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Sufficient Scope in Current Aircraft Technology Developments? --A Systems Analysis Application to the Multi Actor Aviation Technology System

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Air travel demand is growing worldwide with an approximate worldwide long term average of 5 to 6% annually. This growth has both very positive and negative effects. Aviation is deeply embedded in our society. Dramatic decrease in ticket prices has brought to many the possibility of reaching many destinations worldwide in a day's travel. It is claimed by some that the negative effects – such as noise pollution and greenhouse gas emissions - will not become more problematic in the future, because technologies are being developed that will compensate them.
The starting point of this research is to discover whether this claim concerning the potential of current aircraft technology developments is true. In other words: is the current development in aircraft technology capable to contribute to a sustainable development in the aviation sector by keeping current positive effects, while mitigating the negative effects?
Existing research on this issue is mostly trend research, focussing at the average technology efficiency increase and extrapolating this to the future. In a context where multiple actors have to decide about what to do, this extrapolation is not enough. An aggregated number does not reveal the concrete options and causal relations behind it. This paper, therefore, introduces the open and explicit method of systems analysis to answer the question if (and if so, how) new aircraft technology can mitigate the adverse effects of an increasing air travel demand, while keeping the benefits. It presents analytical results in terms of numbers and score cards in order to feed the policy process that eventually should lead to policy in order to solve the problem.
In light of the results of the systems analysis, this paper concludes that current developments in aircraft technology are not sufficient to mitigate the adverse effects of growth. Our research suggests that the combination of the efficiency improvement rate, the growth rate of the demand for air travel, and the long replacement times for older technology do in fact not cancel each other out.
In order to achieve a sustainable development in the aviation sector, this systems analysis approach shows the limited (though important) influence technology can have on the full concept of sustainable development. We suggest to not only invest more into developing ever better technologies, but to also search for non-technical solutions in order to address the full concept of sustainable development.

Keywords: Aircraft technology, sustainable development, air travel demand, scenarios, systems analysis

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1. Introduction

Globalisation in combination with economic growth has increased the demand for international movements. These movements are provided by air transport for a relatively small amount of money; and in short time frames. Most major cities in the world can be reached within one or two days travel. Air transport is extremely efficient in terms of energy use. Per seat-kilometre (i.e. one aircraft seat flown over a distance of one kilometre) approximately the same amount of fuel is used as when driving the same distance by car. However, the aircraft travels at a ten times higher speed (Torenbeek 2000).

Aviation has various adverse effects. Most prominently, this includes effects such as local air pollution due to the emissions of burned fuel, and noise due to engine operations and the air flow over the airframe. Since most airports are located in densely populated areas, many people experience these effects. With respect to noise, aircraft manufacturers have been able to significantly reduce the amount of noise aircraft emit. However, the amount of air traffic has increased. Moreover, there is an increasing awareness that not only the absolute noise level causes hindrance, but also how frequently an individual is exposed to airplane noise (Upham, Maughan et al. 2003). Other adverse effects of aviation include the use of finite resources of materials, like aluminium and crude oil, and, the emission of green house gasses. Aircraft operation thus contributes to climate change (IPCC 1999).

There is a clear dilemma between the described advantages of cheap worldwide transport and the described disadvantages of noise, air pollution, finite resource usage, and contribution to climate change. In solving dilemmas in high-tech areas, people tend to look for technical solutions first. For example, in its press release IP/02/1650, the European Commission states that the program of spending 100 billion Euros on aviation research "…makes a case for joint research projects with technology integration platforms for testing and adopting new technologies, large-scale research test-beds and technological incubators." The mentioned program for research in aviation "…attempts to reduce CO_2 emissions by undertaking research in aerodynamics, weight reduction and by improving the configuration of present technology. Research should concentrate on novel aircraft concepts such as the flying wing and alternative aircraft fuel such as hydrogen, for example (European Commission 2002b)." In other (more elaborate) publications, the European Commission has also stressed the importance of technology developments to contribute to the mitigation of current adverse effects of aviation regarding sustainability issues (European Commission 2001; European Commission 2002a).

The statement that technology will solve the problems, a so called technology fix solution, has been challenged in general. Ellul, for instance, describes that technological 'solutions' for a certain problem might cause even more problems when they are implemented than they solve (Ellul 1964). Tempelman argues that technology is both part of the problem as well as part of the solution, but that a pure technological fix is a myth (Tempelman 1998). Are these general statements about the limitations of technology also valid in the specific field of aircraft technology? The available research suggests an affirmative answer. However, the available research comes from one of two categories: trend analysis suggesting average efficiency improvements, or research that relates efficiency trends to air travel demand expectations for the future.

Williams (2007) describes the potential efficiency improvements due to several technologies (e.g., engine and airframe) on the emissions influencing climate change. Changes to the airframe appear the most promising, with an expected 16% efficiency gain. However, like Peeters et al. (Peeters, Middel et al. 2005), Williams states that an average annual 1% increase in efficiency is already optimistic, while aviation is growing at least 5% each year and is expected to due so in the future. Lee (Lee, 2003) describes the enormous improvements technology has made in the past to reduce fuel use and noise of aircraft, but he expects that the trend line will curb; limited further improvements from current designs are expected. Lee focuses on new designs, like the Blended Wing Body, which is also analyzed in this paper. Babikian (Babikian, Lukachko et al. 2002) analyzes the historical trends in efficiency improvement due to, among other things, technology changes focussing on regional aircraft. Differences with non regional, larger aircraft are not due to technology, but due to operation. For the total effects though, it appears that separating regional from non regional jets makes sense, as is done in this paper (see section 6).

The IPCC (IPCC, 1999) developed several scenarios for future air travel demand and calculates trends of technology efficiency increase. By combining both, IPCC shows the effects that aviation might have on the future atmospheric conditions. The IPCC also presents many technological and non-technological options to reduce the undesired atmospheric effects of aviation in the future. However, they do not relate concrete current new aircraft technology ideas to atmospheric effects, nor do they relate any technology to desired effects of aviation.

These trend analyses of Williams and IPCC on the possibilities of aircraft technology in the future shows that growth in aviation is larger than the expected efficiency increase due to technological measures. In opposition to trend analysis, this article approaches the question from a systems analysis perspective. In complex multi actor studies, like sustainability studies, many different values are contested by different actors at the same time. In these very complex sustainability issues, the type of solution chosen is often technology. However, not all actors are interested in the same values. Different actors might even opt for the same solution for completely different reasons. In order to act, sustainability issues around aviation and technology should be researched and presented systematically, open and explicit on multiple values valued by many different actors.

Decision makers are faced with the issues of sustainability in general and of sustainability and aviation in particular. There are protests against airport expansion, there are huge debates about noise (what is disturbing, how should it measured), and about the economic impact of aviation. So far, the numbers show that aviation is allowed to grow at growth rates higher than economic growth. However, decision making involves making trade offs between the desires and objectives of many stakeholders. Decision makers are constantly challenged to be transparent about there decisions and explain why certain stakeholders have seen there desires taken into account, while others have not.

For transparent decision making, trend figures alone hide too much information. Different parties need to see what is behind the aggregate numbers to make up their minds. Decision makers need the same, in order to be able to explain their decisions. For stakeholders it is not interesting to know weather a certain engine can be improved by another 15% within ten years. They need to know if in a certain time frame (say, 2050), that particular engine will contribute to the satisfaction of certain stakeholders' needs.

This paper adds such concrete and practical information to the discussion about the role of aircraft technology in reaching (more) sustainability. Therefore, it operationalizes the broad concept of sustainable development for aviation into concrete and measurable criteria. It adds, where the sustainability concepts does not already cover the different stakeholders' objectives, additional criteria. Then, it identifies, using technology experts, relevant current ideas for new aircraft technologies. It determines scenarios of plausible potential future states of air travel demand. Finally, it combines the effects of the technologies on the different criteria for each scenario in a score card. The method as such focuses on scorecards as final product. However, only in order to feed the policy process with these scorecards that should lead to the development of policy to address the problem. The policy process itself is not part of this study. This study aims to facilitate this policy process only.

This paper therefore aims to answer the following research question:

"By applying systems analysis, can we identify a contribution to sustainability by some typical current ideas for technological improvements of aircraft; i.e. can these technologies mitigate the adverse effects of the growth in air transport demand within the time frame of 2050 while keeping the benefits?"

As this paper focuses on the need of decision makers (what kind of information do they need to make better decisions) it serves this need by performing a systems analysis. It applies the methodology described by Walker (Walker 2000) and Miser and Quade (Miser and Quade 1985). It focuses solely on aircraft technology and not on any other type of measures (e.g. demand management) that can be taken to mitigate adverse effects of aviation.

Section 2 of this paper, explains the choice for the method of systems analysis and specifies how the methodology will be applied. Sections 3, 4, 5 and 6 present the results of this systems analysis. Section 6 concludes that the combination of the results in sections 3, 4, 5 and 6 lead to answering the research question with a clear 'no'. It is not this particular answer that is interesting (this is already known from for instance trend analysis studies, like the ones described in this section), although this answer gives extra support for existing knowledge. The main added value is the explicit information about what current technological options can do on what criteria (and especially the limited set of criteria that gets influenced by technology). This information is needed to feed the policy debate about what to do. Although not part of the study, section 6 also gives some recommendations for further research on other than technological options that might contribute to solving the problem introduced in this paper.

2. Research Method: systems analysis

The aviation system contains many individuals and groups of individuals, each with their own, often conflicting, interests and objectives. Among these actors there appears to be a dilemma between objectives related to the increasing demand for air travel, and objectives related to the also increasing noise emissions, gas emissions, contribution to climate change and using up of finite resources.

In addition to this dilemma, there is great uncertainty in the choice for potential solutions. There is more than one source of uncertainty. One is the absence of a full scientific understanding of the entire aviation system on a detailed level (all processes, all persons, all technologies and all their underlying relationships). Another source is uncertainty about what new possible developments might happen (both technical as well as non-technical). A third source of uncertainty is the relatively long timeframes in aviation. For example, aircraft have a long lifespan (90,000 flights or an operational life of 25 to 30 years is no exception) or the time it takes to construct extra runways (decades or more). During timeframes like that, the demand for air travel, for example, can change dramatically. Decisions made now, should result in systems that are robust in their functioning on likewise timeframes in an environment which can be completely different than during the time when the decision was made.

To answer the research question stated in the introduction, different possible technological solutions to the described problem have to be compared on their effects. Effects that will differ for the different actors involved in the aviation system (airlines have other objectives than airports). These effects will not be static, as the system will change over time. Especially within the aviation system, long time frames are common, as changes tend not to take place quickly. Building new runways may take decades and the implementation of other flight patterns years to negotiate. Therefore, the effects of potential technical solutions will have to be determined in different possible futures. Ideally, one may find 'robust' solutions by doing this, solutions that will serve most of the actors in most of the possible futures. However, this will not always be the case.

Several common methodologies that can help decision makers might be useful, e.g. Trend analysis, Cost Benefit Analysis or Policy Analysis with Multi-Criteria Score Cards. On the topic of sustainability, aviation and aircraft technology, trend studies are available (e.g. Williams 2007, IPCC, 1999). For specific technologies, Cost Benefit Analyses are too. We want to make a cause to add to the existing studies the application of a method called systems analysis (with multi-criteria score cards).

The many conflicting values and the vast uncertainty make an analysis on systems level obvious, resulting in a multi criteria score card. In the literature this is called 'systems analysis' (or 'policy analysis'). Analysis on systems level requires a helicopter perspective. Details are only of importance when they can influence the to-be-taken decision. Very specific details or small differences in outcomes (of, say, a few percentages) are not important; it is the large differences that matter (Miser and Quade 1985). The aviation system is of such complexity, that it can not be analysed in detail in the long run; the uncertainty is too substantial to make detailed answers (up to many digits) on such a time frame believable.

Systems analysis is a rational, systematic and structured research approach. Its purpose is to assist policymakers in choosing a course of action from among complex alternatives under uncertain conditions (Walker 2000). The approach follows the scientific method by being explicit and open, objective, and empirically based, consistent with existing knowledge, and offering verifiable and reproducible results.

The approach of systems analysis can best be explained by looking at Figure 1. In the centre of the figure, there is a model representing that part of reality that the to-be-studied policy measures will focus upon: the aviation system.

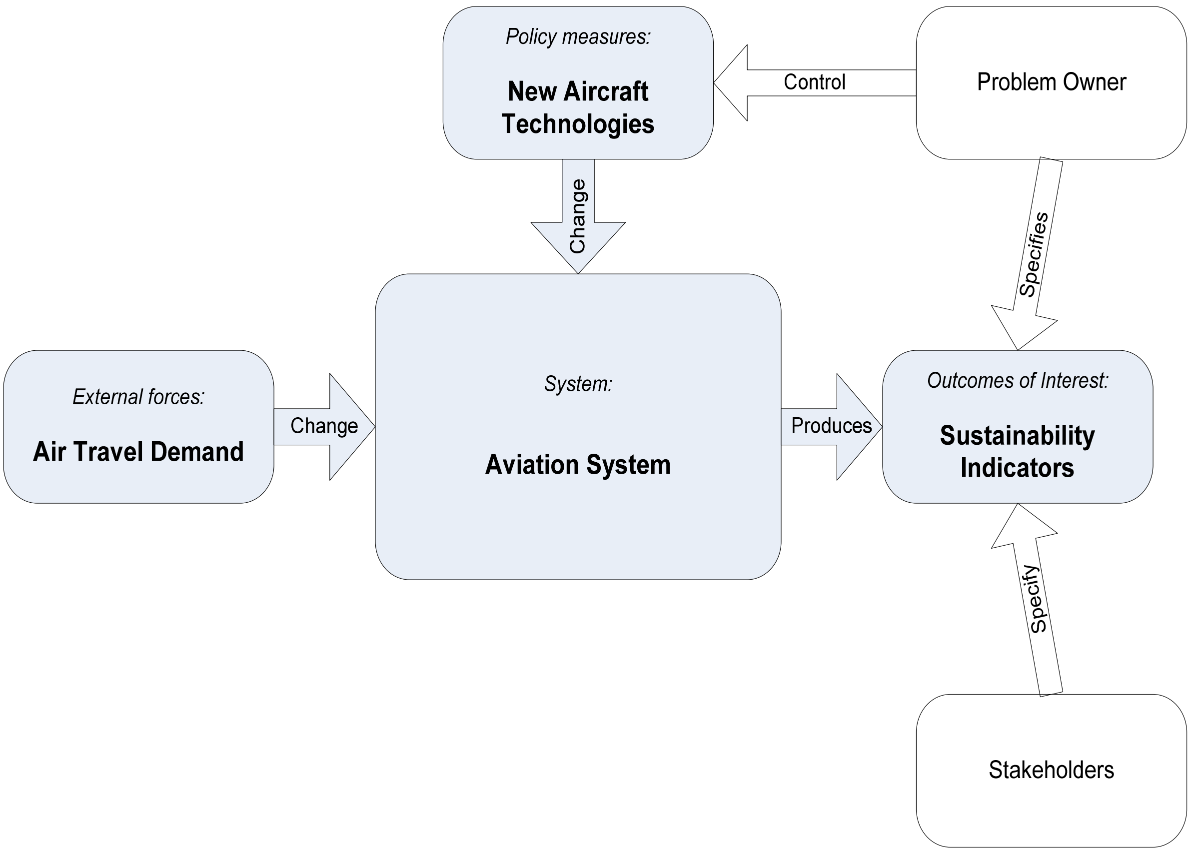

Figure 1. The problem diagram around Sustainable Development and aviation (adapted from Walker (2000)).

Two kind of forces act upon the aviation system from the outside. One kind is out of control of the problem owner and is called "External forces" (in this research: air travel demand). The other kind is completely under the control of the problem owner and is called "Policy measures" (in this research: new aircraft technologies).

External forces are dynamic; they can change over time. Their value at any given time in the future is uncertain. A widely used approach to deal with this uncertainty is the scenario approach (Miser and Quade 1985). The consequences of different possible policy measures have to be determined for a variety of possible futures that are believed to cover the most probable range of possible futures.

In close relation to the objectives of the problem owner and other actors and stakeholders, outcomes of interest are defined. In this research for instance noise and gas emissions are important outcomes of interest. To make these outcomes of interest measurable, indicators are designed that relate closely to the outcomes of interest.

A multi-criteria scorecard presents the results of a systems analysis. All the entries in a certain row of this table represent scores of a particular policy measure (the selected new aircraft technologies) on the several outcomes indicators (see Table 1 for an example of a score card).

Table 1. An example of a scorecard (adapted from De Haan (2007)).

	Outcome of interest 1		Outcome of interest 2			
	Indicator 1.1	**Indicator 1.2**	**Indicator 2.1**	**Indicator 2.2**	**Indicator 2.3**	**Indicator 2.4**
Desired value	*High*	*High*	*Decrease*	*Increase*	*Low*	*Not at all*
Policy measure 1	***6***	***High***	***Increase***	***Decrease***	***1000***	***Very much***
Policy measure 2	***8***	***Average***	***Increase***	***Increase***	***1500***	***A bit***
Policy measure 3	***12***	***Low***	***No change***	***No change***	***750***	***Not at all***

Using scorecards to represent results of the analysis gives a good overview of how each policy measure affects the different outcomes of interest. Trade-offs and dilemmas between policy measures and outcomes of interest can easily be illustrated. An important advantage of using scorecards is that in one overview both numerical and qualitative data can be presented. Non-numerical indicators are often hard to measure and therefore get easily moved aside. The scorecard shows the effect of each policy measure on all types of indicators all together. This facilitates the ease of trading off among the qualitative and quantitative outcomes of interest.

Once a scorecard, as a final product of a systems analysis, is available, the process of decision-making can start. The scorecard should help the several actors in reaching convergence about the final decision. Alternative policy measures can be supported by different actors for completely different reasons. An agreed upon chosen policy measure is the ultimate goal of the analysis, not agreement on the value judgments among the different actors (Walker 2000).

Performing a systems analysis requires carrying out the following list of steps (see Table 2). The first three steps can be categorized as 'objective analysis'. What dilemma forms the heart of the problem has to be identified first. Then, specifying the different actors and their goals, results in the important outcomes of interest for the problem. Thirdly, these outcomes of interest are translated into measurable outcome indicators. In section 3 we elaborate on these first three steps under the heading of 'objective analysis'. The remaining steps 4, 5 and 6 will be elaborated upon individually in the sections 4, 5 and 6.

Table 2. The several steps in a systems analysis study (adapted from Walker (2000a)).

Step:	Task to carry out:
1	Identify problem
2	Specify objectives
3	Decide on indicators
4	Select potential policy measures
5	Analyze policy context
6	Analyze and compare potential policy measures

3. Objective analysis: problem, actors, indicators

This section covers the first three steps of systems analysis applied to the aircraft technology case. It identifies what dilemma forms the heart of the problem (step 1), it specifies the different stakeholders and their goals (step 2), and, it translates these goals into measurable outcome indicators (step 3).

Step 1: Identify the problem - As described earlier, aviation has both positive and negative effects. Many actors in the system consider Sustainable Development as the way in which aviation should develop itself; to both reduce negative effects and keep the positive effects of transport. Many believe technology is being developed to do this. This problem is transformed into the following research questions (see Introduction):

> *"Can current ideas for technological improvements of aircraft mitigate the adverse effects of the growth in air transport demand within the time frame of 2050?"*

The approach of systems analysis requires one actor to be considered the problem owner (see Figure 1). The analysis will be carried out from the problem owner's perspective, but not neglecting any other interest that might be present among other actors in the problem field. In the case of sustainability and aviation the problem owner must have some power over the system to make changes, to act, to make policy. In this study, technological changes are considered. Given the EU current technological perspective in its requested research proposals (see Introduction), the EU Council is considered to be problem owner. This problem owner is considered to be large enough to be able to make changes in the system. Obviously another choice for problem owner would be possible, which would make the perspective of the analysis slightly different, but would not (substantially) change the outcomes.

Step 2: Specify objectives - Given the attention paid to sustainable development by both the problem owner and other actors and stakeholders in the aviation system, it is important to identify what the problem owner (and other stakeholders) mean when talking about Sustainable Development in aviation. The Council of the EU, being the problem owner in this research, (EU council 2001) provides a relatively detailed description of what Sustainable Transport is, which is closer to aviation than the general description by Brundtland (WCED 1987). INFRAS research group, in relation to the EU, (INFRAS 2000) provides a comparable description of Sustainable Aviation. All outcomes of interest mentioned in these two descriptions are identified. The used category labels for the categorization of these outcomes of interest are social factors, environmental factors and economic factors and are presented in Table 3.

Table 3. Factors representing Sustainable Development categorized in three columns: social, environmental and economic.

Social ('*PE*ople')	Environmental (*'PL*anet')	Economic (*'PR*ofit')
PE1: Access Basic access and development needs of individuals and societies being met *Accessibility of remote areas*	**PL1: Ecosystem health** Consistent with ecosystem health Limits emissions and waste within the planet's ability to absorb them *Climate change* *Air pollution*	**PR1: Access** Basic access and development needs of companies being met *Access and travel time speed*
PE2: Safety Safe *Safety*		**PR2: Affordability** Affordable operation
PE3: Human health Consistent with human health	**PL2: Resource use** Uses renewable resources at or below their rates of generation Uses non-renewable resources at or below the rate of development of renewable substitutes *Energy efficiency*	**PR3: Competitive Economy** Efficient operation Supports a competitive economy *Job creation and growth contribution* *Cost recovery of infrastructure costs* *Global productivity*
PE4: Equity Promises equity within and between generations		
PE5: Fairness Fair operation Offers choice *Local and National participation of people in decision making*	**PL3: Impact on land** Low impact on land *Land use*	**PR4: Regional Development** Supports balanced regional developments *Regional and local market changes*

Roman type setting: entry originates from the EU Council definition of Sustainable Transport (2001); italic type setting: entry originates from the INFRAS description of Sustainable Aviation (2000).

Step 3: Decide on indicators - Using publications by each of the considered actors in the aviation system, for each of the factors mentioned in Table 3, measurable indicators have been designed in this research. These indicators represent information about sustainable development that decision makers might need in their decision-making process. A stakeholder analysis revealed some outcomes of interest that are not in the description of sustainable transport nor sustainable aviation. The indicators related to these outcomes of interest are added to the list (labelled ASI, which stands for Additional Stakeholder Indicator). In this research, no single indicator is considered more important than another (it is not a multi criteria analysis, the product is just a multi criteria scorecard); the judgement of that is left to the decision maker, based on the total scoring pattern on all indicators. The indicators designed in this research are listed in Table 4.

Table 4. Designed indicators representing the outcomes of interest (De Haan, 2007).

Code	Outcome indicator	Unit	Desired value or direction of change
PE1-1	Number of connected geographical places via operated air routes in the EU.	#	increase
PE1-2	Average frequency of flight between two airports within the EU area.	Flights/day	increase
PE1-3	Average ticket price for flight.	€/ticket	decrease
PE1-4	Average distance to larger, international airport.	km	decrease
PE1-5	Number of operated larger, international airports in EU area.	#	increase
PE1-6	Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.	#	increase
PE2-1	Number of internal fatalities in aviation.	#/pax km	decrease
PE2-2	Number of internal incidents in aviation.	#/pax km	decrease
PE2-3	Number of aircraft crashes involving aircraft >150 passengers.	#/pax km	decrease
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	decrease
PE3-1	Average fuel use per LTO cycle	ton/year	decrease
PE3-2	Average emission of NO_x per LTO cycle	ton/year	decrease
PE3-3	Average emission of CO per LTO cycle	ton/year	decrease
PE3-4	Average emission of VOCs per LTO cycle	ton/year	decrease
PE5-1	Different type of aircraft in service	#	increase
PL1-1	Total emission of CO_2 during flight operations	Ton/year	decrease
PL2-1	Percentage of renewable fuel of the total amount of fuel used	% (Ton renewable / total ton of fuel)	increase
PL3-1	Land unavailable for other than aviation purposes	km^2	decrease
PL4-1	Noise production of specific innovative aviation technology	dB(A)	decrease
PR2-1	Direct operating cost	€/year	decrease
PR3-1	Number of innovative aviation technologies in use	#	increase
PR3-2	Number of airlines operating	#	increase
PR3-3	Number of transport modes for continental transport (including aviation)	#	increase
ASI2-1	Percentage of flights leaving the airport according to schedule	% (# flights on time / total # flights)	increase
ASI2-2	Average turn around time	h	decrease
ASI2-3	Changes in design and maintenance of aircraft	small/medium/ substantial	small
ASI3-1	Design risk of innovative technology	small/medium/ substantial	small

4. Identification of potential solutions: some new aircraft technologies

This section covers step 4 of systems analysis and identifies potential solution to be further analyzed in the remainder of the analysis. To identify technologies that can be analyzed, first the aviation system is broken down into subsystems to find in which subsystems aircraft related technology plays a role. We first distinguish the landside and airside subsystems; these subsystems come together at airports. We break the airside subsystem into the airfield, demand,

and air traffic subsystems (de Neufville and Odoni 2003). Aircraft related technologies play a role in both the airfield and air traffic subsystems (see Figure 2).

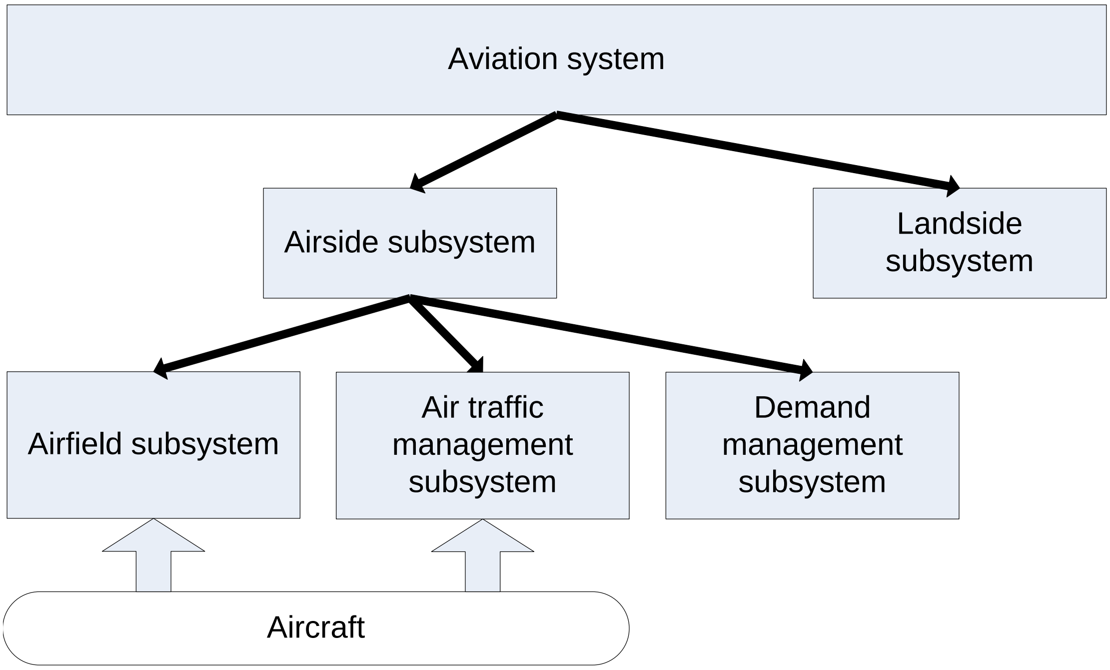

Figure 2. Distinguishing the subsystems within the aviation system that aircraft technology influences.

An aircraft can itself be considered a system composed of four subsystems (see Figure 3): structure, aerodynamics, controls, and propulsion (Anderson 1989; Moir and Seabridge 2001).

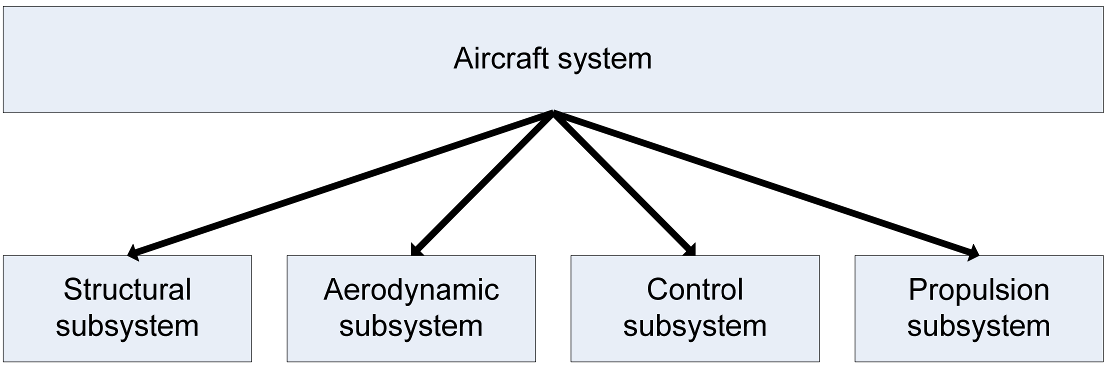

Figure 3. Subsystems of the aircraft system.

Scanning the literature and using interviews with aircraft technology developers and researchers, technologies have been identified in each of these four subsystems that are as innovative as possible (i.e. most promising given certain indicators of performance that are considered important, like noise, or fuel use), but for which a serious preliminary design exists (so that it is possible that the technology will actually be implemented and widely used within the time frame of this research, 2050). It is not that these aircraft technologies are all possibilities that are currently under design or considered, however, this set of technologies is considered to be representative for the different kind of technological options that are present. For this research it is not so interesting to compare all kind of blended wing like technologies, but more what in general there pros and cons are considering sustainability and aviation. In addition to technologies making changes in the four identified subsystems, there are also technologies identified that change the overall aircraft system. One can think of Blended Wing Bodies and Airships. The identified technologies are summarized in Table 5:

Table 5. Identified technologies in the overall aircraft system and its four subsystems considered to represent the different kind of technological options currently under study or present (source: De Haan, 2007).

Structural subsystem	Aerodynamic subsystem	Control subsystem	Propulsion subsystem	Overall aircraft system
Ultra high capacity aircraft *Composite materials*	*High aspect ratio wings*	*Free flight* *Reduced thrust take-off*	*High Speed propellers* *Hydrogen fuelled aircraft*	*Airships* *SkyCar* *Blended wing bodies*

5. Analyzing policy context: plausible future air travel demand

This section covers step 5 of systems analysis. It identifies plausible scenarios for future air travel demand. These scenarios each will be used to analyze the effects of the potential solutions in, in section 6.

New technologies need time to get implemented in a system, especially in the aviation system, which is so resistant to change. The system is resistant to change due to, among other things, the long use phase of aircraft technology (up to 30 years) and due to the very small profit margins in ticket prices, which makes the adaptation of change risky. If a technology can be found that makes a serious contribution to sustainable development, it will contribute most to sustainable development if it is fully implemented and replaces older technologies.

This research assumes that at least a time horizon of 2050 is needed to make it possible that an innovative aviation technology gets fully implemented and replaces older technologies. This assumption is based on the idea that a new technology will come into the system via the introduction of new aircraft. Designing, testing, and initial certification of an aircraft takes approximately 10 years and a lifetime operation of an aircraft will take, for the largest part of the civil fleet, at least 30 years. With the intense use of aircraft every day of the year, after 35 years most aircraft will have been replaced. Even then some civil passenger aircraft might fly some extra years as freighters and some will still fly in less dense markets. However, the majority of aircraft have a design and usage age adding up to a maximum of 45 years. It is based on this reasoning that the choice for 2050 as time horizon in this research has been made.

Taking 2050 as a time horizon requires developing for the analysis some ideas about possible 2050 states of the world. This research used the scenario approach to design scenarios for air travel demand in 2050. Using these scenarios, all aircraft related technologies are then analyzed. IPCC has scenarios of growth in air travel demand for 2050 that are as high as 9 times current demand (IPCC 1999). De Haan developed scenarios based on factor modelling ranging from a low growth scenario of approximately 2.5 times current air travel demand to also an approximate 9 times growth (de Haan 2007). He bases his low growth scenario on findings by Humpreys that the large growth numbers might not be possible because of the increasing resistance to ever increasing airport expansion (Humpreys 2003). This research takes the two extreme values for air travel demand (2.5 and 9 times current demand) as two plausible future states of the aviation system for 2050 and analyzes if any of the identified new aircraft technologies might make a sustainable state of aviation possible in any of the two scenarios.

For that analysis, there is a need to find out what new technology will do in the possible 2050 situations, compared to what the old technology would do in those situations. To find that out, the score of current technology in the two 2050 scenarios on the set of indicators representing Sustainable Development is also determined. In this research this is called the reference case, see Figure 4.

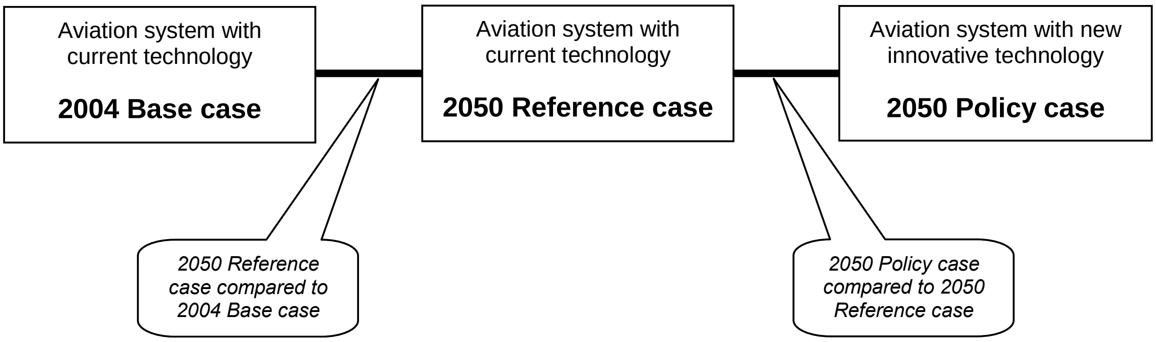

Figure 4. The different scoring cases compared to each other.

6. Analyzing and comparing potential policy measure

This section covers step 6 of systems analysis. It determines the effects of the potential solutions in the different plausible future states of air travel demand, on the criteria that represent the outcomes of interest for the problem owner and stakeholders.

When a set of different new aircraft technologies is identified (in section 4), these technologies need to be compared to each other in their effects. This research used the preliminary design reports of all these technologies to determine what the effect of the technology would be on the outcomes of interest and their indicators. The reports just gave indications on what changes could be expected on outcomes of interest compared to the current situation. An example is that it is expected that the introduction of high capacity aircraft will reduce the direct operating costs per flown seat kilometre by 15%. This research thus has to translate the 15% direct operating cost reduction per flown seat kilometre in a real world situation of 2050 in which there will be a different demand in air travel than there is today.

In general the scoring of the different alternatives on the different indicators representing sustainable development is done by firstly translating all the mentioned effects in the preliminary design reports or studies to an effect per flown seat. Secondly, the share of the particular technology in the future aviation fleet was determined. For Blended Wing Bodies, for instance, it is assumed that only the mid-size (175-350 seats) and large aircraft (more than 350 seats) will possibly consist of these Blended Wing Bodies if they would be introduced. The effect of introducing the Blended Wing Body in the aviation system will affect that system proportionally to the share the Blended Wing Body has in the complete aircraft fleet of 2050. Thirdly, the combination of the share of the particular technology and the number of seats flying around, determines eventually how much an indicator changes compared to the 2004 base case. The effects (compared to the 2004 case, in which all indicator values are set to 1) of all technologies on all indicators can be seen in Table 7 (for the high growth scenario A) and Table 8 (for the low growth scenario B). In the appendix to this article for some criteria it is shown how the values in the tables were calculated.

Table 7. Scorings of new aircraft technologies on indicators for sustainable aviation for the high growth scenario.

Policy case 2050 **Scenario A High Growth** *Indicators →* *↓ Technologies*	*Number of connected geographical places via operated air routes in the EU.*	*Average frequency of flight between two airports within the EU area.*	*Average ticket price for flight.*	*Average distance to larger, international airport.*	*Number of operated larger, international airports in EU area.*	*Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.*	*Number of internal fatalities in aviation per year.*	*Number of internal incidents in aviation per year.*	*Number of aircraft crashes per year involving aircraft >150 passengers.*	*External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)*	*Average fuel use per LTO cycle*	*Average emission of NOx per LTO cycle*	*Average emission of CO per LTO cycle*	*Average emission of VOCs per LTO cycle*	*Different type of aircraft in service*	*Total emission of CO2 during flight operations*	*Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)*	*Land unavailable for other than aviation purposes*	*Noise production of specific innovative aviation technology*	*Direct operating cost*	*Number of innovative aviation technologies in use*	*Number of airlines operating*	*Number of transport modes for continental transport (including aviation)*	*Percentage of flights leaving the airport according to schedule*	*Average turn around time*	*Changes in design and maintenance of aircraft*	*Design risk of innovative technology*
Ultra high capacity aircraft	3.24	2.12	<1	<1	1	2.12	0.99	0.99	0.99	<10.12	0.98	0.98	0.98	0.98	1	9.88	1	<10.12	1	0.97	1	1	1	>1	1	+/-	++
composite materials	3.24	2.12	<1	<1	1	2.12	1	1	1	7.08	0.85	0.85	0.85	0.85	1	7.08	1	10.12	1	<1	1	1	1	1	1	+/-	+/-
High aspect ratio wings	3.24	2.12	<1	<1	1	2.12	1	1	1	10.12	1	1	1	1	1	9.95	1	<10.12	1	0.99	1	1	1	1	1	++	++
Free Flight	3.24	2.12	<1	<1	1	2.12	1	1	1	10.12	1	1	1	1	1	9.92	1	10.12	1	<1	1	1	1	>1	1	-	+/-
Reduced thrust take-off	<3.24	<2.12	<1	<1	1	2.12	>1	>1	>1	10.12	0.65	0.65	0.65	0.65	1	10.12	1	10.12	0.90	<1	1	1	1	1	1	-	-
Propellers for high flying speeds	3.24	2.12	<1	<1	1	2.12	1	1	1	10.12	1	1	1	1	1	5.07	1	10.12	<1	0.85	1	1	1	1	1	+	+
Hydrogen powered flight	3.24	2.12	>1	<1	1	2.12	1	1	1	10.12	0.90	<1	0.21	0.21	>1	0.61	2	<10.12	0.92	1.05	>1	1	1	1	1	++	++
Airships	Airships are not considered in this research as they are not expected to take over any part of the current aviation system																										
SkyCar	SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system																										
Blended Wing Bodies	3.24	2.12	<1	<1	1	2.12	<1	<1	<1	<10.12	0.99	0.99	0.99	0.99	>1	9.10	1	<10.12	0.50	0.99	>1	1	1	1	1	++	++

Note that those that are dependant on growth change to values higher than one (i.e. get worse compared to the total situation in 2004).

Table 8. Scorings of new aircraft technologies on indicators for sustainable aviation for the low growth scenario.

Policy case 2050 **Scenario B Low Growth** *Indicators →* *↓ Technologies*	*Number of connected geographical places via operated air routes in the EU.*	*Average frequency of flight between two airports within the EU area.*	*Average ticket price for flight.*	*Average distance to larger, international airport.*	*Number of operated larger, international airports in EU area.*	*Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.*	*Number of internal fatalities in aviation per year.*	*Number of internal incidents in aviation per year.*	*Number of aircraft crashes per year involving aircraft >150 passengers.*	*External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)*	*Average fuel use per LTO cycle*	*Average emission of NOx per LTO cycle*	*Average emission of CO per LTO cycle*	*Average emission of VOCs per LTO cycle*	*Different type of aircraft in service*	*Total emission of CO2 during flight operations*	*Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)*	*Land unavailable for other than aviation purposes*	*Noise production of specific innovative aviation technology*	*Direct operating cost*	*Number of innovative aviation technologies in use*	*Number of airlines operating*	*Number of transport modes for continental transport (including aviation)*	*Percentage of flights leaving the airport according to schedule*	*Average turn around time*	*Changes in design and maintenance of aircraft*	*Design risk of innovative technology*
Ultra high capacity aircraft	*1.74*	*1.37*	*<1*	*<1*	*1*	*1.37*	*0.99*	*0.99*	*0.99*	*<3.49*	*0.98*	*0.98*	*0.98*	*0.98*	*1*	*3.45*	*1*	*<3.49*	*1*	*0.97*	*1*	*1*	*1*	*>1*	*1*	*+/-*	*++*
composite materials	*1.74*	*1.37*	*<1*	*<1*	*1*	*1.37*	*1*	*1*	*1*	*2.44*	*0.85*	*0.85*	*0.85*	*0.85*	*1*	*2.44*	*1*	*3.49*	*1*	*<1*	*1*	*1*	*1*	*1*	*1*	*+/-*	*+/-*
High aspect ratio wings	*1.74*	*1.37*	*<1*	*<1*	*1*	*1.37*	*1*	*1*	*1*	*3.49*	*1*	*1*	*1*	*1*	*1*	*3.43*	*1*	*>3.49*	*1*	*0.99*	*1*	*1*	*1*	*1*	*1*	*++*	*++*
Free Flight	*1.74*	*1.37*	*<1*	*<1*	*1*	*1.37*	*1*	*1*	*1*	*3.49*	*1*	*1*	*1*	*1*	*1*	*3.42*	*1*	*3.49*	*1*	*<1*	*1*	*1*	*1*	*>1*	*1*	*-*	*+/-*
Reduced thrust take-off	*<1.74*	*<1.37*	*<1*	*<1*	*1*	*1.37*	*>1*	*>1*	*>1*	*3.49*	*0.65*	*0.65*	*0.65*	*0.65*	*1*	*3.49*	*1*	*3.49*	*0.90*	*<1*	*1*	*1*	*1*	*1*	*1*	*-*	*-*
Propellers for high flying speeds	*1.74*	*1.37*	*<1*	*<1*	*1*	*1.37*	*1*	*1*	*1*	*3.49*	*1*	*1*	*1*	*1*	*1*	*1.75*	*1*	*3.49*	*<1*	*0.85*	*1*	*1*	*1*	*1*	*1*	*+*	*+*
Hydrogen powered flight	*1.74*	*1.37*	*>1*	*<1*	*1*	*1.37*	*1*	*1*	*1*	*3.49*	*0.90*	*<1*	*0.21*	*0.21*	*>1*	*0.21*	*2*	*>3.49*	*0.92*	*1.05*	*>1*	*1*	*1*	*1*	*1*	*++*	*++*
Airships	Airships are not considered in this research as they are not expected to take over any part of the current aviation system																										
SkyCar	SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system																										
Blended Wing Bodies	*1.74*	*1.37*	*<1*	*<1*	*1*	*1.37*	*<1*	*<1*	*<1*	*<3.49*	*0.99*	*0.99*	*0.99*	*0.99*	*>1*	*2.98*	*1*	*>3.49*	*0.50*	*0.99*	*>1*	*1*	*1*	*1*	*1*	*++*	*++*

Note the same issues as mentioned above table 7.

A quick glance at the table shows that hydrogen powered flight might have some serious advantages in terms of sustainability. However, there is a good reason to consider the generation of hydrogen, for which nowadays fossil fuels are being used, while the overriding reason for using hydrogen is a too large use of fossil fuels. Nuclear power to generate hydrogen is an option, as well as solar, wind, or tidal power. At the moment however, nuclear power is seriously debated, while the other sources hardly have any capacity to generate enough hydrogen to fly today's fleet of aircraft. With the expected large growth of flight it should be seriously debated whether this hydrogen can be produced in a sustainable way in quantities that can feed an entire worldwide fleet of aircraft in the future.

Taking everything into account, it becomes clear that it is mostly the desirable effects of aviation (such as different possibilities for travelling and turnover for airline companies) that benefit from the growth. The undesired effects of aviation (such as noise production, emission of gas and the use of ending energy sources) worsen. They also increase due to the growth, but the increase is less strong than that of the desirable effects, as a consequence of an increase in technical efficiency. It also shows clearly that it is the growth in aviation that influences mostly the values of the criteria. Technology influences only some. Given both the focus on the development of technology and the focus on sustainability by the problem owner (see Introduction), this is remarkable

7. Conclusions and recommendations

We investigated the extent to which current aircraft technology development can contribute to a sustainable development of the aviation sector given growing demand, by answering the following research question (see introduction):

"Can current ideas for technological improvements of aircraft mitigate the adverse effects of the growth in air transport demand within the time frame of 2050?"

This research concludes that the answer is no; current new technological ideas for aircraft cannot keep up with the growth in air travel demand for the period up to 2050.

As a result of the growth between today and 2050 (aviation demand will increase at least two and-a-half times and at most nine times) the desirable effects of aviation will increase. Due to technological aircraft innovations the negative effects of aviation, per flown seat-kilometre, can be reduced with, depending on the indictor, 15 to 30%. However, the expected increase in aircraft kilometres is nevertheless many times larger than the expected effects of improved technology. The current preliminary designs and prototypes of technological aircraft improvements are, given the growth, therefore still insufficient to improve the overall situation.

Therefore, we are faced with the question whether the negative consequences of aviation should be seen as a problem, or not. If society sees these negative consequences as a problem, then she has to decide to invest substantially more in significantly better aircraft technology development to be able to solve this problem. Furthermore it seems, given the current expected efficiency gains in aircraft technology, very sensible to also consider non-technological options to limit the negative effects of aviation. Technology alone, most likely, will not be enough.

Non technological solutions were not a part of this study; nevertheless we would like to put forward a few ideas which we have come across. Research to determine the possible contribution of these ideas to reduce adverse aviation effects seems very welcome. First, society can choose to accelerate the phase-out of 'old' technologies, when a new technical innovation becomes available. For the already existing segment of the market of clients that want to 'party on the beach', perhaps airplanes can be developed that are optimized for lower velocity and altitude, thereby saving energy. To make the travelling time of less importance, the party should already start on board and continue on the beach. Besides this, the causes for the problem of noise pollution also appear to come from non-acoustic factors, such as the perception of citizens of governmental policy. And finally, what will happen an emission trading scheme (for the emission of gasses, but perhaps also for the emission of noise) will be set up?

Appendix: Example of Calculations

As an example for the calculations that form the basis of the Tables 7 and 8, let's go through the calculations of the scores for the Blended Wing Body. Since very early on in aviation, aircraft have had fuselages for storing payload (passengers and freight), wings mainly for the generation of lift and storage of fuel, and a tail section mainly for stability and control. After these elements were introduced, this threefold configuration was optimized, into a modern, efficient, civil aircraft. Even the latest developments, like Boeing's Dreamliner and Airbus' A380, are seen in this light, essentially not new at all; it is a further optimized product of a paradigm that is as old as the 1950s.

Despite its wide use (and thus its advantageous characteristics), there are some disadvantages to this traditional construction. Vessel shaped fuselages are, for instance, relatively easy to construct and to pressurize; however, their disadvantage is their drag (so-called "parasiting drag"). By only marginally adding to the lift generation, the fuselage largely attributes to the drag. This reduces the effort of the wings, which generate the majority of the needed lift without generating substantial drag to the total vehicle. In addition, tail sections tend to be very heavy, introducing stresses in the fuselage construction. They are relatively complex in their structure and hard to inspect for damage or fatigue cracks.

The idea behind the Blended Wing Body vehicle is to combine the three elements - fuselage, wing and tail - thereby overcoming the traditional disadvantages and reinforcing the advantages of these elements.

Boeing and NASA have performed preliminary design studies for both small and large Blended Wing Bodies. These studies have resulted in some flying scale models. Their findings are that, for large scale Blended Wing Bodies (the size of a 747 and larger), advantages are huge -- approximately 20% reduction in fuel use, 10-15% weight savings, and 10-15% lower direct operating costs (Bowers 2000). A more recent study, such as the Cambridge-MIT Silent Aircraft Initiative currently, has produced a model "SAX-40" that makes these advantages available for smaller Blended Wing Bodies of around 200 passengers. This makes it an option for the replacement of mid-size aircraft that, especially in point-to-point systems, make up a substantial part of the total number of aircraft. These advantages are possible due to the different shape leading to a rise in the lift drag ratio (C_L/C_D) from 17 for the best performing 747 to 25 for the Blended Wing Body. New construction materials are expected to make the construction of this vehicle possible. The scores on the outcome indicators of introducing Blended Wing Bodies into the aviation system are summarized in Table A.1.

Issue is that the scores in table A.1 are valid for Blended Wing Bodies only and the entire fleet of aircraft is not made up of Blended Wing Bodies only. Blended Wing Bodies are assumed to make up 25% of the category of large aircraft (more than 350 seats). Therefore the decrease in CO_2 emission of 20% and the reduction in Direct Operating Cost of 15% is not the score of the whole fleet. The effect of the Blended Wing Body in CO_2 emission on the whole fleet is calculated as follows: using the specific scenario of low growth (see De Haan, 2007, Table 5.12 and 5.13, p. 162-163, chapter 5) for 2050 the total number of aircraft that contain more than 175 seats are:

$$(503484 + 1890988 + 776469) + (165906 + 301519 + 152916) = 3791282$$

Table A.1 The effect on the indicators representing Sustainable Development of introducing blended wing bodies (BWB) into the aviation system

Code	Outcome indicator	Unit	Blended Wing Body
PE1-1	Number of connected geographical places via operated air routes in the EU.	#	No change
PE1-2	Average frequency of flight between two airports within the EU area.	Flights/day	No change
PE1-3	Average ticket price for flight.	€/ticket	Decrease
PE1-4	Average distance to larger, international airport.	km	No change
PE1-5	Number of operated larger, international airports in EU area.	#	No change
PE1-6	Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.	#	No change
PE2-1	Number of internal fatalities in aviation per year.	#/pax km	Decrease
PE2-2	Number of internal incidents in aviation per year.	#/pax km	Decrease
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	Decrease
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	Decrease
PE3-1	Average fuel use per LTO cycle	ton/year	-20%
PE3-2	Average emission of NO_x per LTO cycle	ton/year	-20%
PE3-3	Average emission of CO per LTO cycle	ton/year	-20%
PE3-4	Average emission of VOCs per LTO cycle	ton/year	-20%
PE5-1	Different type of aircraft in service	#	Increase
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-20%
PL2-1	Percentage of renewable fuel of the total amount of fuel used	% *(ton renewables/ total tons of fuel)*	No change
PL3-1	Land unavailable for other than aviation purposes	km^2	Increase
PL4-1	Noise production of specific innovative aviation technology	dB(A)	-10-50%
PR2-1	Direct operating cost	€/year	-15%
PR3-1	Number of innovative aviation technologies in use	#	Increase
PR3-2	Number of airlines operating	#	No change
PR3-3	Number of transport modes for continental transport (including aviation)	#	No change
ASI2-1	Percentage of flights leaving the airport according to schedule	% *(flights on time/total number of flights)*	No change
ASI2-2	Average turn around time	h	No change
ASI2-3	Changes in design and maintenance of aircraft	small/medium/ substantial	Substantial
ASI3-1	Design risk of innovative technology	small/medium/ substantial	Substantial

As the total number of seats in that scenario is 5220388, these 3791282 seats make up:

$$\left(\frac{3791282}{5220388}\right) * 100\% = 72.6\%$$

The effect of 72.6% of the total fleet flying around and having 20% less CO_2 emission on the total fleet is then:

$$1 + (0.726 * (-0.20)) = 0.8548 \approx 0.85$$

However, in the low growth scenario reference case the score for CO_2 emissions of the entire fleet was, compared to the situation in the year 2004, not 1 but 3.49 (see De Haan, 2007, chapter 5), due to the growth of the traffic between 2004 and 2050. Therefore the score for the Blended Wing Body on CO_2 emissions in Table 8 is then: $0.8548 * 3.49 = 2.9831 \approx 2.98$.

References

Anderson, J. D. (1989). *Introduction to flight*. New York, McGraw-Hill Book Company.

Babikian, R., Lukachko, S. P., et al. (2002). The historical fuel efficiency characteristics of regional aircraft from technological, operational, and cost perspectives. *Journal of Air Transport Management* **8**: 389-400.

De Haan, A. R. C. (2007). *Aircraft technology's contribution to Sustainable Development.* Faculty of Technology, Policy and Management. Delft, Delft University of Technology.

De Neufville, R. and Odoni, A. (2003). *Airport systems planning, design, and management*. New York, McGraw-Hill.

Ellul, J. (1964). *The Technological Society*. New York, Knopf.

EU council (2001). *Council resolution on the integration of environment and sustainable development into the transport policy (report 7329/01)*. Brussels.

European Commission (2001). *European transport policy for 2010: time to decide, white paper.* Luxemburg, Office for official publications of the European Communities.

European Commission (2002a). *Visions and roadmaps for Sustainable Development in a Networked Knowledge Society; report of a workshop Co-chaired by the Presidents of the Brussels EU-Chapter of the Club of Rome and the "Factor 10 Institute"*. Luxembourg.

European Commission (2002b). *Aeronautics: European advisory group presents strategic research agenda to help the sector take off (Reference: IP/02/1650).* Brussels.

Humpreys, I. (2003). Organizational and growth trends in air transport. in P. Upham, J. Maughan, D. Raper and C. Thomas. (eds). *Towards Sustainable Aviation.* London, Earthscan Publications Ltd.

INFRAS (2000). *Sustainable aviation - pre study for the ATAG*. Zurich, INFRAS Consulting.

IPCC (1999). *Aviation and the global atmosphere*. Cambridge, Cambridge University Press.

Miser, H. J. and Quade, E. S. Eds. (1985). *Handbook of systems analysis*. New York, John Wiley & Sons, Inc.

Moir, I. and Seabridge, A. (2001). *Aircraft Systems; Mechanical, electrical, and avionics subsystem integration*. London, Professional Engineering Publishing Limited.

Peeters, P. M., Middel, J., et al. (2005). *Fuel efficiency of commercial aircraft: an overview of historical and future trends*. National Aerospace Laboratory.

Tempelman, E. (1998). *Sustainable transport and advanced materials*. Haarlem, Eburon.

Torenbeek, E. (2000). *We nemen een schoon vel tekenpapier (Dutch); fare well speech*. Delft, Delft University of Technology.

Upham, P., Maughan, J., et al., Eds. (2003). *Towards sustainable aviation*. London, Earthscan publications Ltd.

Walker, W. (2000). Policy Analysis: a systematic approach to supporting policymaking in the public sector. *Journal of multi criteria decision analysis* Vol. 9, No. 1-3, pp. 11-27.

WCED (1987). *Our common future; report of the UN commission on Sustainable Development.* Oxford, Oxford University Press.

Williams, V. (2007). "The engineering options for mitigating the climate impacts of aviation." *Philosophical transitions of the royal society A* Vol. 365, pp. 3047-3059.