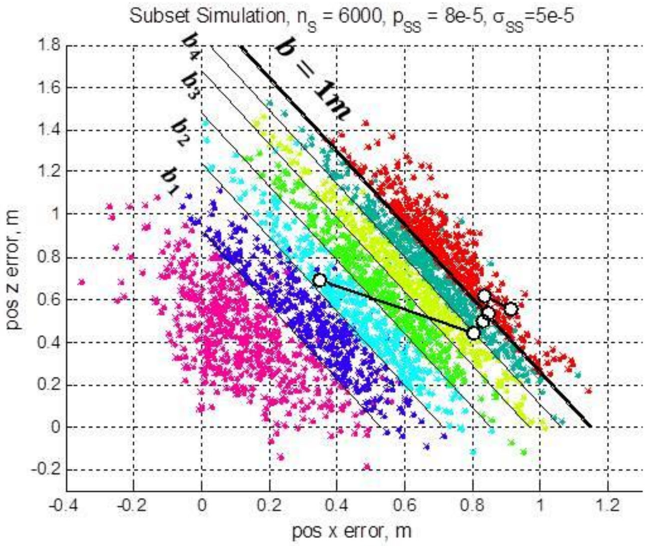
Safety Simulations (5/11)
Subset Simulation - Example

- Significantly more samples in “failure region” despite lower number of total samples by subset simulation



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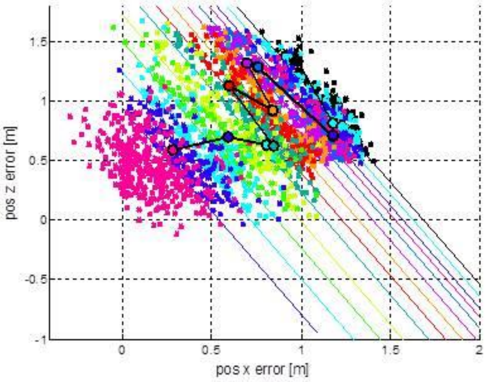
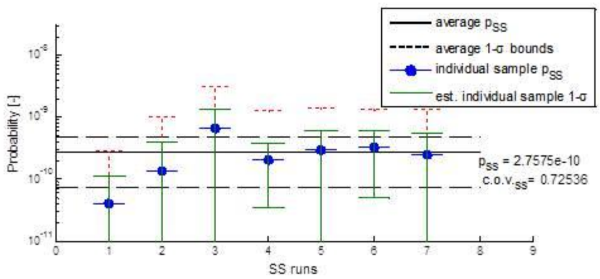
Safety Simulations (6/11)

Results Requirement 1

- Collision between the cruiser and the tanker
- Wind shear and turbulence levels remain within certain limits
  ⇨ Moderate Turbulences
- Probability of collision must be lower than 10^{-9}



$p_{SS}(b = 1.50m)$	$\sigma_{SS,est}(b = 1.50m)$
$2.76 \cdot 10^{-10}$	$2.97 \cdot 10^{-10}$



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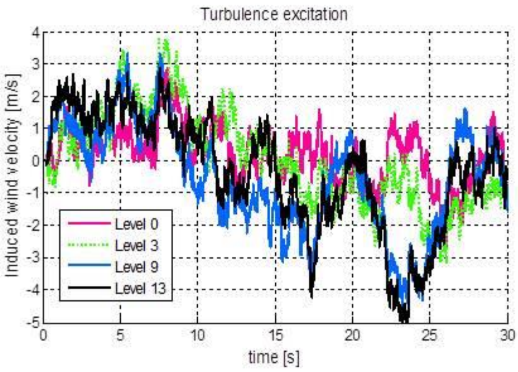
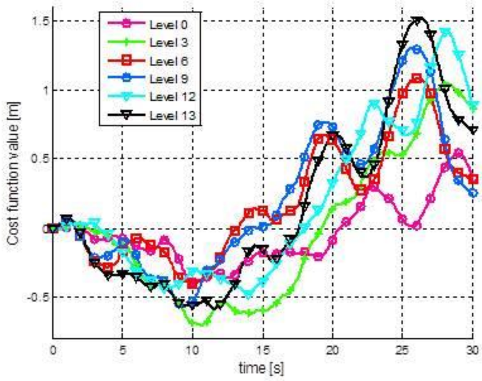
Safety Simulations (7/11)

Results Requirement 1

- Very low probability ⇨ Results highly sensitive to parameter / system changes
- But: It could be shown by simulation that the chosen aircraft configuration can enable safe close formation flight
- Threshold of 1.5 m is far away from collision (@11m)





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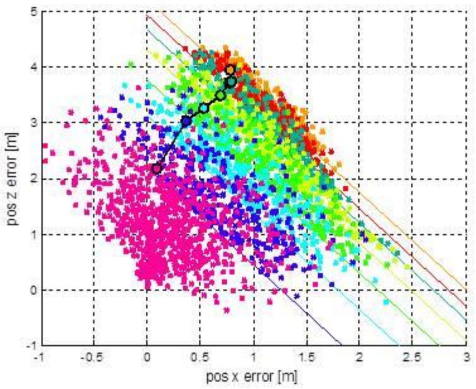
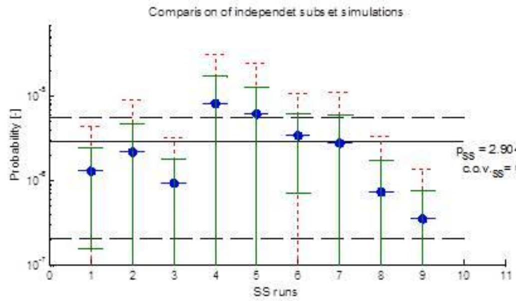
Safety Simulations (8/11)

Results Requirement 2

- Collision between the cruiser and the tanker
- Wind shear and turbulence outside of operational limits
  ⇨ Probability of exceeding moderate turbulences < 10^{-4}
- Probability of collision must be lower than 10^{-5} ✔



$p_{SS}(b = \mathbf{2.75m})$	$\sigma_{SS,est}(b = \mathbf{2.75m})$
$2.90 \cdot 10^{-6}$	$3.05 \cdot 10^{-6}$



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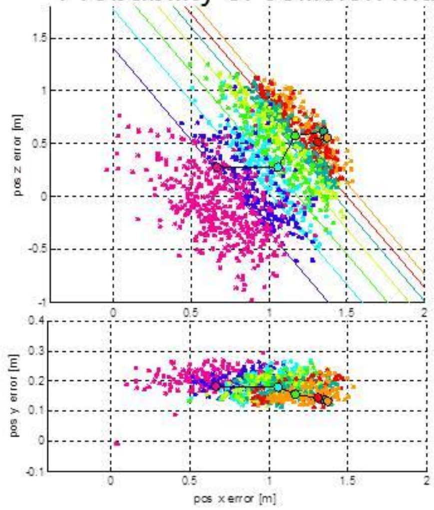
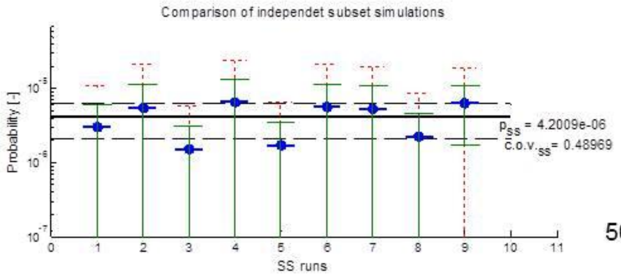
Safety Simulations (9/11)
Results Requirement 3

- Wind shear and turbulence levels remain within certain limits
  ⇨ Moderate Turbulences
- Occurrence of engine error, probability <10^{-4} - 10^{-5}
- Probability of collision must be lower than 10^{-5} - 10^{-4}



$p_{SS}(\boldsymbol{b}=\mathbf{1.4}\boldsymbol{m})$	$\sigma_{SS,est}(\boldsymbol{b}=\mathbf{1.4}\boldsymbol{m})$
$4.20 \cdot 10^{-6}$	$4.14 \cdot 10^{-6}$



50

Safety Simulations (10/11)

Subset Simulation – Conclusion

- Much less samples required compared to classical Monte Carlo
- Shorter simulation time, allowing for faster evaluation of
  - Configuration changes
  - Effects of changes of the control architecture and gains, etc.
- High number of samples in the “failure region”

  ⇨ Enabled the identification of sore spots with respect to:
  - Critical inputs / disturbance excitation
  - Weakness of the FCS algorithms

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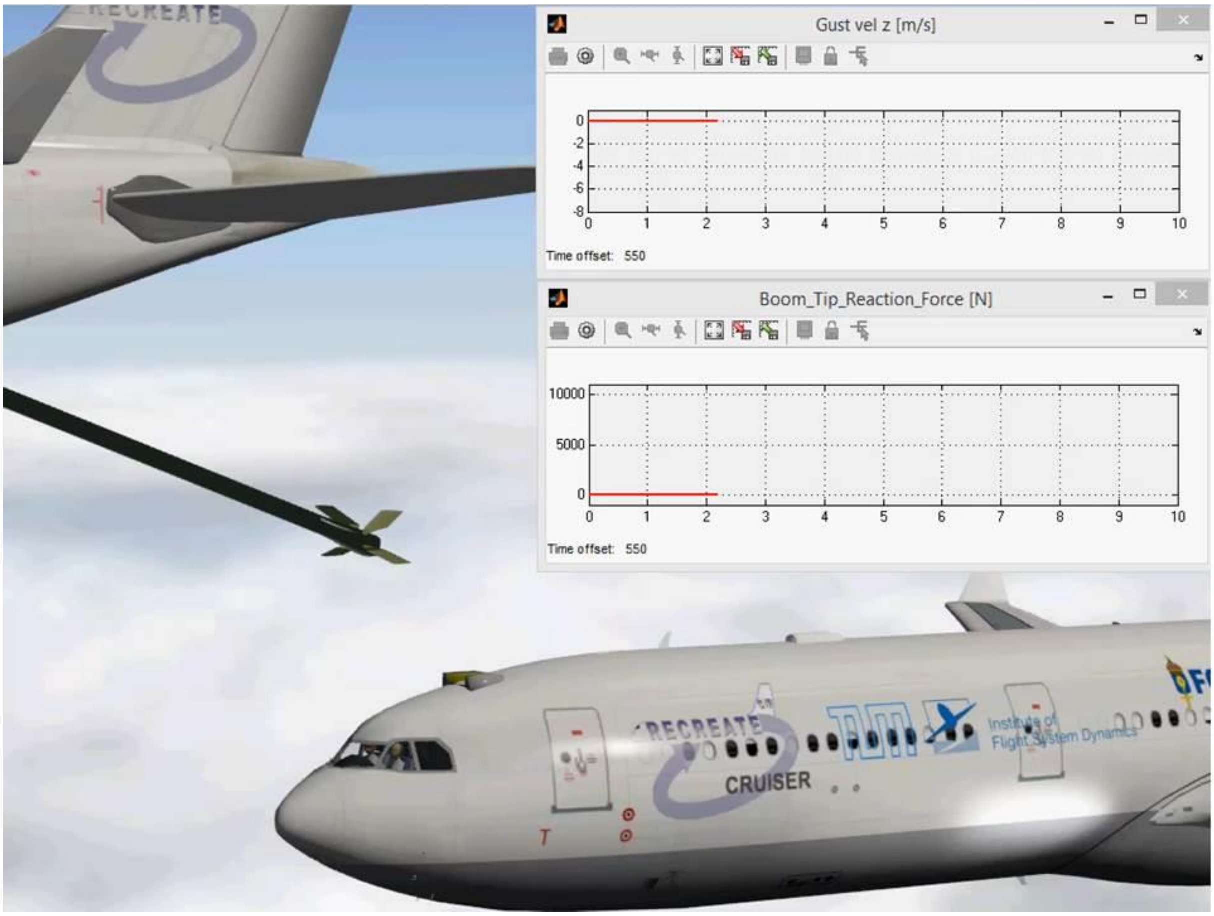
Gust vel z [m/s]
0
-2
-4
-6
-8
0 1 2 3 4 5 6 7 8 9 10
Time offset: 550
Boom_Tip_Reaction_Force [N]
10000
5000
0
0 1 2 3 4 5 6 7 8 9 10
Time offset: 550
RECREATE
CRUISER
Institute of
Flight System Dynamics

Conclusions

- Simulation Models for
  - Aircraft
  - Boom
  - Sensors
  - Control & Navigation algorithms
- That allow for a detailed study of automated close formation flight and aerial refueling
- Automation successfully demonstrated for
  - Two large civil transport aircraft
  - Under adverse environmental conditions

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Conclusions

- Supervision algorithms developed and implemented
  - Detection of critical situations
  - Automatic abort
- Safety proven on a preliminary design level
  - For major safety critical events
- Dedicated / specialized aircraft designs promise even higher safety
- Results also partly applicable to alternative maneuver designs

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Technical University of Munich
Institute of Flight System Dynamics

Swedish Defence Research Agency

WP5 Automatic Flight Control

Technical University of Munich
Institute of Flight System Dynamics

Swedish Defence Research Agency

Appendix F Final results of WP6

REsearch on a CRuiser Enabled Air Transport Environment
WP 6 - Flight Simulation

Final Meeting of
the RECREATE project
Amsterdam
January 29th 2015

Bart Heesbeen - NLR

The research leading to these results has received funding from the European Union Seventh Framework Programme (*FP7/2007-2013*) under *grant agreement* n° 284741.
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WP6 - Flight Simulation
Presentation Overview

1. Objectives of the Flight Simulation Work Package
2. Implementing the Simulation Environment
3. Phase 1 - Simulator Experiment
4. Improvements to the Simulated Concept
5. Phase 2 - Simulator Experiments
6. Results and Conclusions

2

WP6 - Flight Simulation
1. Objectives of the Flight Simulation Work Package

Study the feasibility of concept from pilot's perspective

1. Perform realistic human-in-the-loop evaluations

The new cruiser/feeder operations concept are evaluated in two connected flight simulators, including both normal and abnormal operating procedures and high risk events.

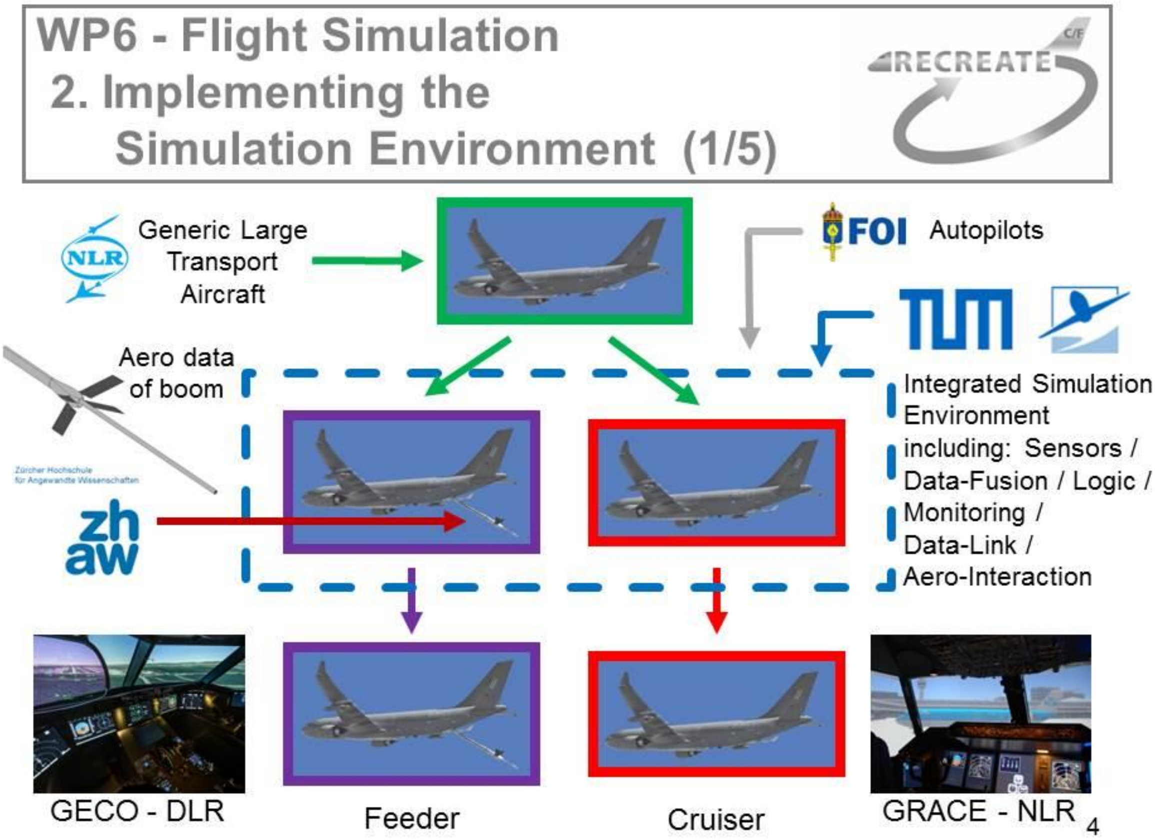
2. Provide valuable feedback and recommendations

Human-in-the-loop evaluations on procedures and operation of the automatic refueling system. Feedback from phase 1 is used to improve the initial design and procedures for phase 2.

Human-in-the-loop evaluations in 2 phases:

Phase 1 - Initial concept and procedures
Phase 2 - Improved concept and procedures

3


WP6 - Flight Simulation
2. Implementing the
Simulation Environment (1/5)
RECREATE
C/F
NLR
Generic Large
Transport
Aircraft
FOI
Autopilots
TUM
Aero data
of boom
Integrated Simulation
Environment
including: Sensors /
Data-Fusion / Logic /
Monitoring /
Data-Link /
Aero-Interaction
zh
aw
GECO - DLR
Feeder
Cruiser
GRACE - NLR
4

WP6 - Flight Simulation
2. Implementing the Simulation Environment (2/5)

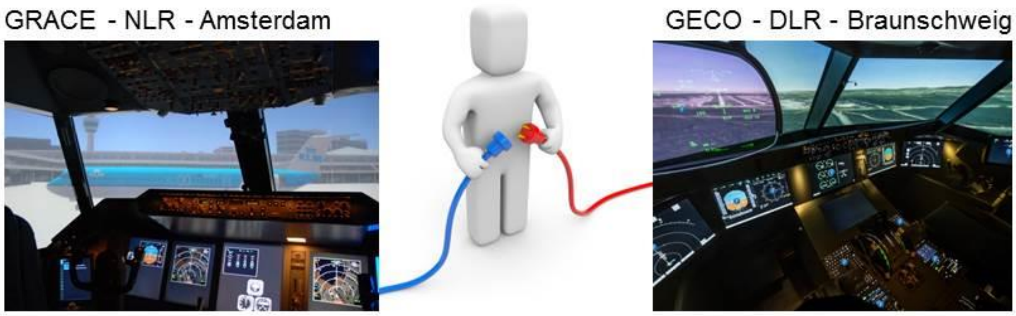
Implementation of DIS interconnection

RECREATE specific interfaces are required:

- ✓ Pilot inputs from GECO cockpit to GRACE
- ✓ Feeder aircraft state simulated at GECO to GRACE
- ✓ Feeder aircraft state simulated at GRACE to GECO
- ✓ Active Master/Slave configuration of Feeder aircraft
- ✓ Data link / CPDLC message events for GRACE and GECO
- ✓ Fuel transfer activation switch and rate

GRACE - NLR - Amsterdam

GECO - DLR - Braunschweig



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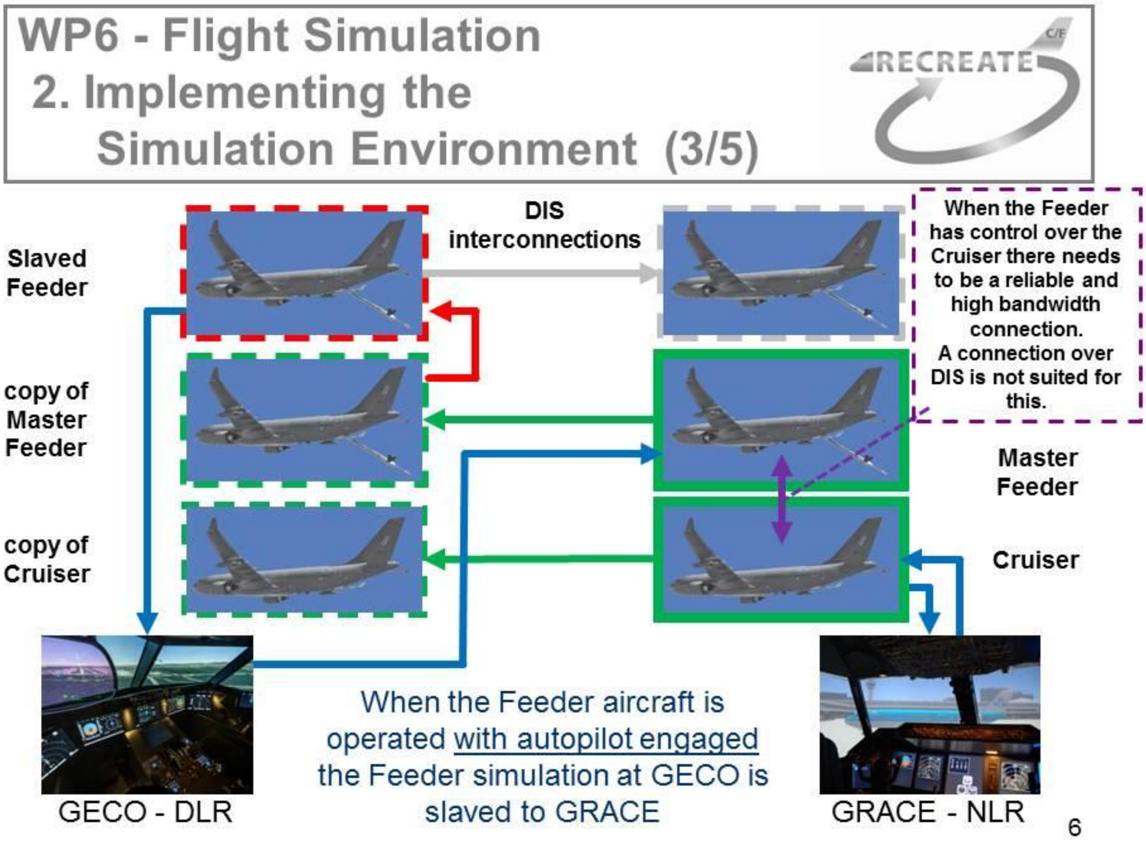
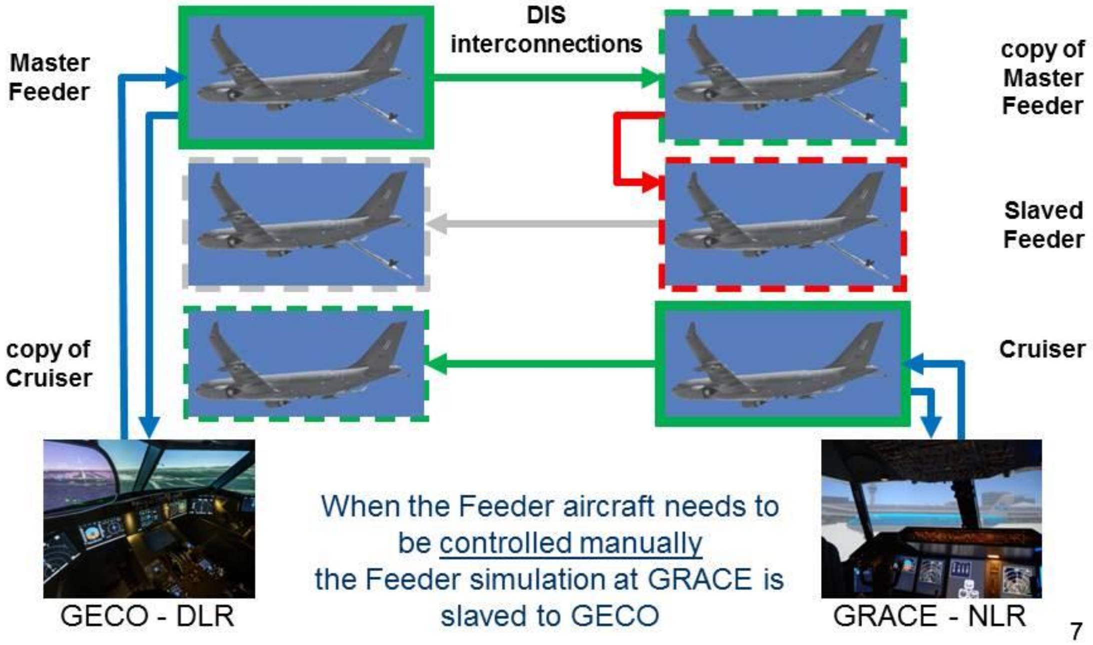
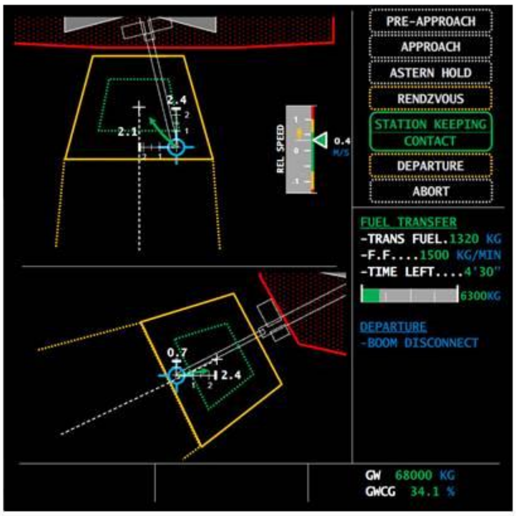

WP6 - Flight Simulation
2. Implementing the
Simulation Environment (3/5)
RECREATE
Slaved Feeder
copy of Master Feeder
copy of Cruiser
DIS interconnections
When the Feeder has control over the Cruiser there needs to be a reliable and high bandwidth connection.
A connection over DIS is not suited for this.
Master Feeder
Cruiser
When the Feeder aircraft is operated with autopilot engaged the Feeder simulation at GECO is slaved to GRACE
GECO - DLR
GRACE - NLR
6

WP6 - Flight Simulation
2. Implementing the Simulation Environment (4/5)



WP6 - Flight Simulation
2. Implementing the Simulation Environment (5/5)

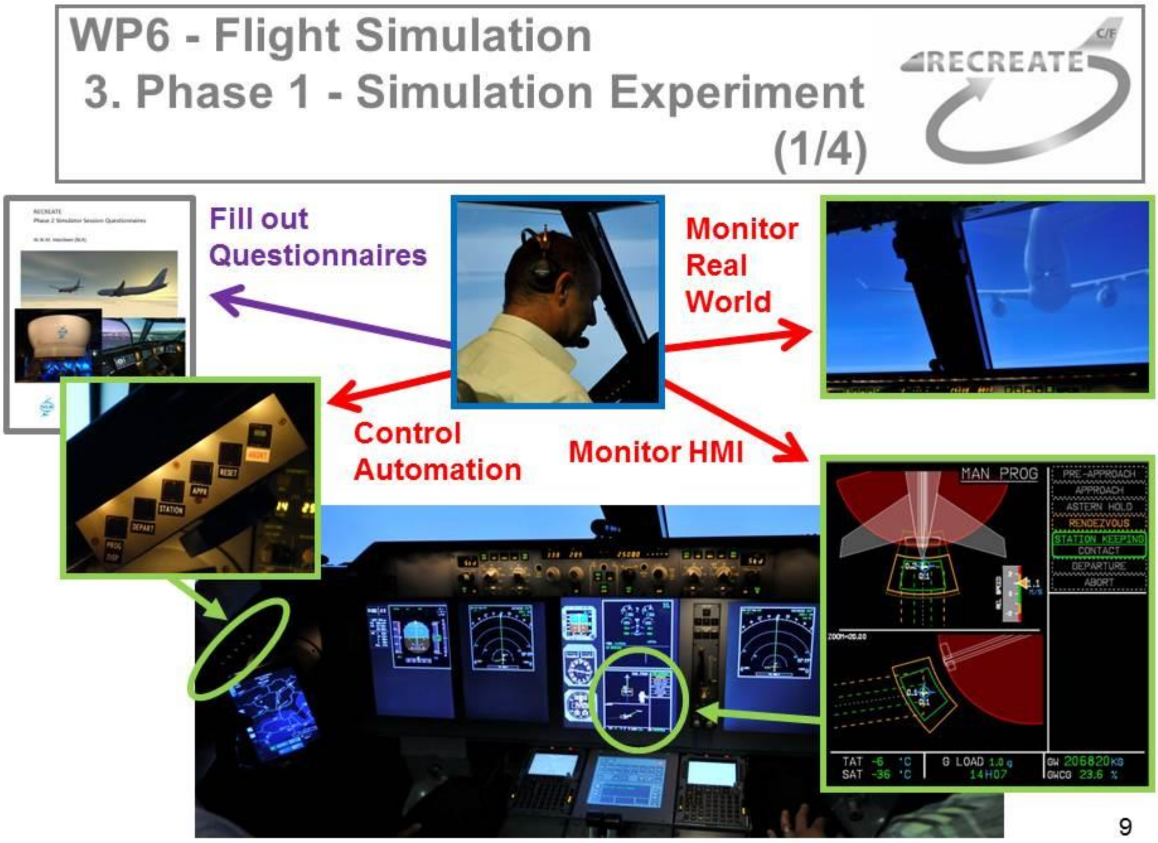
Initial design, iterations and implementation of the RECREATE HMIs



Initial design on paper

Updated and final implementation

8



WP6 - Flight Simulation
3. Phase 1 - Simulation Experiment
(1/4)
Fill out
Questionnaires
Monitor
Real
World
Control
Automation
Monitor HMI
MAN PROG
PRE-APPROACH
APPROACH
ASTERN HOLD
RENDEZVOUS
STATION KEEPING
CONTACT
DEPARTURE
ABORT
9

WP6 - Flight Simulation
3. Phase 1 - Simulation Experiment (2/4)

Controller-Pilot Data Link Communication (CPDLC) messages are used for requests and clearances. This is not different from present-day use for oceanic operations.

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WP6 - Flight Simulation

3. Phase 1 - Simulation Experiment (3/4)

The phase 1 evaluations were executed in August 2013. During the evaluations both GRACE and GECO were flown by a crew of two airline pilots.

The focus of these evaluations was mainly on the use of the RECREATE HMI.

This produced a lot of useful feedback.

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WP6 - Flight Simulation
3. Phase 1 - Simulation Experiment (4/4)

The most important comments and feedback on the RECREATE Human-Machine Interface (HMI)

1. All pilots advised to place the Manoeuvre Progress Display in the primary field of view preferably next to the Primary Flight Display (PFD)

2. Some pilots would like to have the current position error indicated on the PFD possibly making use of the available Instrument Landing System (ILS) deviation indicators

3. Some pilots requested an auto-zoom function on the Manoeuvre Progress Display which should ensure that the relative position to the other aircraft is always indicated

4. Some indications are not intuitive and could be improved

5. Some fonts are too small to read and sometime clutter the display

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WP6 - Flight Simulation
4. Improvements to the Simulated Concept (1/6)

The Manoeuvre Progress Display should be in the primary view of the pilot. An option switch moves the display to the desired location.

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WP6 - Flight Simulation
4. Improvements to the Simulated Concept (2/6)

The pilot should have the active manoeuvre and guidance phase on his PFD. The active manoeuvre phase is now indicated on the Flight Mode Annunciator (FMA) of the PFD.

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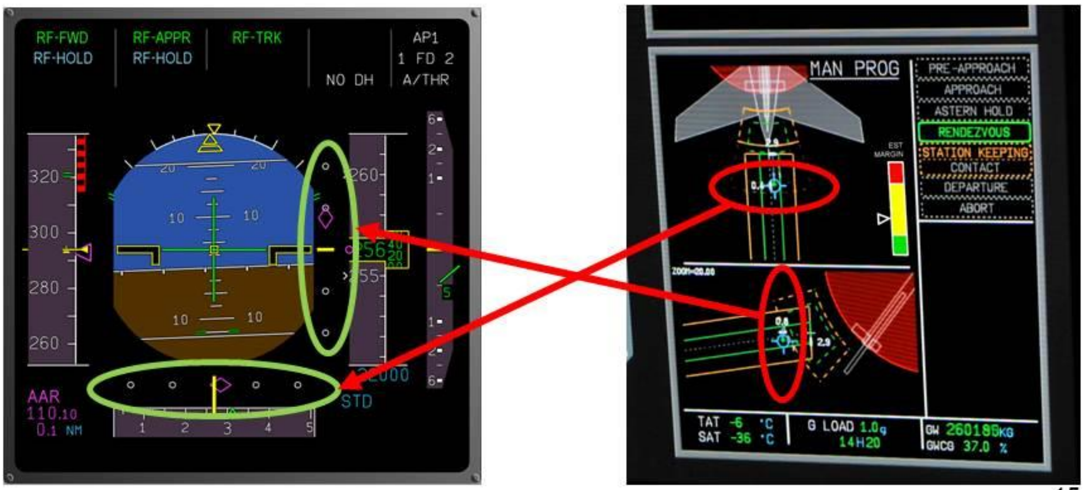
WP6 - Flight Simulation
4. Improvements to the Simulated Concept (3/6)

The pilot wants to have the deviation information on his PFD. The lateral and vertical deviation from the approach path and the station keeping position is now displayed on the localiser and glide slope scales.



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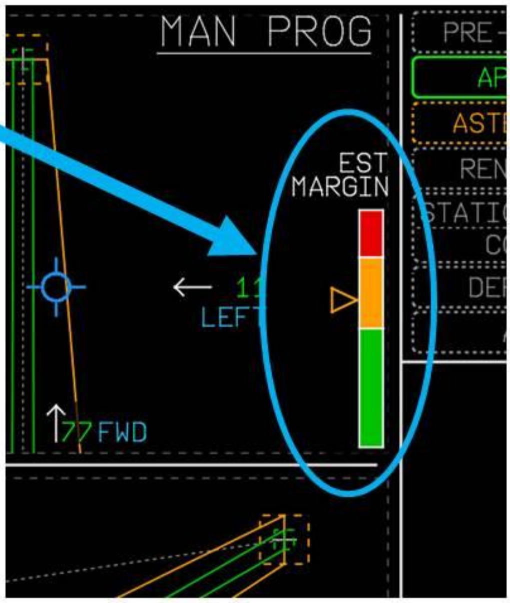
WP6 - Flight Simulation
4. Improvements to the Simulated Concept (4/6)

The Estimated Safety Margin Indicator provides the pilot with a graphical representation of the calculated margin to the deviation limit at which the manoeuvre will be aborted.



The estimated margin is based on:
- the current deviation
- the current deviation rate
- the navigation performance
- the control performance

When the safety margin is exceeded the monitoring system will <u>automatically activate the abort mode</u>

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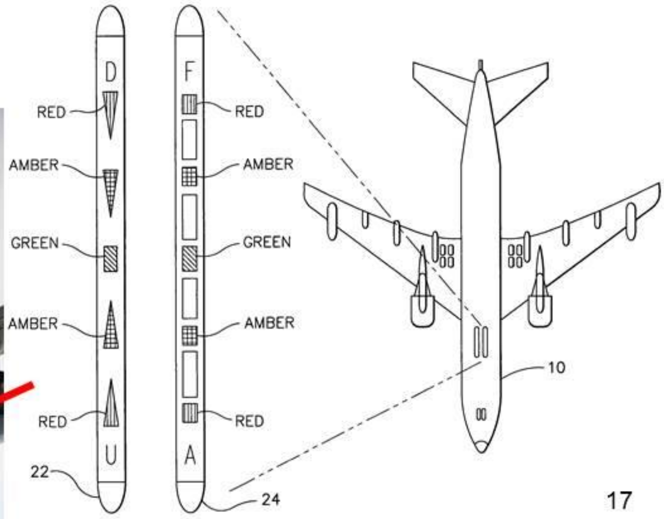
WP6 - Flight Simulation
4. Improvements to the Simulated Concept (5/6)

Lights provide direct feedback to the pilot of the cruiser on its relative position and the minimum safe separation.

The military solution can lead to confusion between both indicators.

<u>Military example:</u>
Pilot Director Lights



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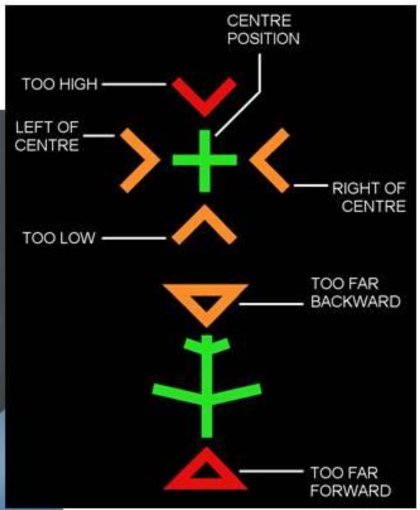
WP6 - Flight Simulation
4. Improvements to the Simulated Concept (6/6)

RECREATE alternative solution:
Active Relative Position Indicator lights



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WP6 - Flight Simulation
5. Phase 2 - Simulation Experiment (1/3)

The phase 2 evaluations were executed in September and October 2014. A total of 26 airline pilots participated in these evaluations.

All the listed improvements were implemented on GRACE and GECO.

The RECREATE concept was fully functional and the pilots could evaluate any situation or condition.

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WP6 - Flight Simulation

5. Phase 2 - Simulation Experiment (2/3)

For familiarisation and training the nominal scenarios without any failures were used.

For the experiment runs there was a set of failure and critical condition scenarios with varying severity:

- Light turbulence
- Increasing turbulence up to moderate
- Engine failure on the cruiser aircraft
- Engine failure on the feeder aircraft
- Refuelling system malfunction, decreasing fuel flow until complete blockage
- Failure of the Estimated Safety Margin indicator during the approach
- Very low visibility, only anti-collision lights visible at close range
- Uncommanded speed brake deflection on cruiser aircraft during refuelling
- Multiple failures introduced one after the other, Relative Position Indicator on feeder aircraft, Estimated Safety Margin indicator, refuelling system and engine failure on feeder aircraft

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WP6 - Flight Simulation
5. Phase 2 - Simulation Experiment (3/3)

Impression of the simulator experiment. [video clip]


Initial Approach


Station Keeping


Final Approach


Refuelling


Astern Hold


Abort

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WP6 - Flight Simulation
6. Results and Conclusions (1/9)

1. Overall acceptance of the RECREATE system

The most important question of the experiment is if the pilots feel that the RECREATE system that was presented in the simulation will provide sufficient safety and the required level of control when it will be implemented in real life.

Pilots	Average Rating
Cruiser	7.7
Feeder	7.3

With these average ratings this is a very good result and this shows that all pilots feel that the presented RECREATE system can really work when it will be implemented in real life.

Rating	Overall Acceptance
1	Unworkable
2	Unreasonable Workload
3	Unmanageable Workload
4	High Workload
5	Much Improvement Needed
6	Some Improvement Needed
7	A Few Improvements Needed
8	Acceptable
9	Quite Acceptable
10	Very Acceptable

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WP6 - Flight Simulation
6. Results and Conclusions (2/9)

2. Perceived workload

Besides the acceptance of the RECREATE system it is also important that the work load of the pilots remains within acceptable limits and preferably comparable to present day levels.

Compared to present day automated approach and landing operations pilots rated their workload as:

Pilots	Average Rating
Cruiser	Slightly higher
Feeder	Slightly less

From the selected concept where the cruiser approaches the feeder from behind it is clear that the workload of the cruiser pilots would be higher than the workload of the feeder pilots. The ratings from the pilots confirm this.

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WP6 - Flight Simulation
6. Results and Conclusions (3/9)

3. Pilots being in-the-loop

On average the pilots of the cruiser aircraft indicated that in 84% of the experiment runs they were always in-the-loop with the execution of the air refuelling operation by the RECREATE autopilot and systems.

For the feeder pilots this was 68%.

This lower number is in line with the lower workload of the feeder pilots and the fact that they have less interaction with the RECREATE system during the operation.

There is still room to improve the RECREATE system to keep the pilots more in-the-loop during its operation.

24

WP6 - Flight Simulation
6. Results and Conclusions (4/9)

4. Information on safety of the operation

The pilots indicated that in 77% of the experiment runs they received enough information on the safety of the operation.

This number is lower than might be expected because during a number of experiment runs some of the safety indications were deliberately removed or the automatic abort function was disabled.

During the debrief about 90% of the pilots indicated that in general they received enough information on safety of the operation.

Some pilots noted that especially during failure situations they would like more information on the type of failure and whether this would affect the safety of their aircraft.

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WP6 - Flight Simulation
6. Results and Conclusions (5/9)

5. Overall safety of the operation

The safety of the operation was on average rated between "Good" and "Satisfactory".

In just a couple of experiment runs some pilots rated the safety "Unacceptable". But again this was during scenarios where deliberately multiple systems were failed simultaneously. This is not a realistic condition but a test case to see the reaction of the pilots to extreme situations.

There has not been a single experiment run where the safety of the operation actually got compromised.

It can be concluded that the safety of the operation under realistic conditions was at least satisfactory.

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WP6 - Flight Simulation
6. Results and Conclusions (6/9)

6. Sufficient control over systems and aircraft

In 97% of the experiment runs the cruiser pilots indicated that they had sufficient control over the automated RECREATE system and the aircraft when required. During the debrief even 100% indicated that in general they had sufficient control. For the feeder pilots this was 90% for the experiment runs and 87% for the debrief.

These lower numbers for the feeder pilots can be explained by the fact that there sometimes was a delay between pilot selection of abort and the reaction of the RECREATE system caused by technical difficulties with the internet connection between GRACE and GECO.

Overall it can be concluded that if the systems were working properly the pilots had sufficient control of the RECREATE systems and their aircraft.

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7. Required RECREATE system components

Almost all pilots indicated that the main cockpit components of the RECREATE system that are required for the safe execution of the air refuelling operation are:

- Manoeuvre Progress Display / Boom Status Display
- FMA indications
- The safety monitoring system with automatic abort activation

Secondary support functions like the use of the ILS deviation indications or the active relative position indicators on the belly of the feeder are only required by 42% and 75% of the pilots respectively.
This is no surprise since these functions are in fact not needed for the safe operation of the RECREATE system during the refuelling operation.

WP6 - Flight Simulation
6. Results and Conclusions (8/9)

8. Feasibility of the presented RECREATE concept

Almost all pilots feel that the presented RECREATE concept can be implemented in real life and can be operated safely.

They also indicated that little training will be required to get used to the operation of the automated execution of the air refuelling by the RECREATE system.

From the cockpit perspective there seems to be no issue in implementing this in real life.

There seems to be more doubt about realising the infrastructure of feeder bases, the availability of the feeder aircraft and the required introduction of new regulations to make these operations possible at all.

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WP6 - Flight Simulation
6. Results and Conclusions (9/9)

Conclusions

The overall conclusion of the human-in-the-loop evaluations of the presented RECREATE concept is that all pilots that participated in the experiments believe that this concept can be implemented in real life and can be operated by the pilots from the cruiser and the feeder aircraft while maintaining the required safety levels and with an acceptable workload for the pilots.

Of course some aspects still need to be improved before actual implementation on an aircraft but no major issues were identified that would be hard to solve. It would be very interesting to investigate if this RECREATE concept can be developed further towards actual implementation.

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WP6 - Flight Simulation

Thank you for your attention

Any Questions?

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