Aircraft Technology's Contribution to Sustainable Development

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Cover: Boeing 747 in KLM colors taking off from Schiphol Airport, April 9th, 2007

Preface

A few years ago, politicians used the words “Sustainable Development” very frequently. It seemed to be a magic concept that should be used, related and applied to almost anything for the good of humanity. Like the concept of “democracy”, also Sustainable Development seemed to be something nobody opposed.

Lately, the attention for the concept Sustainable Development in daily politics seems to have faded away a bit. However, in practice, it is still widely used. For instance, major companies like Shell, British Airways, Unilever and KLM now have, in addition to their traditional annual report, a sustainability annual report that stresses their efforts to balance their initial needs for profit with the improvement in social circumstances and environmental issues.

Some say that the practice of Sustainable Development has not led to any serious changes in processes, but merely has put a small layer on the outside of the process, an idiomatic façade, to make it look nicer in social and environmental respects. They feel that Sustainable Development is merely being used as sales talk, to further boost profit; increasing the adverse social and environmental effects rather than reducing them.

Part of the criticism stems from the fact that it seems to be hard to design a process that can provide profit while addressing social and environmental issues as well. Good intentions are not enough; some serious thinking has to be done to create Sustainable Development.

The thinking starts with determining what the concept means. The next step is to make Sustainable Development measurable in order to determine what policies should be selected and what not. There have been a lot of attempts do to this, with varying degrees of success. When extensive efforts are made to define the concept perfectly, with all important factors included, the definition becomes so wide or so vague that it has little practical meaning. When the broadest possible list of indicators has been created to include all factors one can think of, the list is not very workable. Though very promising and offering a “warm and fuzzy feeling”, the concept of Sustainable Development has led to a lot of confusion. Applying it in such a way that the promised advantages really come out, has proven to be very hard.

This research originated from the desire to apply the concept of Sustainable Development to a specific case. Talking about it is interesting; but putting it into practice is really bringing things further. Using the concept means that Sustainable Development should be defined practically for the specific case and that measurable indicators should be developed. It also means that certain changes people might consider to apply must be evaluated on their contribution to Sustainable Development. Last, but certainly not least, one needs information about the implementation problems and rebound effects of the considered changes.

To many, sustainable aviation sounds like a contradiction in terms, a so-called oxymoron. It will always have the desired positive contribution of providing long-distance transport to people, but it will also always have the undesired and adverse effects of using up resources and disturbing people’s lives by, for instance, producing noise or emitting hazardous substances. It is not so much that aviation itself may become sustainable; in order to have a sustainable society as a whole, the desired effect of aviation, providing transport, has to be achieved with a minimum of undesired effects. It will be a matter of debate whether this minimum of undesired effects is small enough to help make society as a whole sustainable.

This research makes several contributions to the sustainability discussion:

First of all, it operationalizes the concept of Sustainable Development, making it possible to measure the contribution of alternative technological changes to sustainability. This includes a workable set of indicators on which the technological solutions can be scored.

Second, it applies the concept of Sustainable Development to a real case, here aircraft technology in the aviation system. This includes:

- a clear statement of the problem
- a list of indicators
- a listing of possible technical solutions
- scoring these possible solutions as if implemented in some possible future of the aviation system, and
- comparing them to the case when no new technologies are applied

Third, it creates some preliminary designs of aircraft technology considering the concept of Sustainable Development based on ideas of experts about what is promising, what is to be expected, and what are the hot issues in aviation technology development.

Fourth, it describes the major factors that will influence the growth of aviation, giving some possible scenarios for the demand for air travel up to the year 2050.

Fifth, it provides theoretical explanations, ideas, and experimental experiences around the problems that occur when a technological solution has to be implemented; in an actor field with many different and contrasting objectives, providing the technology itself can be seen as the smallest of all problems.

Regarding aviation and its sustainability effects (both positive and negative), different people bring different messages. Some look at the environmental side only -- to noise, to gas emissions and their contribution to climate change, to the use of scarce resources. Others state that the technology to solve all this is available, but purposely withheld from the market. Others look to the aviation system as purely an engineering system, fascinated by technological options to solve problems and improve the situation. Again others look at aviation through economic glasses and try to fit all problems into the structure of a monetized cost-benefit analysis.

Nobody (as far as we know) has taken the many different pieces of ideas, findings, claims, designs, statements, et cetera, and integrated them. In other words, what is lacking is a wide academic assessment of aircraft technology and its contribution to Sustainable Development.

Interesting it is, that from time to time, in politics and the media, the argument is made that, whatever we as humans do, we will come up with new technologies that will take away the negative effects of our actions while still providing the positives. This research provides some objective information related to this statement. Is it likely that current adverse effects in aviation will, given its possible growth, be solved by a technological fix? This research is intended to help in finding answers to this question.

Delft, February 13th, 2007,

Alexander de Haan

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Terminology

This section covers the most used terminology in this research. It is put in front to familiarize the reader with the terms that will be used most often. For each term, a description is given, but also a relation between the term and how it is used in this research.

Actor

A person, or group of persons, that has an interest in the system being analyzed and has the power to make changes to that system. Actors are people involved in the problem at hand. They are concerned about the outcomes of the system, as they have something to win or lose; but they can also take action to change the system to get its outcomes closer to their goals. Their interest is at stake when the values of certain factors in the system change. (See also “Stakeholder”.)

The primary actors in this research are the European Commission, aircraft manufacturers, airports, airlines, and national governments, as described in chapters 2 and 3.

Analyst

Neutral, observing, and analyzing person who supports the decisionmaker by collecting, organizing, and presenting relevant information. Together with the decisionmaker, analysts decide upon what is to be considered as important in a particular analysis. Analysts should be absolutely neutral, objective, and independent. Analysts use an appropriate set of relatively simple tools; their strength is in their characteristic of being sharp observers who can quickly and correctly discriminate. Analysts often need to confront clients or problem owners to reveal hidden objectives, add objectives they forgot, et cetera. Confrontations can be substantial when the results of the analysis are not what the client expected.

The author of this report has, in this research, the role of analyst. As this research has no client (i.e. no-one paid for the analysis), there has been no direct cooperation between the analyst and client in this research. The research however does have a problem owner, the European Commission (see chapter 3).

Decisionmaker

Decisionmakers eventually may use the information from a systems analysis study, such as this research, to make decisions about what policies to implement. Decisionmakers have a certain power to make changes in the system by their decisions. Most of the time they will perceive the current system state as problematic. In that sense they do not differ from problem owners. Decisionmakers become clients as soon as they themselves hire an analyst to perform a systems analysis. (See also “Problem owner”.)

In this research, the European Commission is considered to be the problem owner. Eventually they propose policy that the European Parliament has to approve. The Parliament can be seen as a decisionmaker.

External forces

Factors beyond the control of the decisionmaker that influence the system, and, therefore, the outcomes of interest.

In this research, the demand for air travel in the future is considered an external force. Their exact values in the future of 2050 are unknown. To manage this uncertainty, this research uses the scenario approach (see chapter 5).

Multi-focus solutions

These types of solutions take into account the interest of all actors and stakeholders and all dimensions of the problem over a long period of time. Solutions that contribute to Sustainable Development will be multi-focus solutions, as, by definition, Sustainable Development requires attention to many different aspects simultaneously over a long time frame.

Outcome indicator

A measurable indicator related to the achievement of a goal. The analyst translates outcomes of interest into outcome indicators that can be measured. (See also “Outcomes of interest”.)

In this research, outcome indicators are designed in chapter 3.

Outcome of interest

To the several actors and stakeholders involved in a certain problem, certain factors describing the performance (outcomes) of the system are of special interest, since they are directly related to the objectives of these actors and stakeholders. It is information about these outcomes that, among other things, decisionmakers need in order to come to a good decision. (See also “Outcome indicator”.)

In this research, in chapter 3, the outcomes of interest are determined for the problem owner, the most important actors, and some other stakeholders.

Problem owner

A person, or a group of persons, that perceives the current state of the system to analyze as problematic. Problem owners, like decisionmakers, can make certain changes in the system. (See also “Decisionmaker”.)

In this research, the problem owner is the European Commission (see chapters 1 and 2).

Scenario

Description of plausible developments in the forces driving system change. This forms the context in which the implementation of the policy measures (in this research the aircraft technologies) will be scored on the outcome indicators.

The scenarios in this research represent plausible developments in air travel demand between now and 2050 (see chapter 5).

Scoring

The list of possible solutions must be analyzed in detail. In this research, this is done by determining the relationship between the introduction of these aircraft technologies into the system and the outcomes of interest, represented by the outcome indicators. The values of these outcome indicators are presented in a scorecard; there is one scorecard for each scenario.

The scoring process in this research is carried out in chapter 6.

Stakeholder

A person, or a group of persons, that have interest in the system to analyze, but cannot influence that system to a large extent. The analyst should take the interests of stakeholders into consideration when performing a policy analysis study.

In this research, the citizens living near airports and air travelers are considered stakeholders (see chapter 3).

Sustainable Development

Brundtland's description (WCED 1987) is taken in this research as the starting point for describing this concept: "Sustainable Development is a development that meets the needs of the present generation, without compromising future generations to meet their needs." Using this definition, the concept can be represented in three main dimensions: social (People), environmental (Planet), and economic (Profit).

In this research, the concept of Sustainable Development is operationalized and made measurable with indicators categorized in these three dimensions in chapter 3. Sustainable Development is a form of a multi-focus solution. (see "Multi-focus solution".)

Sustainability

The state of a system that eventually will be reached if a certain system continuously follows a path of Sustainable Development.

System to analyze

Those aspects of the total world that are most relevant for the stated problem. One of the first steps in a policy analysis is determining the system boundary -- which elements of the real world are kept inside the system to analyze, and which elements are outside the system. These decisions have important effects on the outcomes of interest. A too tightly chosen system boundary can lead to invalid results, while a too large chosen system boundary may require an enormous amount of time to finish the systems analysis study.

The specification of the system to analyze is described in the chapters 1 and 2.

Uni-focus solution

A solution that focuses on one dimension of the problem, in one area only, and, leads to short-term gains that do not last long. It might even lead to an increase of adverse effects in other areas of the total problem. It is, so to say, fighting the symptoms instead of providing a real, lasting solution. Sustainable Development has no characteristics of uni-focus solutions, but rather the characteristics of multi-focus solutions.

Literature

WCED (1987). Our Common Future; Report Of The UN Commission On Sustainable Development. Oxford, Oxford University Press.

Summary of main findings

Aviation brings many advantages to society, reflected in its huge growth figures. But, aviation is also criticized for its many undesired effects. The most widely known are noise disturbances and gas emissions, which hurt local living conditions around airports and which contribute to climate change.

Sustainable Development as a concept is brought forward by many of the actors in the aviation system as a way in which aviation can develop itself in order to reduce its undesired effects. Sustainable Development refers to a wide variety of factors, often broken into three categories: social, environmental, and economic.

Some actors refer to expected large technological changes as a potential solution for the undesired effects of aviation in all categories of Sustainable Development. Technology should then, in some way or other, contribute to Sustainable Development.

This research tries to find out if there is some truth in that last claim. As Sustainable Development is, as a concept, referred to as a way to keep the benefits of aviation but reduce the adverse effects, the problem formulation for this research is as follows:

What is the potential of a set of expert-selected new aircraft technologies to contribute to Sustainable Development; i.e. what is their potential to reduce actor defined adverse effects of flying while keeping the benefits?

The word ‘potential’ has in this case two meanings: (1), a theoretical assessment of the contributions various technologies might be able to make to Sustainable Development (by determining the effects of the technologies on actor-determined indicators), and, (2), an implementation assessment, since the possible contribution of a new technology can only turn into a real contribution when the technology is fully implemented. All sorts of barriers might prevent implementation of technology that could contribute to solving the problem stated.

Also, the particular usage of the implemented technology determines whether it will really contribute to Sustainable Development according to its potential to do so. Technological improvements for a specific adverse effect can lead to traffic growth that might even cause larger problems than initially anticipated (the so-called rebound effect). The problem formulation was, therefore, split into two main research questions, with the main research results shown below the questions:

1. What can expert-selected new aircraft technologies contribute to Sustainable Development?

2. How can expert-selected new aircraft technologies with a potential to contribute to Sustainable Development be implemented and used in a way that their potential contribution turns into a real contribution?

Question 1: Given the results of this research, the expert-selected and assessed technologies have a potential to contribute to some characteristics of Sustainable Development, mainly the reduction of noise and gas emissions. However, on these characteristics, technology cannot keep up with the predicted growth in air travel demand, which increases the adverse effects of aviation. Not even in the smallest growth scenario can this increase in negative effects be counteracted by the introduction of new aircraft technology.

Question 2: Some of the selected and assessed aircraft technologies can influence characteristics of Sustainable Development in a desired direction. Two of these characteristics currently receive a lot of attention worldwide: noise around airports and gas emissions with negative consequences such as climate change. Also for this reason, one might decide that implementation of such new technology is worthwhile. This research shows that, especially for the aircraft related innovative technologies considered in this research, implementation of new technology and replacement of old technology takes a long time -- up to 40 years. In addition, many roadblocks (e.g. airport infrastructure adaptations) need to be taken out of the way. Psychological mechanisms, such as discounting and fairness appraisal, play a delaying role in the implementation process. For the aviation system as a whole, two important drivers for innovation appear to be lacking: sense of urgency for change and availability of sufficient amounts of money. The use of technology can be such that second order effects (rebound effects) can be negative and larger than the promising positive effects a technology has in terms of Sustainable Development. It appears that the problem owner, in order to solve this, has to confront the conflict between the ideal of an open free market economy and the adverse effects of flying.

Since this research has shown that current ideas about new aircraft technologies do not seem able to produce big enough positive effects, it is recommended that serious investments be made and incentives created to stimulate the development of other technologies that can contribute to sustainability. In addition, one might search for other options than technology to improve the contribution of aviation to Sustainable Development.

Samenvatting van de belangrijkste bevindingen *(in Dutch)*

Luchtvaart heeft veel voordelen voor de maatschappij die tot uiting komen in de grote groeicijfers. Maar, luchtvaart wordt ook bekritiseerd omdat het veel ongewenste gevolgen heeft. De meest bekende zijn verstoringen door geluid en de uitstoot van verbrandingsgassen. Beide hebben negatieve gevolgen; de kwaliteit van de locale omgeving gaat achteruit en er is een bijdrage aan klimaatverandering.

Duurzame Ontwikkeling wordt als concept naar voren gebracht door veel verschillende actoren in het luchtvaartsysteem als dé manier waarop de luchtvaart zich kan ontwikkelen en waardoor de ongewenste effecten kunnen worden gereduceerd. Duurzame Ontwikkeling representeert een grote variatie aan factoren, die veelal in drie categorieën worden ingedeeld: sociale, milieu en economische factoren.

Sommige actoren stellen dat de verwachte grote technologische veranderingen een potentiële oplossing zijn voor de ongewenste effecten van de luchtvaart in alle categorieën van Duurzame Ontwikkeling. Technologie zou dan, op de een of andere manier, moeten bijdragen aan Duurzame Ontwikkeling.

Dit onderzoek probeert uit te vinden of deze claim waar is. Als Duurzame Ontwikkeling, als concept, wordt gezien als de manier om de voordelen van luchtvaart te kunnen behouden terwijl de negatieve gevolgen worden verminderd, dan is de probleemformulering voor dit onderzoek als volgt:

Hoe groot is de potentiële bijdrage van door experts geselecteerde nieuwe vliegtuigtechnieken aan Duurzame Ontwikkeling; met andere woorden, wat is de potentie van deze technieken om door actoren gedefinieerde negatieve gevolgen van het vliegen te verminderen, terwijl de positieve gevolgen behouden blijven?

Het woord ‘potentie’ heeft in dit geval twee betekenissen: (1), een theoretische meting van de bijdrage die verschillende technieken zouden kunnen maken aan Duurzame Ontwikkeling (door de effecten van die technologieën op door actoren gedefinieerde indicatoren te bepalen), en, (2), een implementatie-meting, omdat een mogelijke bijdrage van nieuwe technologie alleen een echte bijdrage kan worden als de technologie volledig is geïmplementeerd. Allerlei soorten barrières zouden de implementatie van technologie die kan bijdrage aan de oplossing van het beschreven probleem kunnen tegenhouden.

Ook het specifieke gebruik van een geïmplementeerde technologie bepaalt of er een echte bijdrage aan Duurzame Ontwikkeling is in lijn met de potentie van die technologie om bij te kunnen dragen. Technologische verbeteringen voor specifieke negatieve gevolgen kunnen leiden tot groei van het luchtverkeer. Dit kan uiteindelijk mogelijk grotere problemen veroorzaken dan waar de technologische verbeteringen in eerste instantie als oplossing voor waren bedoeld (het zogenaamde rebound effect). De probleemformulering is daarom gesplitst in twee hoofdonderzoeksvragen. De belangrijkste onderzoeksresultaten zijn onder de vragen weergegeven:

1. Wat kunnen door experts geselecteerde nieuwe vliegtuigtechnologieën bijdragen aan Duurzame Ontwikkeling?

2. Hoe kunnen de door experts geselecteerde nieuwe vliegtuigtechnieken die een potentie hebben om bij te dragen aan Duurzame Ontwikkeling worden geïmplementeerd en gebruikt op een dusdanige manier dat de potentie om bij te dragen aan Duurzame Ontwikkeling in een echte bijdrage wordt omgezet?

Vraag 1: Gegeven de resultaten van dit onderzoek, hebben de door experts geselecteerde en gemeten technologieën een potentie om bij te dragen aan sommige karakteristieken van Duurzame Ontwikkeling, met name de reductie van geluid- en gasemissie. Echter, op deze karakteristieken kan technologie niet compenseren voor de verwachte groei in de vraag naar luchttransport. Deze groei zal de negatieve gevolgen van luchtvaart doen toenemen. De toename van de negatieve gevolgen zal door de introductie van nieuwe vliegtuigtechnologie niet teniet kunnen worden gedaan, zelfs niet in het kleinste groeiscenario.

Vraag 2: Sommige van de geselecteerde en gemeten vliegtuigtechnologieën kunnen karakteristieken van Duurzame Ontwikkeling in een gewenste richting beïnvloeden. Twee van deze karakteristieken krijgen momenteel wereldwijd veel aandacht: geluid rond luchthavens en gas emissie dat zaken zoals klimaatverandering beïnvloedt. Ook om die reden kan men besluiten dat de implementatie van dergelijke nieuwe techniek de moeite waard is. Dit onderzoek laat zien dat, vooral voor de innovatieve vliegtuigtechnologie die in dit onderzoek beschouwd is, implementatie van nieuwe technologie en vervanging van oude technologie lang duurt, tot wel 40 jaar. Daar komt bij dat er veel blokkades zijn (bijvoorbeeld noodzakelijk luchthaven infrastructuur aanpassingen) die uit de weg moeten worden geruimd. Psychologische mechanismen, zoals *discounting* en de aanspraak op rechtvaardigheid, spelen een vertragende rol in het implementatieproces. Als het gehele luchtvaartsysteem wordt beschouwd, blijken twee belangrijke drijvende factoren voor innovatie te ontbreken: *sense of urgency* voor verandering en de beschikbaarheid van een voldoende hoeveelheid geld. Het gebruik van technologie kan dusdanig zijn dat tweede orde effecten (*rebound* effecten) negatief en groter kunnen zijn dan de potentiële positieve effecten van technologie op het gebied van Duurzame Ontwikkeling. Het blijkt dat, om dit op te lossen, de probleemeigenaar een afweging zal moeten maken tussen het ideaal van een vrije open markteconomie en de negatieve gevolgen van vliegen.

Omdat dit onderzoek heeft laten zien dat de huidige ideeën over nieuwe vliegtuigtechnologie niet voldoende positieve effecten lijken te produceren, wordt aanbevolen om behoorlijk te investeren in en voldoende prikkels te creëren voor andere technologieontwikkeling die kan bijdragen aan duurzaamheid. Daarnaast kan men zoeken naar andere opties dan technologische om de bijdrage van luchtvaart aan Duurzame Ontwikkeling te verbeteren.

Full Summary

This full summary describes the problem owner and the methodology used in this research. Then, it describes how each different step of this methodology is carried out in this research. Within each step, this summary refers to those chapters in this thesis where detailed information can be found.

Problem owner

The European Parliament (EP) and European Commission (EC) have set the goal that aviation in its territories should develop into a sustainable mode. They expect that, among other things, technological developments should make this happen. In addition, the EC has certain power to steer certain (technological) developments in the European Union by preparing new possible policies. For this reason the EC is chosen as problem owner for this research (see chapter 1 and section 3.3).

Methodology

Systems analysis (see chapter 2) 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 S.1. In the center 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.

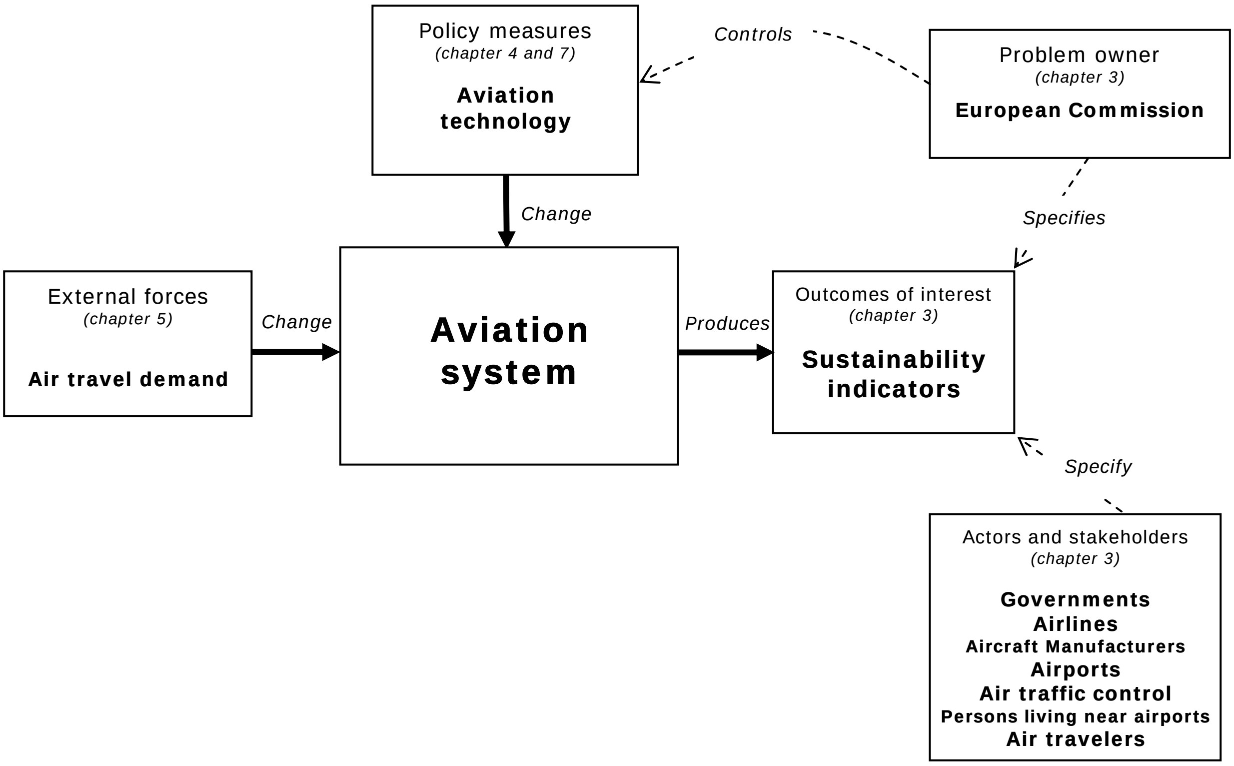

Figure S.1. The problem diagram around Sustainable Development and aviation.

From the outside, two kind of forces act upon the aviation system. One kind is out of control of the problem owner (European Commission) and is called “External forces” (covered in chapter 5). The other kind is completely under the control of the problem owner and is called “Policy measures” (the different expert selected new technologies covered in chapter 4).

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. 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 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 technologies of chapter 4) on the several outcomes indicators (see Table S.1).

	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***

Table S.1. An example of a scorecard.

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 decisionmaking 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.

Performing a systems analysis requires carrying out the following list of steps (see Table S.2).

Step:	*Task to carry out:*
1	Identify problem
2	Specify objectives
3	Decide on indicators
4	Select potential policy measures
5	Analyze potential policy measures
6	Compare potential policy measures and choose one of the alternatives

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

In the following sections, the steps in the systems analysis process identified in Table S.2 will be summarized as carried out in this particular research.

Step 1: Identify the problem

As described earlier in this summary, 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 while keeping the positive effects of transport. The problem formulation is as follows:

What is the potential of a set of expert selected new aircraft technologies to contribute to Sustainable Development; i.e. what is their potential to reduce actor defined adverse effects of flying while keeping the benefits?

The problem formulation is split into two main research questions (see chapter 1):

1. What can expert selected new aircraft technologies contribute to Sustainable Development?

2. How can expert selected new aircraft technologies with a potential to contribute to Sustainable Development be implemented and used in a way that their potential contribution turns into a real contribution?

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 Sustainable Development means when talking about aviation. The literature provides descriptions of the Sustainable Development concept. The Council of the EU (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 (INFRAS 2000) provides a description of Sustainable Aviation. All outcomes of interest mentioned in these two descriptions are identified (see chapter 3). The used category labels for the categorization of these outcomes of interest are social factors, environmental factors and economic factors (these labels resemble the axis People, Planet and Profit; the different cells are marked according to this: PE stands for People, PL, for planet and PR for profit) and are presented in Table S.3.

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*
	PL4: Noise impact Low noise generation *Noise*	

Table S.3. Factors representing Sustainable Development categorized in three columns: social, environmental and economic. 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 S.3, measurable indicators have been designed in this research. These indicators represent information about Sustainable Development that decisionmakers might need in their decisionmaking 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 (labeled ASI, which stands for Additional Stakeholder Indicator). In this research, no single indicator is considered more important than another. Based on the scoring pattern on all indicators, the decisionmaker can make his or her own judgments. The indicators designed in this research are listed in Table S.4.

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

Table S.4. Designed indicators representing the outcomes of interest.

Step 4: Select potential policy measures

To identify technologies that can be analyzed, first the aviation system is broken 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 S.2).

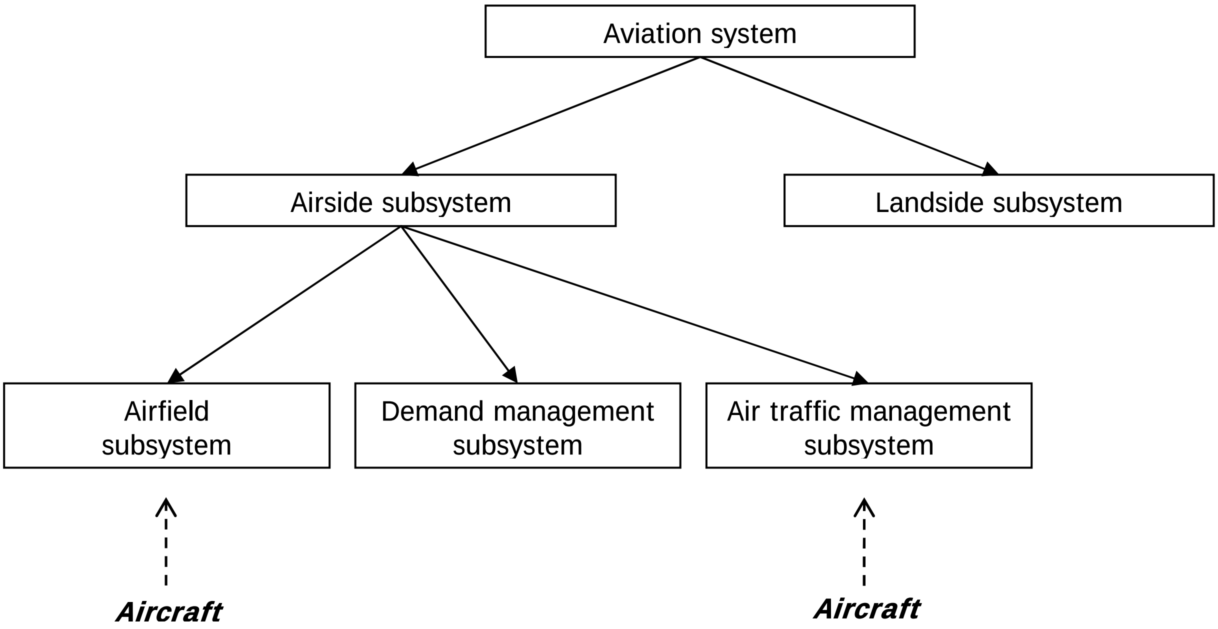

Figure S.2. Distinguishing the subsystems within the aviation system that aircraft technology influences.

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

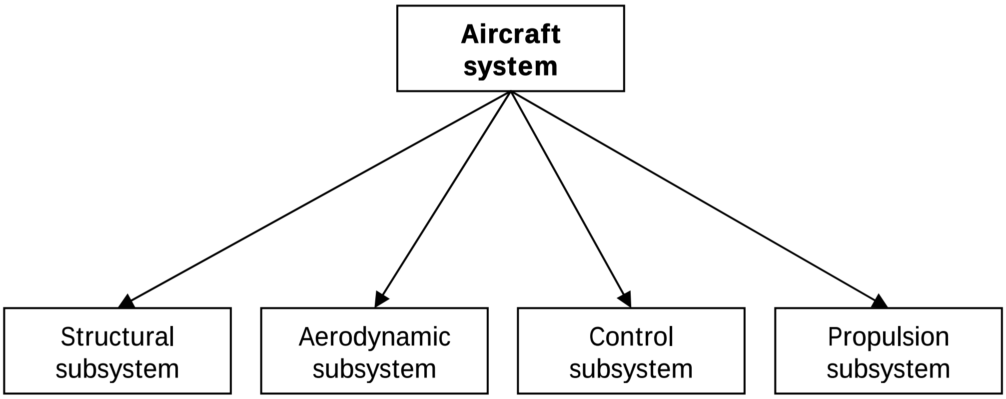

Figure S.3. Subsystems of the aircraft system

Scanning the literature and using interviews, 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). 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 S.5:

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

Table S.5. Identified technologies in the overall aircraft system and its four subsystems.

Step 5: Analyze policy measures

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. Lifetimes of aircraft are usually expressed in numbers of flights, since the number of take-offs and landings determine if the aircraft can still operate safely and economically. With the intense use of aircraft every day of the year, after 35 years most aircraft will have been replaced. Some civil passenger aircraft might fly some extra years as freighters and some will still fly in less dense markets in Africa or South America (like some old Fokker F27s and Boeing 707s and 727s do). 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. Using literature and expert interviews, factors are identified that influence air travel demand. A range of plausible values for these factors between now and 2050 have been assumed, again based on interviews and literature. All possible combinations of values for these factors resulted in a set of 16 possible scenarios for air travel demand in 2050. The two scenarios eventually considered out of the 16 are the highest and lowest growth scenarios in terms of seats flying around in aircraft. The two scenarios are summarized in Table S.6. Note that the numbers are numerical outputs of models. Their value for this research is their orders of magnitude, not their exact values to the last digit.

Possible scenarios	Number of seats	% increase compared to situation in 2004
Base case: *Situation in 2004*	*2 098 056*	-
Scenario A: *2050: High growth in traffic*	*19 131 827*	*912%*
Scenario B: *2050: Low growth in traffic*	*5 220 388*	*249%*

Table S.6. Two scenarios for air travel demand for 2050 compared to the base case (the situation in 2004).

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 S.4.

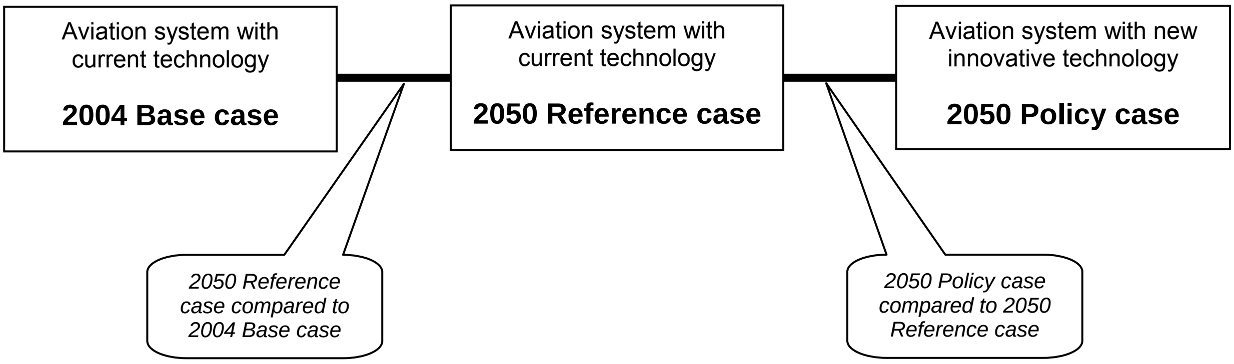

Figure S.4. The different scoring cases compared to each other.

Step 6: Compare policy measure and choose one
When, in chapter 4, a set of different technologies is identified, 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. 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 seat flown by 15%. This research uses scenarios to manage the uncertainty about the future state of the aviation system. Air travel demand is the external factor making up these scenarios (see chapter 5). This research thus has to translate the 15% direct operating cost reduction 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 first translating all the mentioned effects in the preliminary design reports or studies to an effect per flown seat. Second, 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 consist of these Blended Wing Bodies. 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. Third, 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 the Tables S.7 and S.8 (for the high growth scenarios A1 (point-to-point system) and A2 (hub-and-spoke system)) and the Tables S.9 and S.10 (for the low growth scenarios B1 (point-to-point) and B2 (hub-and-spoke)).

Policy case 2050 **Scenario A1** **High Growth** **Point-to-Point** Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<10.12	10.12	<10.12	10.12	10.12	10.12	<10.12			<10.12	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		9.88	7.08	9.95	9.92	10.12	5.07	0.61			9.10	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<10.12	7.08	10.12	10.12	10.12	10.12	10.12			<10.12	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		2.12	2.12	2.12	2.12	2.12	2.12	2.12			2.12	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		2.12	2.12	2.12	2.12	<2.12	2.12	2.12			2.12	
Number of connected geographical places via operated air routes in the EU.		3.24	3.24	3.24	3.24	<3.24	3.24	3.24			3.24	

Table S.7. Scorecard for all considered technologies in the high growth scenario A1 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 **Scenario A2** **High Growth** **Hub-and-Spoke** Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<10.12	10.12	<10.12	10.12	10.12	10.12	<10.12			<10.12	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		10.01	7.08	9.95	9.92	10.12	5.07	0.61			8.47	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<10.12	7.08	10.12	10.12	10.12	10.12	10.12			<10.12	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		2.12	2.12	2.12	2.12	2.12	2.12	2.12			2.12	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		2.12	2.12	2.12	2.12	<2.12	2.12	2.12			2.12	
Number of connected geographical places via operated air routes in the EU.		3.24	3.24	3.24	3.24	<3.24	3.24	3.24			3.24	

Table S.8. Scorecard for all considered technologies in the high growth scenario A2 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 **Scenario B1** **Low Growth** **Point-to-Point** Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<3.49	3.49	>3.49	3.49	3.49	3.49	>3.49			>3.49	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		3.45	2.44	3.43	3.42	3.49	1.75	0.21			2.98	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<3.49	2.44	3.49	3.49	3.49	3.49	3.49			<3.49	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		1.37	1.37	1.37	1.37	1.37	1.37	1.37			1.37	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		1.37	1.37	1.37	1.37	<1.37	1.37	1.37			1.37	
Number of connected geographical places via operated air routes in the EU.		1.74	1.74	1.74	1.74	<1.74	1.74	1.74			1.74	

Table S.9. Scorecard for all considered technologies in the low growth scenario B1 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 Scenario B2 Low Growth Hub-and-Spoke Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Number of connected geographical places via operated air routes in the EU.		1.74	1.74	1.74	1.74	<1.74	1.74	1.74	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	1.74	
Average frequency of flight between two airports within the EU area.		1.37	1.37	1.37	1.37	<1.37	1.37	1.37			1.37	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		1.37	1.37	1.37	1.37	1.37	1.37	1.37			1.37	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<3.49	2.44	3.49	3.49	3.49	3.49	3.49			<3.49	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.90	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.90	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.90	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.90	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Total emission of CO2 during flight operations		3.42	2.44	3.43	3.42	3.49	1.75	0.21			3.13	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Land unavailable for other than aviation purposes		<3.49	3.49	>3.49	3.49	3.49	3.49	>3.49			>3.49	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.90	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Average turn around time		1	1	1	1	1	1	1			1	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su			Su	

Table S.10. Scorecard for all considered technologies in the low growth scenario B2 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Two important conclusions can be drawn from the results of the analysis. One is, that it is very unlikely that technology related to aircraft will, in the time span till 2050, make serious contributions to the level of Sustainability for the whole aviation system. It is true that not all possible technologies are considered, but, the technologies listed are among the most promising concepts (making largest changes in the system) and all are considered to be feasible within the time frame of 2050. It must be made clear immediately that, of course, technology can make the situation on some indicators substantially better if the sector would not grow at all. This is not an open door, but an important finding, because technology thus gives society some extra margin (either in time or in severity of effects) to come up with real sustainable solutions. A combination of two techniques for instance (composites with high speed propellers) could, in a low growth scenario, not substantially deteriorate the level of CO_2 emission for 2050. CO_2 emission is currently a very important and hot topic world wide.

The option of hydrogen and bio-fuel fuelled flight needs some extra attention. This research has not put attention to how hydrogen and bio-fuel can or will be generated. Today's capacity is not enough, but that can change. The problem for hydrogen lies in the fact that hydrogen in large quantities currently cannot be generated in any other way than burning or transforming fossil fuels. The CO_2 emission then takes place when generating hydrogen and not when using hydrogen. The hydrogen option is therefore still an option to consider, since new technologies might be developed in the future that make more sustainable generation of hydrogen possible. For bio-fuels the story is a little different. If bio-fuels come from crop-waste (those parts of the plants that do not get eaten or used for other products), there would be a big sustainability gain. However, it is uncertain if enough of those crop-wastes are available worldwide to fuel worldwide transport. Experts say aviation might be the last industry to change fuel type, since it is the smallest user (compared to the total use of others) and the aircraft is optimized for kerosene usage. For both options, hydrogen and bio-fuels, the same holds true: interesting and promising, but they both need serious developments of other technologies and processes to really be able to contribute to Sustainable Development in the aviation industry.

A second important conclusion is that aircraft related technology appears to be able to influence only a very small number of aspects of Sustainable Development. While a first study (see chapter 3) expected technology to be capable of influencing all designed indicators to some extent, it appears mainly LTO emissions, CO_2 emissions and Direct Operating Costs are really influenced. That makes technology an instrument of limited capabilities in the Sustainable Development discussion. Note that this is not for reasons of not keeping up with growth of the sector, but for reasons of a small number of effects on a concept of Sustainable Development that has such a wide variety of characteristics.

Implementation of analyzed technologies

Should the problem owner of this research decide upon the wish to implement some (or all) of the technologies analyzed, some serious problems arise.

First, it is not easy to implement new technology that requires changes in a system while that system has over the last 50 years been constantly improved to some performance parameters and got locked-in in itself.

Second, while the goal of the virtual client may be improvements in all three categories (social, environmental, and economic) of factors that represent Sustainable Development, individual actors in the system might opt for using these technologies slightly differently and, with that, improving indicators in only one of the three categories (profit, is the expectation).

The issue of implementation is addressed from three different directions. One is identifying *roadblocks* that might block new technological developments from being implemented. The second is seeking parallels between this aviation case and *another case on innovation in the heavy metal industry*. Both industries have a high resistance to change. A third direction uses two glasses through which one can look at the implementation problem and possibly find solutions: *discounting theory* (from the social and economic sciences) and *Technology Assessment*, a school of theories and methodologies that studies technological changes in systems (in its causes and effects) and also has something to say about possibilities to influence technological changes.

Finally, the use of new technology is addressed. New technologies might be designed to contribute to Sustainable Development when used as the designer had in mind. Still, there might be *non-sustainable user behavior* through which a technology, once implemented, can even counter its potential contribution to Sustainable Development.

Direction1: Roadblocks to implementation

This research consulted literature and experts to come up with the following list (Table S.11) of factors that are expected to serve as barriers (‘roadblocks’) for implementing particular technologies.

Table S.11 gives detailed and concrete reasons why specific technological innovations in aircraft do not get implemented easily.

We also investigated whether we could find more general and abstract reasons for the difficulty of changes in the aviation industry by seeking parallels with a study on innovations in another industry (the heavy metal industry). Both industries have an important characteristic in common: compared to other industries they have a relative high resistance to change.

Policy measure	Major roadblocks for implementation
Ultra High Capacity Aircraft	Lock-in at airports (with high costs as a result) Psychological resistance to such large aircraft by passengers and crew. Investment risk aircraft manufacturer. Evacuation not in compliance with current ICAO regulation of 90 seconds. Operators risk: too low load factor. Issue of vortices from wing tips: larger separation times possible necessary; reducing an airports capacity.
Composite materials	Expensive investments. Knowledge not widely available and demonstrated (not yet proven technology) Relatively high development (and thus financial) risks. Requires regulation change in allowable crack size during operation (composites do not crack during life time of aircraft, but when they do crack, flying is not safe).
High aspect ratio wings (on ultra high capacity aircraft)	Lock-in at airports (with high costs as a result). Only useful for very large aircraft; therefore higher development and financial risk.
Free flight	Historically grown patterns of distribution of power and responsibilities must change. Requires large changes in Air Traffic Control: currently small building blocks of responsibilities with plans to bring those to the free market. Capacity issues near airport remain and might be or become bottle neck.
Reduced thrust take-off flight procedures	Concept of ‘captains decision’ (captain finally decides/has final responsibility what is best for safety in a given situation) can counter prescribed procedure. Requires changes in historically grown patterns of distribution of power between captains and air traffic controllers.
High speeds propellers	No economic incentive with cheap oil; oil price can increase a lot before economic incentive is present. Old fashioned look. Different fleet circulation across the world due to slightly slower flight speed, requires adaptation of accepted ideas of schedules by travelers. A possible lower flying altitude causes less comfort. Less comfort due to increased noise inside aircraft
Hydrogen fueled aircraft	Large investments, high financial risk. Increase in land use due to extra fuel storage places. Lock-in effects related to aircraft paradigm; aircraft is currently optimized for kerosene. No sufficient capacity for hydrogen generation worldwide.
Blended wing bodies	Large investments, high financial risk. Lock-in at airports. Evacuation not in compliance with current ICAO regulation of 90 seconds.

Table S.11. Factors that form a barrier for implementing promising innovative aviation technology.

Direction 2: Another case; technological innovation in the heavy metal industry

The resistant to change aviation system has some parallels with the heavy metal industry that is also relatively resistant to change. A study by Moors (2000) on innovations in the heavy metal industry revealed some four requirements that have to be met before innovation takes place. These requirements are:

(1) The presence of a sense of urgency in the form of a serious event or an expected crisis; (2) an internal and external open network with a high density of different actors; (3) it is easier to implement a radical technological innovation that replaces the whole system than one that only partially makes replacements; and, (4) the availability of enough money.

Of the prerequisites for the appearance of radical technological innovations in an open market, as formulated by Moors (Moors 2000), at least two are clearly not met in the aviation system. There is not yet a serious sense of urgency and there is also not sufficient money available. May a governmental agency, like the problem owner in this research, still want to steer in the direction of more sustainable aviation by means of the implementation of more new technological innovations, it should at least try to meet the above four prerequisites.

Knowing both specific and general reasons why new technologies do not get implemented easily in a resistant to change system like the aviation system, the next section seeks for explanations by looking at the system through the glasses of the social and economic theory of discounting. It also investigates the approach of Technology Assessment to see if anything can be done to address the problem that new technology does not get implemented easily in the aviation system.

Direction 3: Discounting and Technology Assessment

In chapter 7, the current attitude of actors in a system towards large changes is represented in the psychological behavioral theory of discounting and a practical approach of Technology Assessment, studying and facilitating technological change, is introduced to find solutions for the resistance to change.

Discounting theory, when coming from an economic direction, points at the fact that interest makes future earnings less interesting than earning a same amount today. This is so, because, due to interest, that same amount today will have grown to a larger amount in the future. Psychological research adds many other factors to the discounting theory. Among others, future earning can be of less importance to humans because the situation might change, therefore, earning a same amount of money in the future is of less interest than earning it today. For costs, the opposite explanation exists; costs are preferred as far away in the future as possible and not today.

Discounting gives explanations for why promising (in terms of their contribution to Sustainable Development) technologies do not get implemented. In the resistant to change aviation system, a lot of investments have to be made at the start of a new technology design project. It might take at least 10 years before the first exemplars are certified and can be sold to a potential customer. Full benefits for Sustainable Development will only occur after the complete old technology fleet is replaced, some 30 years later. That means that the situation is exactly the opposite as in the ideal case according to discounting theory: huge costs are in the start of the process, while the benefits (“income”) come far in the future. This situation is generally true for new technologies (always some investments are required first and earnings come later), but in the aviation system the earnings and investments lie particularly far from each other, especially when it comes to earnings contributing to Sustainable Development.

One can represent the situation of deciding for or against the development of certain technology in its most simple form by having two actors depending on each other. Both of the actors usually want different earnings. It appears that actors willingly block actions from the other actors as soon as they perceive their income as being too different from others. This is strange from a utility maximizing point of view: no matter what income can be earned, as long as it is more than a net zero, not blocking any development should be preferred over blocking it. Actors look at each other and compare their relative earnings, more than they decide only upon whether they make a profit or not. This finding is important for the problem owner of this research that in one or other way will have to make sure that the earnings of implementing technologies that contribute to Sustainable Development get redistributed in such a way over the different actors in the field that they all agree on implementation. This is an extra requirement to the requirements introduced by Moors in the comparative study on introducing innovations in the heavy metal industry.

Technology Assessment (which is not a single method, but a school of thought, having its own theories and methodologies) originally focused on the role of Early Warning Systems; trying to predict the possible effects of the introduction of a new technology in society. Newer forms of Technology Assessment, like Constructive or Interactive Technology Assessment, focus a lot on the process of opinion forming and decisionmaking around technological innovations. In several rounds of meetings, all actors try to come to a commonly shared point about what is considered to be the problem, whether it is needed to do something about it, whether technology can be a suitable solution, what technological options there are, how they should be implemented, et cetera. This, no doubt, takes a lot of time, if in systems with many different actors and stakeholders having different and contradictory objectives, an agreement can be made at all.

Technology Assessment stresses that by a slow process of rounds of agreement on parts of the problem and the solution, more commitment is created for the chosen way among the actors and stakeholders in the system. Also, lots of attention is paid to the actual gradual change in opinion about the possibility of certain technological options. In other words, it is tried to reduce the resistance to change a bit.

This research assumes that it is not easily possible to get all major actors and stakeholders in the aviation system in an Interactive Technology Assessment procedure from beginning to end, and focused on a simple intervention method that also has as goal to reduce the resistance to change in people. Basically, what it tries to do is to change people’s mindsets so that the roadblocks for implementation of promising (in their contribution to Sustainable Development) technologies (see Table S.11) are not seen as a dead end, but as a start for which solutions have to be found.

What is needed then, is an intervention method. Not so much the gathering of data is important, that can be done with questionnaires, interviews, literature study et cetera. However, what must be done is a change in the actors itself that all together determine in what direction the system will develop. As intervention method role playing is chosen.

Under supervision of the author, Drost (2005) developed an initial form of this intervention method. Several people with background knowledge of the aviation system were invited to come to the experimental laboratory. First, their resistance to making changes in the aviation system was measured using a questionnaire. After that they were asked to identify all possible roadblocks for implementing a certain technology (in the experiments, the High Capacity Aircraft A3XL was chosen, this gave comparable results as can be found in Table S.11, though on a more detailed level). These were then categorized. The experimentally found categories were safety, logistics, ground handling, aircraft characteristics and human factors.

The experimentees were given roles after this problem identification round. The different roles were the same as the actors identified in this research:

- Governments;
- Airlines;
- Aircraft Manufacturers;
- Airports;
- Air traffic control;
- Citizens living near airports, and;
- Air travelers

The group was then asked to rate (using a point system) the relative difficulty to solve the mentioned roadblocks in each of the categories. That category of problems that received most points was then further addressed in the session. The idea was that if anything could be done about the category of roadblocks that is perceived to be the hardest to solve, that other categories of roadblocks would give less problems to take out of the way.

From their particular role, the experimentees were asked to identify all possible options they could think of to solve the problems in the chosen category. After a small coffee break the group was taken out of their roles and, as a group, assigned to combine the brainstorm ideas and design an overall solution to the considered problems in the chosen problem category.

The supervisors of the experiment then introduced the idea that the experiment was over and started to hand out lunch sandwiches and drinks and started informal talks about non related issues. However, this was part of the experiment. The supervisors slowly steered the talking into the direction of the aviation system and its resistance to change. The eye-opening moment came at the end, when the group, which was now busy agreeing with each other that changes in the aviation system are very hard and that the particular considered technology (A3XL) would never be implemented, when the supervisor suddenly presented the solution that the group had recently designed to overcome the most important category of problems.

The main objective of this intervention method was (Drost 2005) to give the participants new insights in possible creative solutions around implementation problems of new, innovative technology due to the resistant to change aviation system. The idea is that this would make participants more open for new innovations in aviation. Secondary objectives of the intervention method, some of them supporting the first main objective, are: (1) make actors learn about each others perspectives, objectives and interests, (2) creating group-atmosphere: ‘we are going to solve this implementation problems’, (3) Sharing information among different actors and (4) creating new possibilities for out of the box thinking.

Direct evaluation and follow up evaluation in the weeks after the experiment showed a difference in the attitude of the experimentees towards the resistance to change in the aviation system. Compared to the moment before the experiment, more possibilities for change in the system and possibilities for implementing new technologies were seen directly after the experiment, but also in the weeks following.

The idea behind this experiment is that it is possible to design an intervention method that can help crack the existing tunnel vision ideas of experts that makes changes in the aviation system hardly possible.

Even after we know something about why new technologies do not get implemented easily in the system, we have not addressed what happens when these new technologies get implemented. Problems may then arise if users act differently with the new technology than the designers intended. The next section addresses the issue of non-sustainable user behavior that designers might not have intended, but that might happen.

Non-sustainable user behavior

As the concept of Sustainable Development shows, many indicators should be addressed at the same time before a real contribution to Sustainable Development is made. However, technology can to a certain extent be used to address certain particular outcome of interest. In a way, technology can be used to even optimize a single outcome of interest. If, for instance, a technology of high speed propellers has the effect that the current flights of the total fleet of aircraft in the world are much less noisy, there is room for growth at airports. As airports are often noise restricted (that means that their actual physical capacity is much larger than what is being used, as using to the total physical capacity would lead to unacceptable noise exposures for citizens around the airport), according to those restrictions suddenly many more flights are possible. This then can lead to much more growth of the sector, more burning up of fuels, more congestion, more delays, etc.

In order to prevent that the introduction of new technologies that potentially can contribute to many different outcomes of interest related to Sustainable Development does not lead to a way of usage such that only one outcome of interest is addressed and the others get neglected or get worse, experts in the aviation system were asked their opinions on this issue.

A final remark on markets versus regulation

According to experts, an important role for the problem owner of this research (the European Commission) is to continuously monitor the technological developments. New developments might give new technological possibilities to, for instance, reduce noise levels or increase safety levels. When these new technological possibilities are there, it is possible to require these new lower levels of noise or new higher levels of safety by law. By setting these new regulations there will be an incentive to implement and use the new technologies.

However, regulations raise another issue: not all actors in the aviation system can afford these new technologies, since they will require new investments and probably changes in procedures. These particular actors will be put at a serious disadvantage if these new regulations would be set. They could find themselves with no other option than to either make a large investment or lose their license to operate. This approach runs counter to the ideas on having free and competitive markets.

Nevertheless, governmental institutions, such as the European Commission and Parliament, have a responsibility to set standards for noise, safety, and emissions, thereby choosing for what is acceptable in terms of adverse aviation effects versus what standards for overall sustainability are technologically possible.

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1. Introduction

1.1 Introduction

This chapter describes the importance of aviation to the world as well as its undesirable effects. It brings up the concept of Sustainable Development: according to some actors in the aviation system this is a solution to these adverse effects.

A central actor is chosen as the problem owner of this research. Systems analysis is introduced as the methodology that can help decisionmakers (the problem owner) in making their decisions about changes in the aviation system contributing to Sustainable Development. The chapter finalizes with the research questions for this thesis and the thesis outline.

1.2 Undesirable effects of aviation

Aviation is a rapidly growing industry; it is deeply embedded in society and therefore of great importance to the world and its economy. The positive effects of aviation are in general hardly questioned. There is, however, both concern and disagreement about the negative effects of aviation activities.

Nowadays, the major negative effects of aviation that are mentioned are noise, local air quality, fuel use, contribution to climate change and safety incidents (IPCC 1999; Upham et al. 2003).

In general the negative effects of aviation are rather complex in both their cause and effect. Take as an example the several issues that are related to the use of fuel for the propulsion system.

Aviation is currently heavily dependent on crude oil for its propulsion. Alternative energy sources or carriers are not yet available. The current civil jet aircraft itself is optimized for the use of kerosene, a crude oil product (Torenbeek 1982). With increasing oil prices, this optimization has only increased in the 1990s (Torenbeek 2000). The increasing growth in flown kilometers might move aviation with its CO_2 emissions in the near future to a high rank in the list of most climate influencing activities (IPCC 1999). CO_2 emissions of aircraft are also worse than CO_2 emissions from other sources because they are emitted at higher altitudes (IPCC 1999). Today, the CO_2 emissions of aircraft are not yet listed in the Kyoto protocol, since allocating aviation emissions to a particular country is very hard. Where to allocate the emissions from a Royal Dutch KLM flight from Boston to London with a mix of European and American citizens on board? If the demand for aviation keeps rising, and the emission problems increase, it might be that some sort of Kyoto-like protocol comes into existence for aviation. When states are really forced to meet CO_2 emission targets, it will be harder and harder to keep ignoring activities like aviation.

In addition to the issue of CO_2 emissions and climate change, there is the issue of availability of crude oil. A lot of uncertainties exist (that is, different parties have substantial different opinions) on the availability of crude oil in the future. Some parties expect a sharp decrease in the availability of crude oil to appear within the next 25 years, while others think crude oil availability won't decline at least until 70 years from now; see for instance Deffeyes and Shell

(Deffeyes 2001; Shell 2001). For an industry that takes approximately 10 years to develop and certify an aircraft and, after that, operates it for up to 30 years of service, this means there can already be fuel uncertainties about the aircraft designs currently on the drawing board that have to replace today's aircraft.

Availability of crude oil is strongly related to price. When crude oil prices rise, more crude oil can be economically distracted from oil fields and the total economic available amount increases. There have been some large price changes in the past, in the 1970s, but also more recently in the period 2003-2005, the price of a barrel crude oil almost trippled. These large price fluctuations seriously contribute to the uncertainty related to the use and availability of crude oil products for aviation purposes.

Noise

Noise is hot issue near airports. A lot of the larger airports in the world are not restricted in their number of flights per year due to physical capacity (runways, gates, etc.) but due to their noise capacity (an example is Amsterdam Airport Schiphol). Many large airports have noise restrictions in one or other form, e.g. more noisy aircraft are not allowed to land and take off, or higher landing fees have to be paid. A lot of European major airports have a noise contour. This contour provides a maximum amount of noise that is allowed to be made over a year and is translatable to a certain number of take offs and landings of certain types of aircraft per year on certain times during the day. Noise capacity is often referred to with the term 'environmental capacity', but that will not be done in this research to prevent misunderstanding of the environmental category of issues of the concept Sustainable Development ('Planet').

Congestion

Nowadays, many travelers experience delayed flights. There are several reasons for that, like unstable and unfavorable weather conditions. But a more and more influencing reason is congestion: too many aircraft are flying through the skies reaching the capacity limit of the system. The result is comparable to a traffic jam. For instance, aircraft have to circle before they get permission to land. Or, aircraft take off later than scheduled, since the route to their destination airport is not yet cleared.

Congestion is not only a problem for air travelers, but it also costs a lot of money for operators. In addition to that, continuously congested airports get less attractive. Especially within the current very competitive market in Europe about what airports can remain serving as hub airports, congestion is a serious threat.

Congestion is definitely an outcome of interest to several stakeholders, including travel organizations, airlines, airports, and passengers.

Congestion also leads to more fuel use and noise (aircraft circling on lower altitudes at lower than optimal speeds and engine settings).

Local air quality

Aircraft engines that are running on low thrust settings largely determine local air quality near airports. With this engine setting, the engine performs way out of the optimal zone and produces relatively high ratios of pollutants like ozone, carbon oxides (CO), sulfur oxides (SO_x), unburned organic particles (C_xH_y), Nitrogen oxides (NO_x) and black smoke. Almost every air traveler will have noticed the typical smell of burned kerosene on an airport.

Fuel use

In the popular press, aircraft are often accused of using huge amounts of fuel. Indeed, for a flight over the Atlantic Ocean, a typical 747 will need approximately 80 tons of fuel, which is, in absolute sense, a lot.

This should be viewed in comparison with other modes of transport. An Airbus A-330 uses 1 liter of fuel to carry 40 seats 1 kilometer. A car uses roughly 1 liter of fuel to carry 4 seats 10 kilometers. However, cars average 100 km/h, while current civil aircraft average slightly under 1000 km/h. Propeller aircraft can even perform more efficient than this, though at a lower speed and height (Torenbeek 2000).

Compared to cars, aircraft don’t seem to perform so badly: per seat kilometer, an aircraft is very fuel-efficient compared to a car. Especially when one considers the fact that cars usually do not have four people on board, but only one, while in aircraft on average 70% of the seats are filled. Only, by using aircraft, people fly such large distances that the total amount of used fuel is still very large.

The availability of cheap fuel might eventually be very problematic for the aviation industry. But one can also look at the problem from another direction: an industry that uses, in absolute numbers, a lot of crude oil might be problematic for the long term availability of crude oil and therefore for society as a whole.

The problems around fuel use will rise. The number of flown kilometers has been growing in huge numbers over the last decades. For the future, such a growth trend is also expected. For instance, the International Panel on Climate Change (IPCC) has several scenarios for CO_2 emissions for 2050, ranging from an increase of 1.6 to 8 times the amount of CO_2 emission in 1990 (IPCC 1999). As CO_2 emissions are directly related to fuel use, this implies a substantial growth in fuel use by the aviation industry for 2050.

This fact introduces some extra uncertainty for the industry, as the availability of (cheap) crude oil is not guaranteed for the period until 2050. Even worse, some parties in the world already question the availability of crude oil in 2030 in the way it is being used today (Deffeyes 2001). This time frame lies well within the normal operating age (around 30 years) of aircraft that are put into service today.

Climate change is affecting the whole world. Its main causes are nowadays seen to be the burning of fossil fuels. With it, the accumulation of gases in the atmosphere that have the ability of trapping heat radiated from the surface of the Earth increases, thereby preventing heat radiation from escaping into space.

According to the IPCC (1999), in 1992 aviation was accountable for 2.4% of the CO_2 released into the atmosphere due to the total world burning of fossil fuels. As growth in the aviation sector is higher than in other sectors, it is likely to expect that aviation in the future will be responsible for a larger percentage of the amount of CO_2 released into the atmosphere due to the burning of fossil fuels.

Safety

The last point of the main negative effects of flying is safety. It is not so much the safety level per flown passenger kilometer that matters. That number shows that flying is by far the safest way of transport. But due to the fact that so many flights are flown every day, every now and then a large crash happens, like the El Al crash on Amsterdam Bijlmer in the 1990s.

The more air travel demand grows, statistically, the more of these crashes will occur, without aviation becoming, statistically, less safe. However, the industry sees an increase in major crashes as problematic, as every major crash scares people from flying.

Safety is a broad concept, and within aviation several measures of safety are common. One is external safety; an important issue for the general acceptance of aviation especially near large urban areas. External safety is the chance that a person on the ground gets involved in an aircraft incident (like a crash). Models are usually used to predict the level of external safety. After the incidents at Lockerbie and the World Trade Center, concern for external safety has risen.

There is also internal safety, the safety of the passengers and crew in the aircraft. This level of safety is usually expressed in the number of casualties per flown kilometer of one passenger. Note that a Boeing 747 with 500 passengers flying one kilometer, already counts for 500 passenger kilometers.

A third issue related to safety that gets registered is the number of incidents. These are dangerous situations arising due to all kind of reasons, but not leading to fatalities. Usually the safety number related to incidents is also expressed in the number of incidents per flown passenger kilometer.

Safety, according to experts (see chapter 4), will always be an issue in aviation that is looked at and is, therefore, an outcome of interest for many stakeholders and actors in the system.

Possible Solutions

When, in general, these negative consequences of aviation are seen as problematic by society, people might start thinking about solving these problems.

One can focus on different kinds of solutions and distinguish on the two extremes of a continuum *uni-focus solutions* and *multi-focus solutions* (Figure 1.1).

Figure 1.1; The difference between unifocus and multifocus solutions on the two extremes of a continuum.

The European Commission, an organization that is capable of influencing parts the aviation system, is in its press release IP/01/123 very clear on what lines aviation should develop, two of which are already mentioned:

- Safety;
- Reducing congestion;
- Toward a sustainable mode.

Sustainable Development is a broad concept for which no clear set of measurable indicators exists yet, though it is an outcome of interest to at least one important actor in the system, the European Parliament and the European Commission, the virtual client of this research.

However, the European Council adopted a description of what Sustainable Transport is (EU Council 2001). With aviation being an important transport mode, this definition gives clues to what the virtual client considers to be developments that contribute to a state of sustainability. It states that a sustainable transportation system is one that:

- *Allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promises equity within and between successive generations;*

- *Is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development;*

- *Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise.*

In general people tend to look for technical solutions for problems occurring in high-tech areas, such as the aviation industry. 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."

These statements clearly indicate that technological developments are expected to contribute to the mitigation of current adverse effects of aviation regarding sustainability issues.

It might well be that the total sustainable solution will benefit from several so-called sub-solutions in different areas that strengthen each other. If that happens, then technology could well be one of those sub-solutions. Then, technology will be *part* of the solution and not make up the entire solution (Tempelman 1998).

However, this research will focus only on the technical engineering solutions. With this choice, the author does not automatically agree with the idea that technology alone will solve all problems. The aim of the study is to find out to what extent expert selected technologies can help in solving the problem.

This study tries to determine the extent that technology can contribute to Sustainable Development by performing a systems analysis in which expected technological innovations, designed to improve certain current adverse effects of aviation, will be scored on their merits to Sustainable Development in different scenarios of air travel demand in the future of 2050. In addition, it studies the problems around possible implementation of new technologies in the aviation system.

Solutions that contribute to a Sustainable Development (a concept that will be elaborately described in chapter 3) will have characteristics of multi-focus solutions. A Sustainable Development requires attention to a lot of different aspects of the problem all together.

Within the continuum of uni- and multifocus solutions also different types of solutions exist. Examples are: setting noise restrictions on night flights (a legal type of solution), influencing consumer travel behavior (a demand management type of solution) or coming up with new, innovative technical artifacts (a technical type of solution).

It might well be that the total solution will benefit from a combination of several different types of so-called sub solutions that strengthen each other. However, this research will focus only on one type and that is the technical engineering type of solution.

If technology could solve all problems, no other type of solution would be necessary. No behavioral changes would have to be enforced; whatever man would do, technology would make sure it would not hurt society and the environment too much. This sound of *technological fix* solutions can be heard from time to time in the media and is being expressed over and over again by some politicians. It is, however, ex ante not immediately clear if such a technological fix solution is possible. Technology can make activities much more efficient, producing more positive effects at the cost of less negative effects. But, this is also a strong incentive for growth: more of the same activities, as the positive effects are rewarding and the negative effects are taken care of by the new technology. As long as this growth is not too large, the overall problem is still smaller than before the introduction of the new technology. However, economic incentives can easily boost the activities to such high levels that, despite the new technology, the situation gets worse than before.

Technology alone, therefore, may or may not be enough to reach a sustainable state (that is, to reach sustainability), in which, ideally, all current problems are solved for the long term and in a way that all stakeholders see all their interests taken into consideration. Therefore, a solution to current adverse effects of aviation, if any such solution exists, is not automatically always a completely *technical fix* solution. The introduction of a good piece of engineering work *alone* might not be enough to satisfy all stakeholders and solve all of the problems. It is this issue that forms the interest for carrying out this research.

Nevertheless, technology, since it is deeply embedded in our society, definitely will play a role in moving toward a solution for current negative effects of aviation.

What is assumed in this study is that the introduction of technology might create room for society. It might give society at least more time to come up with other solutions. In essence, the introduction of new technology might give some additional margin that can be filled in by society on different ways. Take for example an aircraft engine that can produce the same amount of thrust, but at a lower fuel consumption rate. The margin that this technological introduction creates can be filled in with an environmental goal in mind, by simply using less fuel for transporting the same number of people and goods in the same amount of time. But it can also be used for economic goals. In that case using the same amount of fuel as before the introduction of the new engine technology leads to more profit by transporting more people and goods. This could, however, set in a chain reaction of lowering the ticket price and creating more demand for air transport (the so-called ‘rebound effect’). The final result would then be burning up much more fuel than in the original situation, though the engine itself has become much more efficient.

1.3 Problem Owner

A systems analysis is carried out to support and facilitate decisionmaking. It is meant as a basis for action (Miser and Quade 1985). Therefore, a systems analysis requires a client, or, at least, someone who experiences the current state of a system as undesirable or problematic. This problem owner, who must have certain power to make changes in the system, will then, after the analysis, have the opportunity to make use of the results when making decisions. This section deals with the problem owner for this research.

The European Commission and Parliament are able to influence several aviation system elements in Europe, by applying regulation and setting policy measures. These aviation system elements can, for instance, be construction firms, airports, air traffic control systems, as well as influencing the demand for air travel by setting pricing policies.

A national government is not capable of influencing the aviation system to a large extent, as aviation has an international orientation. A country could for instance raise taxes on aircraft fuel. International airliners flying to that country will quickly see the opportunity to fill up their tanks abroad, which could sometimes require extra flights and with that an increase in the noise and gas emission and a statistical lowering of the external safety.

Worldwide organizations, such as the United Nations, can operate only when its member states agree. A lot of discussion boards on aviation issues are active under the flag of the United Nations. The United Nations has also a vision on the future of aviation and on sustainability. In practice, however, the United Nations has even far less power than local governments to enforce any changes in the aviation system.

A problem owner in a policy analysis study must be able to make real changes in the system. Otherwise, no policy measures can be implemented and one can only describe what the system does or will do, without changing it to more favorable conditions.

On a continental scale, the European Parliament and the European Commission can fulfill such a role of problem owner.

The Council of the EU (EU Council 2001) gives a definition of what they consider to be sustainable transport. It is this definition that will be used as a starting point for operationalizing sustainable aviation in chapter 3.

Since neither the European Parliament, nor the European Commission is the sponsor of this research, nor have they asked for this research to be carried out, the rest of this research will refer to the European Parliament and European Commission (the problem owner) as being the '*virtual* client' for the work.

1.4 Paths leading to unsustainable choices

This study also addresses, as stated earlier, the issue of implementation (see research question 2). After the analysis, one might know which technologies have a potential to contribute to Sustainable Development (if any exist). However, one still does not know if these technologies can and will be implemented in the aviation system. If implementation would come 'automatically', the adverse effects of aviation as they exist today, might be 'automatically' solved in the future.

The dilemma in the problem formulation illustrates partly why implementation of new aircraft technologies can not always be expected. We would like to keep the benefits of flying, but get rid of the adverse effects. So far no policy measures have been identified that would seriously reduce the adverse effects of aviation without reducing the positive effects, such as cheap, fast, and comfortable flights.

In this light, it is important to know something about why individuals tend to let systems (here the aviation system) come into states that produce a lot of adverse effects for society. There are several reasons why people haven't chosen the path leading to sustainability. An approach to understand, explain and predict human behavior on issues regarding Sustainable Development is research on so-called social dilemmas, especially common resource dilemmas. In the behavioral sciences, a lot of attention is paid to these social dilemmas which resemble issues of sustainability remarkably well (Midden and Bartels 1994; Nicolaij and Hendrickx 2003).

In situations in which people have to choose between short-term personal gains (in social science this is called a *defective choice*) and long-term group gains (called a *cooperative choice*) on a scarce and slowly regenerating public good (fresh air, oil, clean water, etc.), they find themselves in a mixed motive position (Forsyth 1999). They are, with their other group members, competitor and cooperators at the same time. They are competitors, as whatever someone takes for himself or herself is not available to others anymore. They are also cooperators, as leaving enough for the future benefits the whole group in the long-term.

Van Lange gives some clear hints on what to do to encourage people to think about the long-term group benefits and act more in favor of the group (by making more cooperative choices) instead of acting for short term personal benefit (making more defective choices) (Van Lange 1989).

- Assign prices to short term personal gain (pricing defective choices);
- The effect of individual behavior must be visible;
- Encourage good communication among group members;
- People must be aware that others can see their behavior;
- Create a stronger group identity.

Several of his recommendations have been practiced in reality. Success factors differ, as it is not easy to directly apply all of this advice in real world settings. How do you, for instance, create a stronger group identity among the people worldwide that are using the scarce and non-renewable public good crude oil? Another example, pricing, is an issue that cannot always be easily implemented in a free market economy without contradicting the principles that a free market economy is based upon.

Within social dilemmas, Chapman found that people have the tendency to discount in a way Chapman called positive time preference (Chapman 1998; Chapman et al. 1999). In short, this means that people in general want nice things now and not in the future and bad things especially not now but as far in the future as possible. Nice things now are worth more than the same nice things in the future. There appears to be a discount rate comparable to interest rates, as one Euro today is worth more than one Euro in 10 years from now.

This tendency of discounting that people have appears to highly encourage short term personal gain (defective choice) in social dilemmas and is therefore a force one would like to counterbalance from a Sustainable Development point of view. There are, however, findings by Nicolaij and Hendrickx (Nicolaij and Hendrickx 2003) that indicate that people do not discount in all areas in the same way. Financial issues are differently discounted than medical issues. And some issues, like ethical or environmental issues, are not discounted at all by a large number of the people (up to 50%) who have been performing in the experiments as experimentees (Nicolaij and Hendrickx 2003).

A very strong force that can influence people in social dilemmas is the (social) pressure that results from being held accountable for one's deeds (Semin and Manstead 1983; Forsyth 1999). As soon as people's behavior is open enough that others can see it or see the result, people tend to shift their behavior toward what they think the group norm is (Forsyth 1999). Observed behavior from others appears to be a stronger basis for what the group norm in such a situation is, than an overall existing moral norm. When behavioral norms in society for several resources are clearly *huge usage* instead of *savings for later*, this, too, can help to promote the choice for short term personal gain (defective choice) rather than for cooperative choice.

1.5 Methodology

The aviation industry includes many actors, each having its own interests. It faces complex problems. For example the global decrease in air travel demand after the September 11th incident at the World Trade Center, led to the bankruptcy of several large airlines like Swissair and Sabena.

The problems in the aviation industry that have just been described have many alternative solution directions, each of which has lots of different consequences; the number of stakeholders in the aviation system is large; and the uncertainty about future external developments is high.

According to Miser and Quade (Miser and Quade 1985) these characteristics make this system a good system to be analyzed by the methodology called systems analysis or policy analysis.

Policy analysis is about providing information to decisionmakers directly, or, in more common cases, to advisors of decisionmakers. Its aim is never to come up with the one and only solution to the problem, nor is it to rank possible solutions on their level of desirability. Policy analysis studies can provide assistance to decisionmakers in choosing a good course of action from complex alternatives under uncertain conditions (Miser and Quade 1985; Walker 2000).

However, after having performed a policy analysis study, the resistant to change aviation system will not automatically adopt technological changes that some actors in the system might see as favorable. In addition, introducing new technologies could indeed bring sustainability closer (so one can speak of a Sustainable Development), but the particular way of using of these new technologies could also lead to optimizing single things. One could think of technology that gives far less gas emissions with much more thrust. This margin filled in with more seats for cheaper ticket prices might result in such a growth of the sector that the situation is, emission and noise wise, worse off than originally, while only the ticket price shows positive developments for society (cheaper flights).

Therefore, in addition to a classic systems analysis study, expert opinion by doing interviews will be performed to investigate roadblocks (preventing implementation) and information about unintended usage (unsustainable use) of new technologies.

Policy analysis is applied in this aeronautical multi-actor setting in order to inform policymakers in their process of deciding along what lines aviation should develop itself in the long term and how to support such development, if reaching a state of sustainability is the ultimate goal.

In addition to informing policymakers, this study might also inform actors in the aviation industry. Because, with the expected air transport growth in the future, it might not be wise for the industry to sit and wait to see what the outside world is going to do with respect to the adverse effects of aviation. Aircraft stay in service for over 30 years, so it takes a considerable amount of time to introduce large changes in the system.

This is in contrast to the automobile industry, in which there is practically a complete turnover over the entire car fleet within 15 years. As a result of this, the vast majority of all cars are now equipped with catalytic converters, which were introduced in the late 1980s and early 1990s to reduce the amount of hazardous substances in the exhaust fumes. Due to this system change, it has been possible to dramatically reduce the most hazardous substances in car emissions per driven kilometer (like carbon mono-oxide) within a time span of only one and a half decades. A comparable system change in aviation would take roughly three times this length. If, in addition to a life span of 30 years for an aircraft and a 10 year period for design and certification, also other considerations would be taken into account, like the very small profit margins of airlines, the process of system change might take even longer.

1.6 Research questions

The goal for this research is to find out what contributions expert selected aircraft related technologies in the aviation system can make to Sustainable Development. Technology that is currently in the design phase, or technology that is expected to develop in the near future, will be focused on improvements on the current adverse effects due to flying. Therefore, one can identify a dilemma between, on one side, optimizations in one domain of aspects (e.g. environmental aspects when the issue of noise is considered) and, on the other side, addressing all issues that play a role for the concept of Sustainable Development. The problem for this research is formulated as:

What is the potential of a set of expert selected new aircraft technologies to contribute to Sustainable Development; i.e. what is their potential to reduce actor defined adverse effects of flying while keeping the benefits?

The word 'potential' has in this case two meanings: (1), a theoretical assessment of the contributions various technologies might be able to make to Sustainable Development (by determining the effects of the technologies on actor determined indicators), and, (2), an implementation assessment, since the possible contribution of a new technology can only turn into a real contribution when the technology is fully implemented. All sorts of barriers might prevent implementation of technology that could contribute to solving the problem stated.

Also, the particular usage of the implemented technology determines whether it will really contribute to Sustainable Development according to its potential to do so. Technological improvements for a specific adverse effect can lead to traffic growth that might even cause larger problems than initially anticipated (the so-called rebound effect). The problem formulation was, therefore, split into two main research questions:

1. What can expert selected new aircraft technologies contribute to Sustainable Development?

2. How can expert selected new aircraft technologies with a potential to contribute to Sustainable Development be implemented and used in a way that their potential contribution turns into a real contribution?

Question 1

This research, among other things, carries out a systems analysis (Miser and Quade 1985; Walker 2000). It uses a set of outcome indicators for what Sustainable Development in relation to aviation means (chapter 3). Upon these outcomes indicators, technological innovations will be scored. This scoring gives clues on how to use the margins that are provided by the new technology with the goal of a Sustainable Development in mind. Eventually, it will be the choice on how these margins will be filled in that determines the level of Sustainability, or the contribution to a Sustainable Development.

What this study does in fact, is give an idea what the potential of expert selected aeronautical technologies is to contribute to Sustainable Development by scoring these technological innovations on outcome indicators representing Sustainable Development.

Question 2

Providing information about the potential to contribute to Sustainable Development is one thing, real implementation of certain technological developments is something completely different.

As any system has a natural resistance to change, if only for reasons of internal stability, also the aviation sector does not automatically welcome all changes. For example, the current paradigm of the airplane, a cigar-like fuselage with halfway two wings and a tail section, is as old as the 1950s. With every new design, it has not basically changed; though it has been very much improved in terms of, for instance, fuel efficiency, direct operating costs, safety and noise (Anderson 1989).

This study also pinpoints at the implementation problem by performing an actor analysis and interviewing experts, listing the possible roadblocks and showstoppers in the aviation sector that can prevent promising technologies from being implemented.

But the implementation problem also consists of the different possibilities to use new technology in the system. As addressed earlier in this section, the economics are such that there is a strong incentive for growth of the total system. This strong incentive will favor user options of this new technology that do not use the new technologies for reducing the adverse effects of flying, but to support growth.

If a certain technology has a potential to contribute to Sustainable Development, but one actor’s most favorable way of filling that margin is something that would contradict Sustainable Development, one has to think in advance about how to prevent this unsustainable choice from becoming reality. Else, introducing this technology makes no sense from a Sustainable Development point of view, and it can even have a counter effect, meaning that the total situation becomes less sustainable.

For answering these two questions, the research has to answer the following set of sub-questions:

System definition

- What is considered the problem and what is the system of interest?

Outcomes of interest

- What is Sustainable Development?
- What are the associated outcomes of interest for the several actors and the related measurable outcome indicators?

Selecting technological developments

- What current and future new aviation technologies selected by experts are likely to be promising in terms of their contribution to sustainable development?

Uncertainty: scenario development

- What are the relevant future air travel demand scenarios (in terms of number of seats) within which to evaluate the innovative aviation technologies?

Scoring the technological developments

- What is the relation between the promising innovative aviation technologies and the outcome indicators?
- What will current technology and its incremental improvements produce on the outcome indicators in the base case (that is, business as usual or the *do-nothing* option)?
- What contribution could ideal implementation (that is, full implementation without exceptions replacing any remaining old technology) of the most promising innovative aviation technologies make to Sustainable Development (i.e. making the situation in the future better than today) in the future scenarios?

Identifying roadblocks and non-sustainable user options

- What roadblocks can be identified that might prevent promising innovative aviation technologies from being implemented?

Generating explanations for these roadblocks and non-sustainable user options

- What explanations can be identified for these roadblocks and non-sustainable user options, thereby suggesting actions that could prevent them?

1.7 Thesis outline

The overall structure of the remainder of this dissertation is shown in Figure 1.3.

Chapter 2 describes the approach of systems analysis as carried out in this research and relates the different steps in that analysis to the chapters of the thesis in which these steps are carried out.

Chapter 3 defines the outcomes of interest, resulting from the objectives of the problem owner, the actors, and the stakeholders. A large part of the chapter is devoted to the objectives of the problem owner. The objectives are directly related to the concept of Sustainable Development, which is a very broad concept. The chapter therefore starts with a general overview of how Sustainable Development is defined. After that, the concept is customized to what it means in an aviation context. The chapter uses the widely known distinction between People (social), Planet (environment) and Profit (economy). So far, the social part of sustainability, *People*, has often been forgotten or moved aside as being too hard to make measurable.

In addition to sustainability issues, the chapter lists the objectives of the other actors and stakeholders in the system. It transforms the resulting outcomes of interest into outcome indicators.

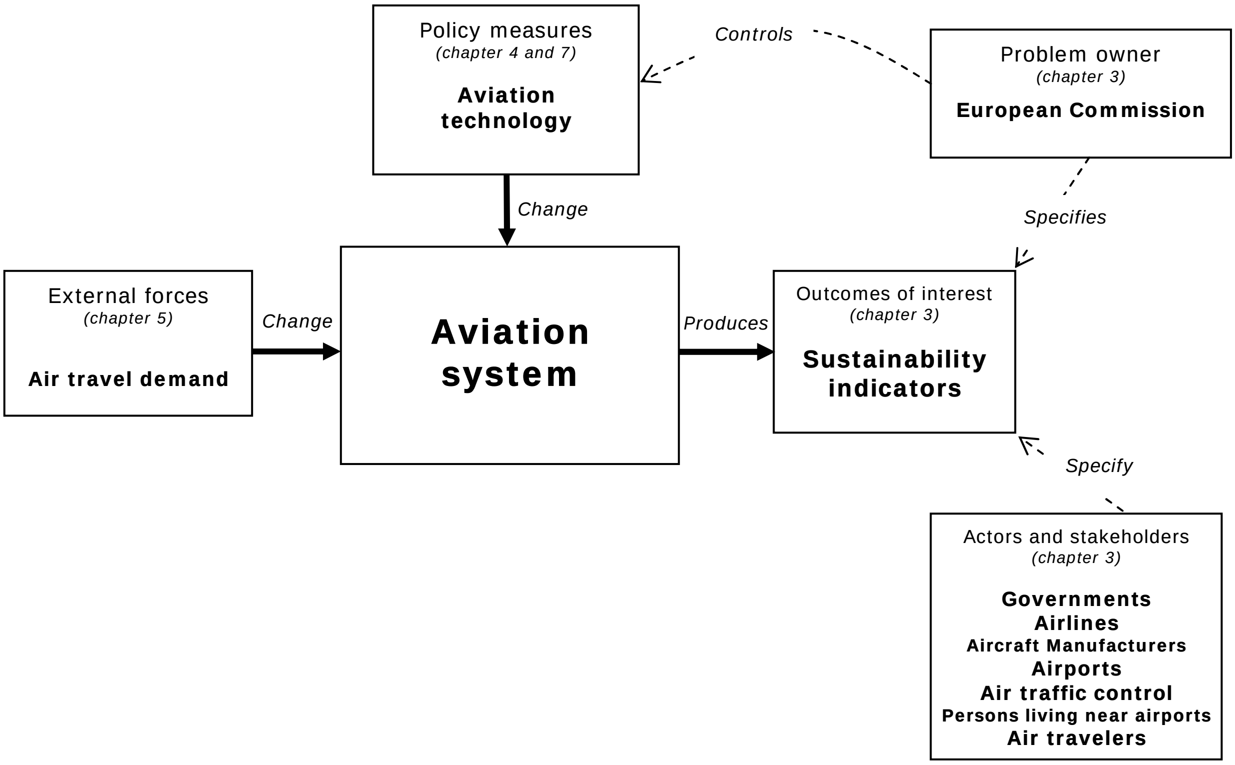

Figure 1.3. A relation between the content of the different chapters in this thesis.

Chapter 4 is the chapter in which expert selected innovative new aviation technologies that might contribute to Sustainable Development are presented. Several preliminary engineering design studies of promising technologies from the literature are presented. In addition, several new preliminary designs (co)-supervised by the author are introduced, such as a three deck Ultra-High capacity aircraft for 1001 passengers, a modern version of the Airship, and High-Aspect ratio wings. These promising options are studied in more detail in chapter 6, where they are scored assuming they are implemented in one of the future aviation scenarios for the year 2050.

In Chapter 5, several scenarios are designed for the time period until 2050. The external force is air travel demand. The air travel demand scenarios are based on current existing scenarios (that usually have the year 2020 as their time horizon) with some additional assumptions and additional factors stemming from literature and interviews. Causal factor modeling is chosen as methodology.

Chapter 6 performs the scoring of the technologies. It scores current technology (the reference case or *do-nothing* option) in the scenarios of Chapter 5. In this case, no innovative aviation technologies are introduced. This chapter also scores the promising innovative technologies from Chapter 4 for all scenarios of Chapter 5, in the ideal situation in which all promising technologies are fully implemented. It finishes with a discussion of the level of sustainability of the reference case compared to the new technology policy case.

Chapter 7 is on barrier analysis and unsustainable user options. In this chapter, using literature and expert opinion, roadblocks are listed and explanations are identified for the existence of these roadblocks and of non-sustainable user options.

The final chapter (Chapter 8) discusses the results. This chapter answers the list of sub questions stated in section 1.6. The chapter also reflects on the usability of the (scientific) methods used in this research for investigating questions on the broad issue of Sustainable Development.

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2. Methodology of Systems Analysis

2.1 Introduction

Knowing, from chapter 1, what the importance is of aviation for society, but also the negative effects society has from aviation and the desire to do something about it, we now describe a research approach that can help in deciding what measures to take. When issues are of high societal importance (like aviation is) and the suggested idea of a Sustainable Development is not immediately clear to everybody, there is a strong need for a structured approach. Systems analysis is such a structured approach. Walker (Walker 2000a) states that "Over the past 50 years, policy analysts … have developed a systems-based approach and a set of tools for examining public policy issues that illuminate the uncertainties and their implications for policymaking, that identify tradeoffs among the alternative policies, and that support the policymaking process."

This chapter starts explaining (in section 2.2) the need for an approach like systems analysis for the particular problem addressed in this thesis and gives an overview of it. After that, in section 2.3, the several steps needed to complete a systems analysis are introduced and operationalized in detail and related to those chapters in this thesis in which these steps are carried out. The chapter ends (in section 2.4) with the discussion of several other widely used research approaches and explains why these approaches were not chosen for this research.

2.2 Systems analysis

Systems analysis is about large changes; the method is not suitable for determining detailed numerical outputs to several decimals. This section first shows why this methodology is suitable for the problem at hand. This is so, because the improvements that are needed to reach a state of sustainability are not a couple of percentages, but factors like 5, 10 or more times better than today.

Sustainable Development is a process that stretches from today until a relatively far away time horizon. Some take 20 years into account (Anderson 1998), some 80 (Shell 2001), and others the philosophical point infinity. Some think mankind must become 4 times more efficient with their use of natural resources (Weizsäcker 1998); others come up with factors of 20, 50, or more (Jansen and Heel 1999).

A simple way of illustrating the efficiency needed when working in the Earth's buffer zone (a zone in which you can change certain parameters without changing the system as a whole very dramatically, over a period of, say, 50 years, compared with the efficiency today) is the IPAT model (Weizsäcker 1998; Jansen and Heel 1999). The IPAT model says that the impact on the environment (I) equals the number of people (P) times their affluence (A) times the technological efficiency (1/T).

For an illustrative calculation, the following is assumed (Jansen and Heel 1999):

- Impact, I, of today should decrease or at least not increase, so it stays at least the same: 1;
- Population, P, raises a by factor 2 by 2050;
- Rate of inconvenience per unit of consumption or service, affluence, A, increases by a factor of 5, as developing countries will raise to the level of consumption the Western World has today;
- Technological efficiency, 1/T, must rise in order to keep up pace with growing P and A and at the same time keeping I equal to 1.

Substituting these values in the equation results in:

$$\left.\begin{array}{r} \mathrm{I} = \mathrm{P} \cdot \mathrm{A} \cdot \mathrm{T} \\ 1 = 2 \cdot 5 \cdot \mathrm{T} \end{array}\right\} \rightarrow \quad \mathrm{T} = \tfrac{1}{10}$$

Technology should, in this example, be ten times more efficient to keep the environmental impact equal to that of today, when population and affluence grow in the future.

This IPAT model is, of course, too simple. Apart from discussions on the precise numbers, the model gives the impression that nothing but the technology is controllable and that only from the technology we may expect solutions.

But, what this model correctly illustrates is that the technological part of the answer to the need for more sustainability must be raising efficiency of factors. Whether these factors are 4 or 50 cannot be predicted by using IPAT, but the model illustrates that just 3 or 5% improvement is by far not enough.

The challenge for the engineer is to keep the technological efficiency in pace with additional growth of consumption, welfare, et cetera, if the answer should come from technology alone.

According to this illustrative model, aviation technology, if it is to contribute to more sustainability, should therefore seek and develop ways to keep on fulfilling its service while in the meantime raising its energy and material efficiency substantially (big changes) and not by some few percentages (small changes) (Jansen and Heel 1999).

One of the goals of this research (see chapter 1) is to find out if there are any aircraft related technological innovations (either existing prototypes or ideas still on the drawing board) that could make the aviation system contribute to Sustainable Development. The aviation system is very complex, with a lot of different actors involved that all have different objectives. It is by no means clear in advance what changes in the system, if any, will be acceptable for all actors and stakeholders, and, also contribute to more Sustainable Development. Next to this, the aviation system has uncertainties in time, both in the long and in the short term. The volume of passengers and cargo in the future is not known and predictions about it differ as much as from a total collapse of the system to an ten time growth in 50 years. Short term uncertainties about future demand exist after incidents like the SARS epidemic or the 9/11 attacks in the past years. A sudden disruption in the number of passengers ran most of the world’s airlines into a financial crisis that not all airlines could survive.

Reaching the desired goals of this research from chapter 1 in such a complex and uncertain system requires a rational, systematic, and structured research approach. For decisionmakers to decide what policy measures to implement, the result of this rational, systematic and structured approach should be the kind of information that reveals the consequences of implementing such policy measures in the system.

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

Systems analysis will not replace the decisionmaker. On the contrary, the decisionmaker will have to do a lot of work, both during the analysis (by providing all kinds of information) and after it (by using the results of the analysis for decisionmaking). Systems analysis can assist the judgment process of what policy measures to implement (if any) by clarifying the problem, presenting alternatives, and comparing their consequences (Walker 2000a).

The approach of systems analysis can best be explained by looking at Figure 2.1. In the center of the figure, there is a model representing that part of reality that the policy measures to be studied will focus upon. The model can be any kind of model, from a detailed computer model to a more abstract qualitative model.

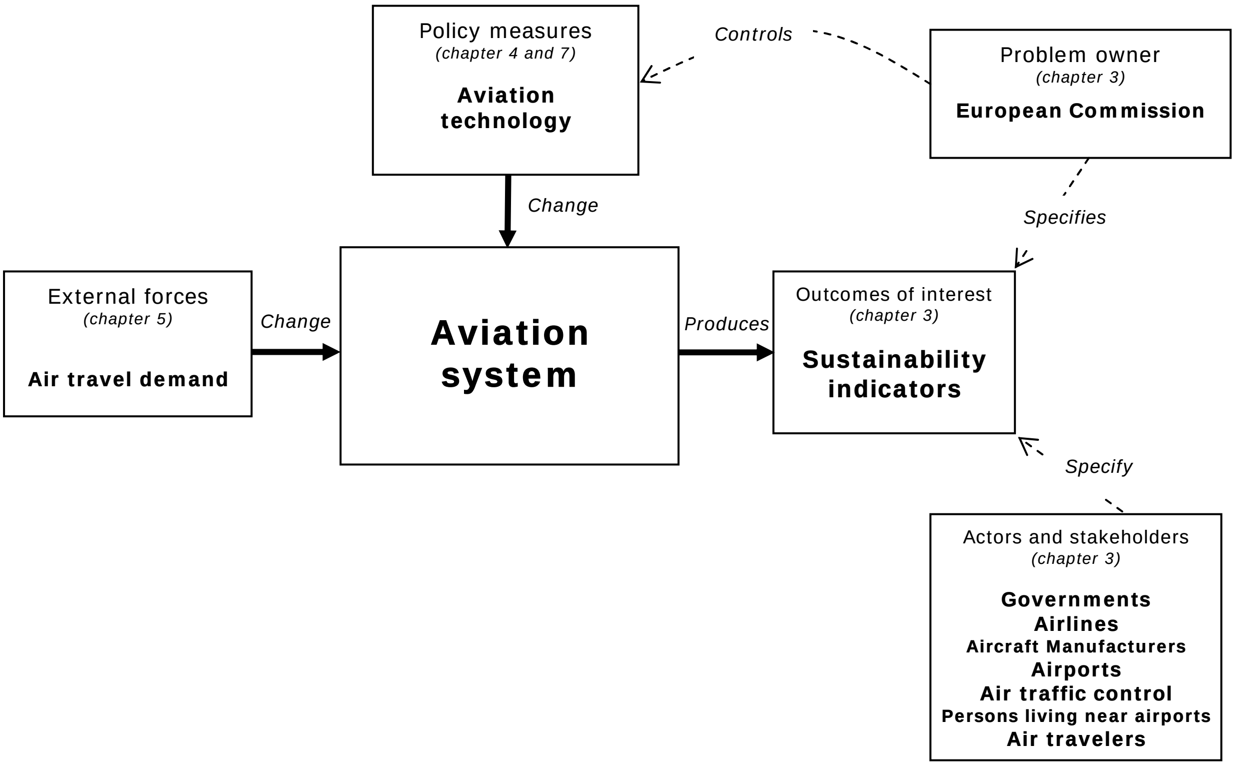

Figure 2.1. The problem diagram around Sustainable Development and aviation.

From the outside, two kinds of forces act upon the system model. One kind is out of control of the problem owner and is called ‘external forces’. The other kind is completely under the control of the problem owner and is called ‘policy measures’. These measures include both specific policy changes and accompanying measures that enhance the implementation of the chosen policy changes.

External forces are dynamic, they can change over time. Their values at any given time are very uncertain. Any specific future state of the external forces will actually occur with probability zero. The future is largely unknowable; that is a fact that system analysts and policy analysts have to deal with. A widely used approach to deal with this uncertainty is the scenario approach. The consequences of different possible policy measures are determined for a variety of possible futures that are believed to cover the most probable range of possible futures (Walker 2000b).

In general, policymakers have objectives. They want to reduce the amount of noise that originates from aircraft operation, or they want to increase the capacity of an airport. In order to reach these objectives, policymakers implement policies. When in a systems analysis study it has to be determined if certain policy measures bring the objectives of the policymakers closer, the effect of the suggested policy measures will have to be measured in some way. If the contribution of the aviation system to Sustainable Development has to rise, then, one needs indications for what Sustainable Development is, in order to see what policy measures will bring this objective closer and what policy measures don't.

For each of 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 are related as closely as possible to the outcomes of interest. It usually requires a huge effort from the analyst to come up with a set of indicators that represent the outcomes of interest well and are also acceptable to the problem owner and other actors and stakeholders (Miser and Quade 1985). The value that the different indicators can take does not always have to be numerical. Also statements like 'increase' or 'very much' can be very useful and informative indicator values.

In order to present the results of a system analysis, Goeller (1972) introduced a table with the impacts of a policy measure in different columns and the policy measures in different rows. The entry in a specific cell of this table represents a score of a particular policy measure (row) on a particular outcome indicator (column). The overall representation is called a scorecard (see Figure 2.2).

	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***

Figure 2.2. An example of a scorecard.

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. Using color schemas to indicate the best (e.g. green, dark grey) and the worst (e.g. red, light grey) policy measure for each outcome indicator will make it easier to identify promising policies (Miser and Quade 1985).

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 get easily moved aside. The scorecard shows the effect of each policy measure on all types of indicators all together. This facilitates trading off between qualitative and quantitative outcomes of interest.

It is tempting to use an aggregate indicator that summarizes all outcome indicators in the scorecard. With such an aggregate indicator (e.g. a weighted average of all scores) it is easy to rank all the policy measures from best to worst. However, this research does not make use of such kind of aggregate indicators. These indicators suffer from a lack of detail; decisionmakers have no clues about the reasons for the ranking and a lack of confidence in the analysis can be the result. In addition, lots of subjective judgments are required to translate the values of the various indicators into a single overall unit (often money, so things have to get monetized). Also the translation of the, often implicit, preferences of the decisionmakers into explicit weighting factors (needed to create a ranking of measures from an impact table or scorecard as presented in Figure 2.2) introduces lots of subjective judgments.

Once a scorecard, as a final product of a systems analysis, is available, the process of decisionmaking can start. The scorecard will 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 so much agreement on the value judgments among the different actors.

2.3 Steps to complete a systems analysis

Performing a systems analysis requires carrying out a number of steps (see Figure 2.3).

Step:	*Task to carry out:*
1	Identify problem
2	Specify objectives
3	Decide on indicators
4	Select potential policy measures
5	Analyze potential policy measures
6	Compare potential policy measures and choose one of the alternatives

Figure 2.3. The several steps in a systems analysis study, adapted from Walker (2000a).

This section describes in detail each of the steps needed to complete a systems analysis and operationalizes these steps in detail, relating them to the chapters in this thesis in which these steps are carried out.

Step 1 – Identify problem

The first step is identifying the problem. According to Miser and Quade (1985, p.127) a " … problem formulation … implies isolating the questions or issues involved, fixing the context within which the issues are to be resolved, clarifying the objectives and constraints, identifying the people who will be affected by the decision, discovering the major operating factors, and deciding on the initial approach."

Identifying the problem also includes a clear and summarizing formulation of the problem in one sentence. This problem formulation is dilemmatic in nature. For instance: reducing noise around airports, without decreasing the airport's capacity. Explicitly stating the dilemma (noise versus capacity) gives a clear view on the essence of the problem.

The actor that perceives the problem, or at least admits that it exists, can be called a problem owner. If there is also a desire to solve the problem, the problem owner might become a client and hire an analyst to provide information needed to make decisions about policies that might solve the problem.

For this research, the problem formulation can be found in chapter 1. Attention in the media for all kind of adverse effects of flying triggered the consciousness that there might be a problem around aviation. Further study of the literature, of reports published by several actors in the aviation field (aircraft manufacturers, airlines, and airports), studying governmental reports and interviewing experts in the field, revealed the most important problematic issues regarding aviation. These appear to be: bad local living circumstances around airports due to noise and gas emissions, contribution to climate change, ever increasing delays for air travelers due to seriously increasing congestion in the air and a perceived reduction of safety by the public. The delays and congestion are not so much directly caused by aviation, but more by the growth of air travel demand. It is this demand that is described in the reports to be desirable, only, the effects of this growth in terms of congestion and thus delay are described as problematic. The same holds true for the perception of safety. Due to the ever increasing number of flights, more accidents happen, while aviation per flown seat kilometer stays just as save. The current size and continuous high growth figures of air travel seriously increase the mentioned problems, although, for some actors, these growth figures are perfectly in line with their objectives.

Every actor presents different solutions for parts of the problem, like cleaner and more silent engines or different flying routes near airports. However, among others, the European Commission (EC), presents an overarching concept as the solution to all problems around aviation. This concept is called 'Sustainable Development'. The EC sees Sustainable Development as the way aviation should further develop itself in the future.

The challenge with the problems around aviation is to keep the benefits that flying has for society, but reduce, or preferably get rid of, the adverse effects of it. This research takes the conceptual solution of the EU, a Sustainable Development, as its starting point and analyzes if new innovative aviation technology can bring the desired Sustainable Development closer by reducing the adverse effects of flying while keeping the benefits.

Step 2 – Specify objectives

Once a problem is perceived and someone has been identified as the problem owner who wants to solve the problem, it has to be determined what the precise objectives of that problem owner are. The problem owner may have multiple objectives. These objectives are usually not all in line, but are often contradictory.

The analysis becomes even more complicated because actors and stakeholders besides the problem owner are usually involved in the problem, each of them having his or her own set of objectives.

This research studied the scientific literature and other publications (such as annual reports) by the several actors in the aviation system to determine each actor's objectives. For the problem owner, who sees contributing to Sustainable Development as the primary objective, much more specification of what this concept actually means was necessary. The concept Sustainable Development had to be operationalized. Already, in all kind of publications by the EU, the problem owner has given hints and glimpses of what is meant by Sustainable Development. However, a long section of the third chapter is spent on operationalizing the concept of Sustainable Development. The combination of all actors' objectives forms the outcomes of interest in this research. These can be found in chapter 3.

Step 3 – Decide on indicators

When it is determined what the objectives are and the analyst and client have come to an agreement about the outcomes of interest of the system, it is time to operationalize these outcomes. The operationalization is necessary in order to determine the impact of the several policies that are under analysis (see Figure 2.4 for a relation of these outcomes to other elements in a policy analysis study). Preferably, these operationalizations, usually called proxies, criteria, or outcome indicators, are measurable quantitatively. This is, however, not always possible and therefore qualitative indicators might be present in the list of criteria as well. Often, qualitative analysis gets ignored and only quantitative impacts are assessed. This easily leads to the ignorance (or reduced attention) of objectives of some actors and stakeholders, resulting in an ignorance of the complete study by policymakers or an attack of the study by these ignored actors and stakeholders (Walker 2000a).

An important issue that always comes up when designing indicators is the preferences of the actors. Different actors consider different outcomes of interest and thus different indicators important. The research needs more indicators than only those of interest to the problem owner. A result of the different preferences of the actors is that there is room for negotiations on the final policy to implement, as not all outcomes are of the same high importance to all actors in the system. The research itself will not treat any of the indicators as more important than another.

This research used already available material of the different actors to identify as many outcome indicators as possible. The sources were, for instance, white papers, Internet Websites, journal articles, and annual reports. Not for all outcomes of interest, this was sufficient to find indictors, so the research has done some indicator design itself too. This design process is based on literature study and accompanying expert opinion. Chapter 3 presents the results of this indicator creation process.

Step 4 – Select policy measures

It is not uncommon for clients to formulate their problem in terms of solutions they have already thought of. “We can’t get rid of the noisiest aircraft” is an example. Instead, the actual problem could be “How can we get rid of the aircraft noise, without reducing the peak hour capacity of the airport in terms of landings and departures”. Decisionmakers tend to have one or more possible policies in mind that they assume can solve (part of) their perceived problem. However, as Miser and Quade (1985, p.132) state: “… alternatives considered … may be wide-ranging and need not be obvious substitutes for each other…”. Selecting alternatives is not only listing the ideas of the client; it is a creative process for which a good understanding of and knowledge about the problem is required.

This research only takes innovative aircraft related aviation technology into account as the type of policy to be analyzed (see chapter 1). The virtual client of this research does not specify much more than that it assumes that new technology will play a large role in solving their perceived problem with adverse aviation effects (see chapter 3 about the ideas and wishes of the problem owner). It adds though, that it will support these technological developments (for instance by the Framework programs) without specifying the type of technology, nor giving ideas about the direction of its development.

To come up with detailed policies (alternatives, certain innovative aviation technologies that could reduce the adverse effects of aviation), this research also created its own designs. In addition, the literature and other media (like Websites, more popular press on aviation, discussion boards on the Internet about aviation, and so on) have been scanned for alternatives. There has also been performed a round of interviews among professors and practitioners in several fields of aerospace engineering. The different alternatives considered in this research are presented in detail in chapter 4.

Step 5 – Analyze policy measures

The essence of step 5 is to determine the relationship between the possible future implementation of each alternative identified in step 4 and the outcome indicators specified in step 3. For this, usually models of the system are used; both quantitative and qualitative in nature.

As explained in detail in chapter 5, this research takes 2050 as the moment in time for which the alternatives must be analyzed. The main reason for this is the long time it takes to replace all currently designed and operated technology by new innovative aircraft related aviation technology. This replacement time is assumed to be around 40 years (see chapter 5). To be able to determine the effect of the alternatives when implemented in the aviation system in 2050, information is needed about how that system looks like in 2050.

The future, however, is unknown and largely unknowable. One way to deal with this uncertainty is to analyze the alternatives in a range of possible futures, and, thus, make use of different scenarios. Each scenario will have one scorecard (like in Figure 2.2) in which the modeled consequences are presented of the different alternatives when they would be implemented in that particular future aviation scenario. The scenario approach requires a causal understanding of factors that influence those characteristics of the aviation system that influence the outcomes of interest.

In determining the outcomes of interest, the model developed in this research requires information about the possible future state of the demand for air travel (see for instance Figure 2.4).

For the future state of air travel demand in 2050, the situation is a bit complex. In the model that relates the scores on the outcomes of interest to the different alternatives to be analyzed, the air travel demand is represented by the available number of seats. A literature survey revealed a list of factors that influence air travel demand and also a possible range of values for these factors in the future. These ranges of factors had to be extrapolated to 2050 in this research. Both the identified factors and their possible values were then checked by experts before a model was built (chapter 5). This model generates, based on the assumptions for the values of the different factors, several possible futures for the size of air travel demand. It is in each of these futures that the consequences of the implementation of each alternative are modeled. The results are presented in one scorecard for each scenario (in chapter 6).

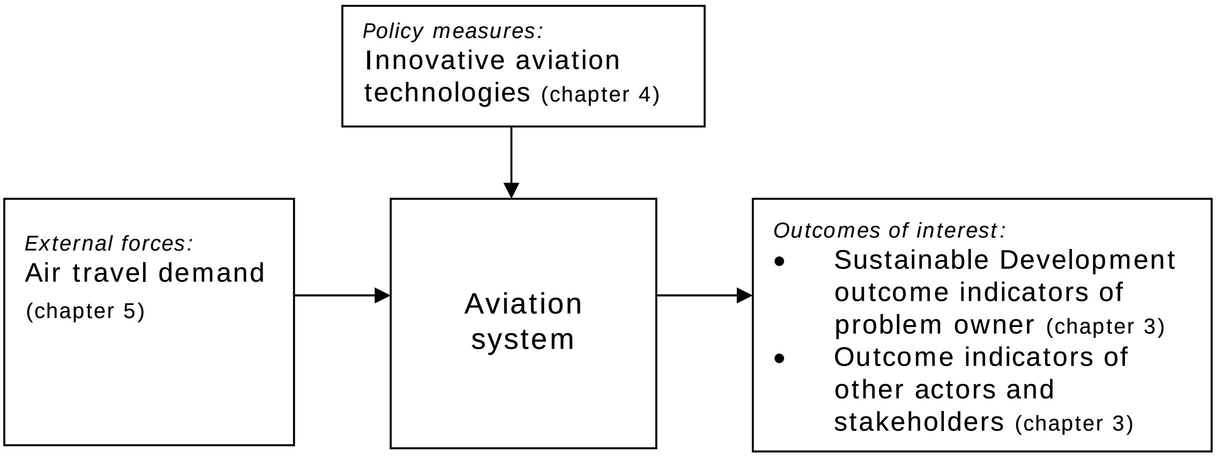

Figure 2.4. Some essential policy analysis elements and their relationships.

Step 6 – Compare policy measures and choose one

When, as the result of step 5, all scorecards are available, the consequences of the several alternatives in the different scenarios can be compared. Is there any alternative (or combination of alternatives) that will have the desired consequences (as stated by the problem owner) in any of the scenarios? If more than one can be found, trade-offs can be made among the alternatives based on their different consequences. If no alternative produces the desired consequences in any of the scenarios, one could conclude that, given the imperfections of the analysis, no solution is reasonably available, or one could opt for going back to step 4. This will depend on the amount of resources and the desire of the client to both solve the problem and make use of a policy analysis study in helping decide for a policy to implement.

Chapter 6 presents the outcomes of the 2050 aviation system when each of the new technologies is implemented, but also when no new technology would be implemented. This last case is the so-called reference case or do-nothing option. To this reference case the scores of the innovative aviation technologies get compared.

This research could not identify any alternative that produced the desired outcomes in any of the considered scenarios. Given the constraint that only technological options were considered as possible alternatives, no alternative could be found for the virtual client and problem owner of this research that would solve their problem.

Comparing the scorecards of chapter 6 (i.e. comparing the innovative aviation technologies to the base cases and the reference case) shows that some alternatives could make the 2050 aviation system situation more desirable than current technology would do in 2050. One could therefore argue that some considered technology could well contribute to an overall policy solving the problem in which, next to technological alternatives, also other types of alternatives are considered.

Therefore, this research devoted chapter 7 to the problems arising when implementing the best performing alternatives. So called roadblock factors, which could completely block the implementation of the innovative technologies, have been identified. In addition, also rebound factors have been found. These factors do not oppose implementation, but they enhance certain ways of using the innovative aviation technologies in such a way that the desired positive effects on the adverse effects of flying disappear or even turn into making the adverse effects worse than before the implementation. Methodological, this chapter relies heavily on interviewing experts.

An initial approach for breaking the resistance to change among the actors in the aviation system has been designed and tested several times on experimentees that played the role of the real actors in the aviation system. The aim of this intervention method is to stimulate creativity and to take away tunnel vision type of mechanisms present within the actors. In such a way, implementation of the most promising innovative aviation technologies of chapter 4 is assumed to be enhanced.

2.4 Other possible research methodologies for steps 5 and 6

So far in this chapter it has been explained why systems analysis is a good research approach for the problem around aviation and Sustainable Development as described in chapter 1. It is much easier to explain why an approach is suitable, than to answer the question why, in general, not another approach or methodology is used. However, in trying to say something about that last question, this section covers some other possible research approaches for addressing the problem of aviation and Sustainable Development. For each approach or methodology, it is explained why that particular approach or methodology is not chosen for this research.

Mathematical modeling for step 5

Using a mathematical model to answer research question in general raises the impression of hard data and reliable, detailed numerical predictions, at least, at first sight. Mathematical modeling however, requires a detailed and reliable determination of the parameters in the equations used to produce the detailed and accurate numerical results.

In this research case about aviation and Sustainable Development, it was not expected that the values for these parameters would be available in the literature. Already detailed descriptions of what Sustainable Development means in terms of the aviation system appeared to be lacking.

What is left then is determining the value of the parameters by making estimations yourself or by interviewing experts. Both approaches would result in far from accurate estimations.

However, as the research has a time horizon of 2050, one can not do better than a rough estimation, given all the uncertainty that is present. As the research questions are about identifying large changes between policy measures that have not even be designed in detail yet, it seems that a method that is heading for determining and showing the large differences between the policy measures available (like use of expert opinions), is to be preferred over an option that strives for the accurate details (like mathematical modeling). Therefore, mathematical modeling has not been used in this research as research methodology.

Cost Benefit analysis for step 6

In problems where uncertainty exists about what policy measure to implement to solve the problem, a cost benefit analysis can be of use. It shows in one single indicator (usually monetized, so in terms of money; see also the discussion on aggregate indicators in section 2.2) the expected effects of a certain policy measure implemented in a certain system for a certain scenario. These are, for the type of research in this thesis, precisely the two problems with cost benefit analysis: an aggregated single indicator for the effects and the monetization of all effects.

Different actors in a system can chose for the same policy measure to solve the problem, but for completely different reasons. It is not so much the agreement on what effects are important and what not that matters, but the agreement on what policy measure to implement. Cost benefit analysis does not give insight into the variety of effects; it aggregates all these effects in one single indicator. As discussed in section 2.2, by aggregating, it removes the possibility for different actors to look for the effects for their individual important indicators.

Sustainable Development is a wide concept (see chapter 3). It is also used widely as an umbrella term that covers a lot of outcomes of interest that are very hard to measure, much less able to be translated into a single scale, like money. The monetization of all effects, as a cost benefits requires, is hardly possible when one would like to score a broad variety of effects all part of the concept of Sustainable Development.

For these two reasons, multi criteria scorecards are preferred to cost benefit analysis. A score card shows the effects of the different policy measures on all important indicators. It also shows the pure effect, without translating it into another scale (for instance monetizing).

Delphi for step 6

When the goal of the policy process is agreement, in the end, on what policy measure to take and when the goal of this research is to facilitate that policy process, it is, at first glance, not strange to think of a Delphi procedure. A Delphi procedure is a technique that uses different rounds of questioning and answering and feed back to the participants (usually experts in the problem field) to get agreement among actors.

It might be true that the particular goal of this thesis is to, in the end, facilitate the decisionmaking process, but it also would like to reduce the fuzziness and vagueness around the concept of Sustainable Development. Therefore it has as a particular goal to operationalize Sustainable Development for the aviation system. Delphi is not suitable for rationalizing the problem, determining what the problem exactly is and determining what indicators are used by the different actors to make choices among the different possible actions to take. Delphi might give an agreement on what experts think is the best thing to do, but it does not give insight in the problem. For outsiders, it is not possible to trace back how these experts came to their agreement (if they would reach it). The scorecard approach gives that insight, since it opertionalizes the problem and shows exactly what effects policy measures have on what indicators.

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3. Outcomes of interest

3.1 Introduction

Now that the problem has been identified (chapter 1) and the research approach has been chosen (chapter 2), it is time to think about the objectives of the actors involved in the aviation system and decide on the criteria to use in the analysis (see steps 2 and 3 of the systems analysis approach in Figure 2.3). The goal of this chapter, therefore, is the identification of a set of outcome indicators for the outcomes of interest of the virtual client (problem owner) and other actors and stakeholders. These indicators will be used in chapters 6 and 7, to score the change towards sustainability that several innovative aviation technologies (the “tactics”, described in chapter 4) make to the aviation system in the various “scenarios” (chapter 5).

This chapter identifies the several actors and stakeholders in the system to analyze, i.e. the aviation system. For each of these, their objectives are determined and indicators are defined that reflect these objectives.

For the problem owner, whose main objective is for aviation to develop into a sustainable mode, the design of a clear set of measurable indicators is quite an effort. Therefore a lot of attention is paid to the design of a set of indicators for the concept of Sustainable Development.

This design process starts with a brief description and historical overview of the concept of Sustainable Development. It then turns to the level of existing definitions (or descriptions) of Sustainable Development and chooses a combination of two definitions as a reference point.

This reference point will be decomposed along three dimensions: Social, Environmental and Economic, after which it is further operationalized in terms of indicators that will be scored for the several tactics (innovative aviation technologies) in different scenarios in chapters 6 and 7.

In order to find out what part of the system is looked at and, thus, what part of the system can be influenced by the introduction of new aircraft related aviation technology, this chapter starts with a systematic decomposition of the aviation system.

3.2 Aviation system

The ‘aviation system’ is a large system consisting of many social and technical subsystems. Each of these subsystems consists of many technologies, groups of people, individuals, and relationships between them. This section aims at a systematic description of the aviation system to more clearly point at the places where aircraft related new technology could be introduced and influence other parts of the system.

A common distinction within the aviation system is to speak of a landside and an airside (de Neufville and Odoni 2003), see Figure 3.1. The landside part (the part after unboarding the aircraft, and before boarding) is not investigated in this research; parts of the airside are, however. On the airside, de Neufville and Odoni distinguish the airfield with among other things its capacity and delay characteristics, demand management, and air traffic management (ATM). Of these, demand management (including scheduling, ticket pricing, congestion pricing, and slot allocation) is not further investigated here. Within the other two subsystems, airfield and ATM, aircraft play a substantial role. They influence, for instance, the size of airfields; their noise characteristics influence the environmental capacity; their turn-around-times influence the delay and their flight envelopes and vortex characteristics the ATM possibilities.

Technological changes to the aircraft are the essential studied elements in this research. What technological changes to aircraft can reduce the currently widely experienced adverse effects of flying, while still keeping the option to fly, that is, keeping the benefits of fast and relatively cheap worldwide transport?

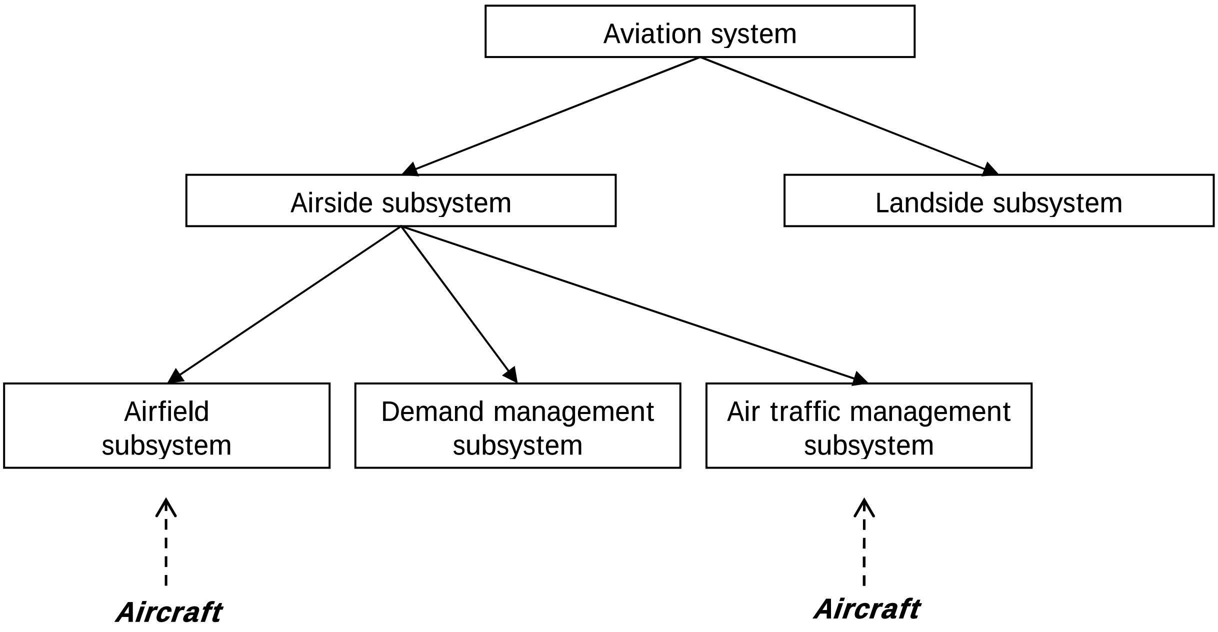

Figure 3.1. Distinguishing several subsystems within the aviation system, and the subsystems that aircraft technology influences.

It is important to see the relatively limited part of the aviation system that can be influenced by new aircraft related innovative technology. The demand management subsystem, for instance, can not be influenced, although some actors seriously consider reducing the demand for flights as an option to reduce adverse effects of flying. This limited influence also limits the size of the system from which indicators can be identified that can measure the sustainability performance of the technologies. However, this rather limited part of the system also makes it possible to have very detailed measurable indicators while still measuring all important elements of the concept of Sustainable Development.

The next section starts the design of indicators for the concept of Sustainable Development.

3.3 Problem owner

The goal of the problem owner of this research is to find ways to get closer to achieving sustainable aviation. Therefore this problem owner must be an actor, which means that this person or organization is able to make real changes in the system; otherwise, policy measures cannot be implemented and one can only describe what the system does without changing it to more favorable conditions.

In addition to actors (people or groups that can make changes in the system), there are also stakeholders in a system. Stakeholders are defined to be people or groups that have an interest and objectives concerning issues in that system, but are unable to make changes in that system to get closer to creating their objectives. Though these stakeholders can surely perceive and experience a problem within a system, they cannot be defined as a problem owner. Making a policy analysis makes only sense if there is more than one option that can be implemented and if the problem owner has the power and responsibility to affect the implementation.

Problem owners, therefore, who perceive a problem in the aviation system and are also capable of implementing policies in the aviation system that relate to the implementation of innovative aviation technology, are not so widely spread. Large technology companies most certainly have an effect on the technology that gets developed. But their capability to enforce the use of particular technology throughout the aviation system is limited. Next to that it is questionable if these specific actors have the same wide scope of objectives that society as a whole has.

A more neutral non-profit national government seems at first sight a better choice as the problem owner. A democratic government ideally represents all people in society and therefore should have knowledge about the full range of objectives society has. However the power of governments to change systems is often over-estimated. Especially within the current political climate of the free market and liberalization of formerly governmentally owned institutions (like railways or energy companies), governments don’t seem to have very extensive steering power. They leave a lot of that steering power over to free market forces. Governments have their remaining steering power over their own territory. For an international operating system like the aviation system, a national government is too small to be able to enforce or enhance changes that lead to more favorable overall system conditions.

On a continental scale, the European Commission (EC) pays serious attention to sustainability in relation to transport. They also refer to technology as a serious candidate to help overcome the undesirable effects of aviation. The EC does research work on issues that the European Parliament (EP) has to take decisions about. EP decisions force all European Union (EU) member states to act accordingly. This reduces national governments’ steering power, but increases the ability of the EC and EP to make changes in the aviation system since this system crosses the borders of the member states.

Europe is an industrialized continent. It is expected to consume the largest share of air transport within a decade or so (Airbus 2004). This seems to be the ideal place to work on sustainability within the aviation system by introducing innovative technology. Thus, the EC seems to be the most suitable group that could make use of the analysis results in this report. It, therefore, seems logical to choose the EC as the problem owner.

The reports and press releases by the EU and EC about aviation and its unwanted effects usually address noise, safety, local air quality and also tend to mention sustainability as something to strive for (e.g. IP/01/123 of September 2001). In addition, EU and EC publications on sustainability issues show a wide interpretation of this concept and, among other things, definitely include noise, safety and local air quality. Also the other side - the desired effects of aviation - are mentioned there. These are things like meeting the basic access and development needs of individuals and companies or, although indirectly, economic issues like profit.

The next section addresses the issue of sustainability and narrows it down to outcomes of interest and eventually indicators that can be used in a policy analysis study. After that, the objectives of other actors and stakeholders are identified and also transformed into outcomes of interest and indicators. This chapter concludes with a set of indicators representing all actors' and stakeholders' objectives.

3.4 Sustainable Development

Meadows (1972) was one of the first authors to relate local environmental problems to global origins and effects. Meadows' conclusion was that a closed system like the Earth cannot sustain exponential growth of human activities, such as population growth, industrialization, and food production, forever. At a certain time, a collapse is unavoidable (Meadows 1972). This idea was not new, as Thomas Robert Malthus already in 1798 published his work "An Essay on the Principle of Population" in which he showed the discrepancy between life growing at exponential rates (2, 4, 8, 16, etc.), while food supplies grow at linear rates (2, 3, 4, 5, etc). Excessive population growth could only be checked by so-called Malthusian Catastrophes.

Approximately 10 years after Meadows, in the 1980s, it became clear that not only using up the resources was a potential problem, but the capacity of the Earth's system to resolve disturbances was a potential problem too (Partidario 2002).

As a result of this finding, a United Nations committee was formed to find out what should be done to avoid catastrophe. In 1987, the ex-Norwegian prime minister Brundtland, published the output of this committee, the report "Our common future" (WCED 1987), in which she introduced the most recited description of Sustainable Development:

"Sustainable Development is development that meets the needs of the present generation, without compromising the ability of future generations to meet their needs."

Her report stressed the importance of the limited capacity of the Earth's buffer zone and the importance of social equity, within a generation as well as between generations. It states that "overriding priority should be given to the world's poor" out of reasons of justice and fairness. A world social state with a few very rich and a lot of people so poor they can hardly satisfy their most basic needs, is socially very much out of balance. However, the last centuries have shown that such a state can be, though morally unacceptable, long lasting.

Some five years after Brundtland's report, in Rio de Janeiro 1992, the World Summit was organized around the two issues of overusing buffer capacity and the inequity of spreading the wealth over the different nations in the world.

The latter issue was covered for two reasons. One, already mentioned by Brundtland, that an out of balance social system with large differences between a small wealthy Western World and a very large and poor Developing World is unacceptable for reasons of justice and fairness (WCED 1987). Two, because the developing countries would and could only join and cooperate if there was a future for their people, so they were in a position to care about a future.

Since the publication of Brundtland's report in 1987, a lot of definitions of the concept Sustainable Development have emerged (Partidario 2002; Upham et al. 2003). The topic of Sustainable Development has proven to be very interesting for people (as it receives so much attention), very fertile for scientists (an area of intense research), and a very confusing concept (as there are so many definitions).

Recently, the Organization for Economic Cooperation and Development (OECD) presented four principles that cover the essence of the concept of Sustainable Development. These principles are (OECD 2001):

- *Regeneration*: Use of renewables within their rates of natural regeneration;
- *Substitutability*: Use of non-renewables limited to possibilities of substitution by renewables;
- *Assimilation*: No release of hazardous substances exceeding assimilative capacity of the environment;
- *Avoiding irreversibility*: Maintaining or restoring the integrity of the ecosystem should be safeguarded.

This presentation of the concept of Sustainable Development is slightly more specific than Brundtland's definition of it, as it points to specific topics and shows in what direction specific developments and progress should be made. The OECD, however, focuses almost exclusively on environmental issues, such as waste, emissions, and the use of resources. Though some issues of social justice are indirectly covered by critically looking at emissions and resource usage, the OECD description of Sustainable Development does not specifically pinpoint social issues of justice, equity and equality within and between generations.

An effort to define sustainability in the context of air transport is a study sponsored by the Air Transport Action Group (ATAG). Hired by ATAG, the Swiss INFRAS Consulting group published a study called Sustainable Aviation (INFRAS 2000). INFRAS describes Sustainable Development in social, environmental, and economic terms, a well-known distinction that is also used by, for instance, Shell (Shell 2001). INFRAS identifies indicators for each of three axes: social (People), environmental (Planet) and economic (Profit).

On a higher level of abstraction than aviation, the European Union has defined sustainable transport (European Council, 2001), see Table 3.1. There is a remarkable resemblance between what the European Union defines as being sustainable transport and the indicators INFRAS identifies as useful providing information on what sustainable aviation is.

Table 3.2 decomposes the EU adopted definition among the social, environmental, and economic axis. For each axis, we have indicated what elements are found to be important by the European Union and by INFRAS.

Sustainable transport,

- **Allows the basic access and development needs of individuals, companies and societies to be met safely and in a manner consistent with human and ecosystem health, and promises equity within and between successive generations;**
- **Is affordable, operates fairly and efficiently, offers choice of transport mode, and supports a competitive economy, as well as balanced regional development;**
- **Limits emissions and waste within the planet's ability to absorb them, uses renewable resources at or below their rates of generation, and, uses non-renewable resources at or below the rates of development of renewable substitutes while minimizing the impact on land and the generation of noise.**

Table 3.1. The European Council's description of sustainable transport (EU Council 2001).

	Social	Environmental	Economic
European Union	Basic access and development needs of individuals and societies being met	Consistent with ecosystem health	Basic access and development needs of companies being met
	Safe	Limits emissions and waste within the planet's ability to absorb them	Affordable operation
	Consistent with human health	Uses renewable resources at or below their rates of generation	Efficient operation
	Promises equity within and between generations	Uses non-renewable resources at or below the rate of development of renewable substitutes	Supports a competitive economy
	Fair operation	Low impact on land	Supports balanced regional developments
	Offers choice	Low noise generation	
INFRAS	Accessibility of remote areas	Energy efficiency	Job creation and growth contribution
	Safety	Climate change	Access and travel time speed
	Local and National participation of people in decision making	Noise	Global productivity
		Air pollution	Regional and local market changes
		Land use	Cost recovery of infrastructure costs

Table 3.2. A decomposition of the definition of sustainable mobility by the European Council and INFRAS' description of sustainable aviation into outcomes of interest, along the social, environmental, and economic axis.

Regrouping the entries in Table 3.2 and combining the entries that more or less cover the same outcomes of interest in one cell yields Table 3.3.

Social	Environmental	Economic
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*
	PL4: Noise impact Low noise generation *Noise*	

Table 3.3. Regrouped table of outcomes of interest with the entries covering comparable issues in one cell. 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).

This table now contains a set of outcomes that decisionmakers need information about if they want to be able to make a decision on issues related to aviation and Sustainable Development. It is based on two descriptions: (1) a description of sustainable transport by the European Union, and (2) a description of sustainable aviation by INFRAS.

The content of this table is specific enough to make the design of outcome indicators possible and is not conflicting with the more abstract and wider definitions of Sustainable Development by Brundtland (1987) and OECD (2001).

For each of the numbered cells in Table 3.3 (PE1, PE2, ..., PL1, etc), we design outcome indicators. Before each outcome indicator is presented, a short explanation of why the specific indicator is chosen is given. The outcome indicator itself is presented in a table, including its units and its desired direction of development (i.e. its objective) in order to contribute to the overall concept of Sustainable Development.

At the end of section 3.5, a table is presented containing the overview of all outcome indicators.

Using indicators to measure outcomes of interest is certainly not new; many studies follow the same approach. Many attempts to make the concept of Sustainable Development measurable have been carried out. One of the problems is that the concept and the application area are both wide and deep: Sustainable Development for a society has so many aspects that either the list of indicators is detailed and endless or the number of indicators is limited but they are broad and very hard to measure. The advantage for this study is that, despite the broadness of the sustainability concept, the application area, aviation technology, is narrow enough to make a workable set of measurable indicators, even if the values of these indicators have to be estimated for half a century in the future.

Existing studies and usage of indicators related to Sustainable Development (see Table 3.4), each on a different aggregation level, are for instance United Nations Commission on Sustainable Development (United Nations Commission on Sustainable Development 2001), the European Environmental Agency (EEA 2001), and a periodically performed measurement of the Sustainable Development situation in the EU region by EuroStat, the European Statistical Office (EuroStat 2001). A study that has a more specific focus on transport is for instance SUMMA (Sustainable Mobility, policy Measures and Assessment) which was coordinated by RAND Europe (Summa Consortium 2005). Their set of outcomes indicators is presented in an article by Walker et al. (Walker et al. 2006).

Publication	Published by	Dimensions addressed	Indicator range
Indicators of Sustainable Development (2001)	United Nations commission on Sustainable Development (UN-CSD)	Social, Economic, Environmental, Institutional. The institutional dimension measures how well government and society cooperate in a Sustainable Development strategy. It is related to both the institutional framework and the institutional capacity.	Addresses state of sustainability, actions influencing sustainability and actions towards more sustainability.
Measuring progress towards a more Sustainable Europe (2001)	EuroStat, European Statistical Office	Same dimensions as UN-CSD.	Based on UN-CSD list of indicators with some added, adapted or omitted to better fit the European situation.
Indicators tracking transport and environment integration in the European Union (2001)	European Environmental Agency	Addresses 7 key issues: 1. Is the environmental performance of the transport sector improving? 2. Are we getting better at managing transport demand and at improving the modal split? 3. Are spatial and transport planning becoming better coordinated so as to match transport demand to the needs of access? 4. Are we optimizing the use of existing transport infrastructure capacity and moving towards a better balanced intermodal transport system? 5. Are we moving towards a fairer and more efficient pricing system, which ensures that external costs are internalized? 6. How rapidly are improved technologies being implemented and how efficiently are vehicles being used? 7. How effectively are environmental management and monitoring tools being used to support policy- and decision-making?	Indicators based on DPSIR framework: Driving forces, Pressures, State, Impacts, Societal responses
SUMMA: Sustainable Mobility, policy Measures and Assessment (2005) and (Walker et al. 2006)	SUMMA Consortium with RAND Europe as Project Coordinator	Social, Environmental and Economic.	Addresses the state of sustainability of the transport system.

Table 3.4. Some recent publications of lists of indicators related to Sustainable Development in general and more specific to Sustainable Transport.

This research aims at determining the contribution of aircraft technology in the aviation system to sustainability in some future scenarios. This has strong parallels with the SUMMA approach (see Table 3.4). So, for each of the numbered cells in Table 3.3, publications of the problem owner have been studied for clues to what the problem owner sees as essential and, thus, should be covered by indicators. Then, further research has been done using the above-mentioned studies to find additional indicators to fully cover the sustainability concept.

Later in the chapter, additional indicators are identified that are related to the specific objectives of the other-than-problem-owner actors and stakeholders.

3.5 Outcome indicators for Sustainable Development

3.5.1 Social outcome indicators ("People")

PE1: Access.

The EU argues that there is an important role for a good transport system in supporting a strong and competitive economy in the EU region (European Commission 2001). According to the description of sustainable transport, adopted by the EU Council in 2001, a transport system should be fulfilling the basic access and development needs of society. The better access to the transport system, and, the more it meets society's development needs, the larger the contribution of such a transport system to Sustainable Development.

In terms of aviation, the outcome of interest 'accessibility and development needs' can be split into a physical and economic component. Physical accessibility relates to how many geographic places are connected via air routes. When more places are connected, more people can have easier access to the aviation system (since, on average, the access points are closer together) and benefit from the advantages. The economic element relates to how expensive it is to make use of the aviation system. This relates directly to ticket prices and fares to transport goods. It also relates to the costs people have to make to reach a geographic place that has air connections to other places.

INFRAS considers the accessibility of remote areas an important issue in the sustainability discussion. The EU transport policy White Paper (European Commission 2001) seems to support this idea by mentioning the importance of connecting the new Eastern Europe member states to the transport network.

Indicators then should represent the number of connected geographic places and the frequency of flights between those places to resemble physical accessibility. Economic access can be represented by the cost for air transport in ticket prices and the average distance to an airport people have to travel to get air connections. The last one can be represented by the number of operated larger airports in the EU area. Also, there should be an indicator to measure the number of large airports in the more remote areas (North and East) of the EU.

The suggested social outcome indicators for "access" are listed in Table 3.5.

Code	Outcome indicator	Unit	Desired 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

Table 3.5. Indicators representing the outcome of interest “Access” (PE1).

PE2: Safety

Air travel has always been one of the safest ways to travel, when looking at the number of fatalities per flown passenger kilometer (Anderson 1989). The general public has expectations based on that history of safety (KLM 2003). Safety in terms of absence of danger leading to a low number of fatalities and injuries is an objective on its own. ICAO measures accident rates in number of fatalities (deaths among passengers and crew during flight operations) per 100 million passenger-kilometers (ICAO 2004). Incidents, violations of safety standards that do not cause any deaths, are also measured by ICAO (ICAO 2004). They also are good indicators for safety, as they measure the occurrence of potentially very dangerous situations.

According to the EU transport White Paper (European Commission 2001), an issue that is closely related to safety is the growth figure for the demand of air transport. Curbing the growth figures could result from media coverage of large crashes in aviation. Although, statistically, aviation may stay safe (as the number of fatalities per traveled kilometer does not increase), the absolute number of crash occurrences might affect the growth figures. If the growth figures of the last decades continue into the next few decades, more crashes in which large aircraft are involved will take place. Statistical safety might be something else than public’s perceived safety. Since especially the larger crashes (i.e. crashes of aircraft with lots of people involved) will have the impact of curbing aviation growth (as the EU white paper states), this factor needs a separate indicator.

The safety issues described so far are categorized as “internal safety.” External safety is the level of safety for the people on the ground influenced by flight operations. Since the larger airports of the world usually lie closely to densely populated areas, low levels of external safety may still lead to seriously endangering lots of people’s lives. Fear for aircraft crashes around airports is usually high among citizens. This fear is enforced by the media attention aircraft disasters receive. This attention is much larger for aviation related disasters than for road, rail, or chemical plant disasters (Rose 1992).

External risk measurements are usually expressed in chances for fatalities for one person or a group of persons in a certain area due to a certain activity in or around that area. Determining the values for these indicators usually involves causal analysis of relevant factors and expert judgment (RIVM 2001; Place 2002). Among these causal factors the number of people living in the surroundings of the airport is one, since the risk that has to be measured is related to people.

Measurements like this unfortunately don't work for our study. We consider the introduction of new, innovative aviation technology. There is no way that these instruments will directly influence the number of inhabitants around airports worldwide. As soon as an indicator gets influenced by other factors than the analyzed policy measures or the considered external forces (as in this case by the number of people that live around an airport; a number that is different for each location on Earth), the indicator is of no use for the analysis.

Amsterdam Airport Schiphol uses a risk measurement that does not contain the factor of people living near airports. This so-called Weight of Risk measurement is a product of flight movements, the chance of a flight to crash, and the average take off weight of the aircraft. No factors from the surroundings are taken into account (RIVM 2001). For the measurement of external risk in this particular analysis, this seems to be the appropriate indicator.

The suggested indicators are listed in Table 3.6.

Code	Outcome indicator	Unit	Desired direction of change
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 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

Table 3.6. Indicators representing the outcome of interest "Safety" (PE2).

PE3: Human health

Human health usually gets measured in the medical literature in terms of occurrences of something undesired: once per 60000 people or so. For example, a flu is called epidemic if more than a certain amount of people per 1000 people are caught by the virus.

It is quite problematic to relate the occurrence of a disease (or the general loss of wellness) to specific aviation activities. It would require the specific part of occurrence per type of disease that is caused by aviation. Given the many factors that can cause diseases, it is already very hard to find a relationship between aviation activities and diseases at all. There will always be other factors that are also likely to have caused disease occurrences.

Another approach is to not measure the effect (the loss of wellness) but to measure some possible or plausible particular causes of these effects within the aviation system. The EU points at two aviation related factors that it believes are the major factors influencing people's health: (1) noise, and, (2) gas emissions influencing climate and local air quality (European Commission 2001). Both noise and climate change are covered under outcome of interest PL4 and PL1 and are therefore not taken into account further at this stage.

The deterioration of local air quality starts when extra gasses are emitted to the already naturally present type and amount of particles. These particles can come from different sources related to aviation: refining crude oil to kerosene, people traveling by car or train to and from the airport, or the burning of kerosene in aircraft itself.

Since this research focuses on the analysis of new innovative aviation technology, it is plausible to narrow down the local air quality outcomes indicators to gas emissions of aircraft. The main problematic emissions for local air quality due to aviation activity are nitrogen oxide (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs). A meta-study of studies that investigate possible relationships between the emission of these kinds of gasses and reduced wellness could not strongly prove the existence of a relation; though, some effects are plausible to have been caused by gas emission, although other factors could also have caused it (Hume and Watson 1999). However, the smell of VOCs near airports raises the awareness of people about local air quality and in general enforces anxiety for the effects of it on human health.

The concentration of particular particles in the air around airports is strongly influenced by characteristics of the surroundings such as soil, buildings, and the weather. Innovative aircraft related aviation technology will have effect on the origin of the gas emissions, but not on the characteristics of the surroundings in which these gasses are emitted. Therefore, measuring concentrations is not of much practical use, since the relationship between the emissions and the actual concentrations is influenced by many more factors than the aircraft technology. So, the indicators should focus on the emissions themselves rather than the concentration of particles in the air near airports.

An aggregate measurement for emissions is the total amount of fuel that gets burned during an average landing, taxiing, and take off cycle (LTO). However, as different gasses cause different effects (VOCs smell badly and are related to cancers, while CO is poisonous as it blocks oxygen uptake in the blood system), it is necessary to decompose this aggregate measurement into separate measurements for NO_x, CO, and VOCs.

An issue that has been receiving growing attention is the occurrence of diseases due to being in an aircraft: cabin related diseases. For passengers, the main concerns are negative effects, such as thrombosis due to sitting in the same position in a small place for a long period of time. The cabin environment with high levels of circulated air and relatively low moisture levels can cause breathing related diseases and infections due to viruses and bacteria that accumulate in the air supply system. For frequent flyers and the cabin crew there is an extra issue: that of receiving higher doses of cosmic radiation (related to cancers of all kind) than people on the Earth’s surface. As these issues are caused by the inevitable conditions long haul passengers find themselves in and can not be seriously related to the introduction of innovative aviation technology, they are not further taken into consideration here.

The indicators for the human health outcome of interest suggested above are listed in Table 3.7.

Code	Outcome indicator	Unit	Desired direction of change
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

Table 3.7. Indicators related to the outcome of interest “Human Health” (PE3).

PE4: Equity

In relation to the outcome of interest equity, the UN Commission on Sustainable Development (UN-CSD) mentions the following issues as important (United Nations Commission on Sustainable Development 2001):

- Distribution of poverty;
- Distribution of employment and income;
- Distribution of gender, ethnic groups, and age;
- Distribution of access to finance and natural resources;
- Intergenerational opportunity.

More in general, the Commission states that equity involves a degree of fairness (see also PE5) and the inclusiveness with which resources are distributed.

The Statistical Office of the European Communities (EuroStat) measures progress towards a more sustainable Europe. For this, it has adopted the proposed indicators for Sustainable Development as published by the UN-CSD, while making modifications to suit the European situation. As Eurostat tries to measure general Sustainable Development (to which innovative aviation technology might contribute), it covers a wide range of criteria on which the influence of innovative aviation technology cannot be determined.

The outcome of interest equity gets measured by EuroStat through determining (EuroStat 2001):

- What part of the population lives below the poverty line;
- The inequality of income;
- The rate of unemployment, in general and for youth in particular;
- The social benefits per capita;
- The female to male wage ratio;
- Child welfare.

EuroStat explains social benefits as a long-term response indicator of problems related to equity, in particular high levels of unemployment and the growing importance of older citizens in the labor force.

On the issue of the social dimension of Sustainable Development, a workshop of the presidents of the Brussels EU-chapter of the club of Rome and the Factor 10 Institute states that (European Commission 2002): “Only a fair share of resources, development opportunities for all and a perspective for global equity can open up the door for global contracts of restraint within ecological sound limits."

Overviewing the issues that are considered to be related to the outcome of interest equity, the one issue that innovative aviation technology seems to be able to directly influence is the issue of resources. Aviation makes use of scarce resources in terms of construction materials, land, and crude oil products. A bit more exotic, is the noise and gas emission issue, since aviation uses parts of the very scarce source of silence and clean air close to airports by making noise and emitting gases during flight operations.

It is questionable if innovative aviation technology can directly influence the access and equal distribution of those resources within one generation, though, no doubt, aviation technology will influence the quantity of the resources. In relation to that, it seems appropriate that less use of the resource is not counteracting the desire for access and equal distribution of resources when it comes to equity within generations, and that it is directly contributing to equity between generations by leaving more of the resource available for the future.

Indicators for the use of resources are designed under the outcomes of interest PL2 (Resource use), PL3 (Impact) on land, and PL4 (Noise impact).

While the literature does not provide very precise clues to what is important for the particular case of aviation technology and Sustainable Development, let's have a general look at the aviation system to see where possible inequities are. The effects of aviation can be split into two parts: (1) positive or desired effects (like fast and cheap transport all over the world) and, (2) negative, adverse effects (like noise, gas emissions, and contribution to climate change). Inequities are present when either no equal access to the positive effects is present, or the negative effects are more experienced by one group of people than by another.

In its current state, both parts of inequity are found in the aviation system. The developed countries have a disproportionate large share of access to the aviation system compared to the developing nations. Similarly, the local negative effects (noise, local air quality) are also felt more by these developed countries. However, the global effects of climate change and resource use are distributed over all nations, also the ones that hardly make use of the aviation system.

Again innovative aviation technology can increase the positive effects (more access, faster travel, and lower fares) and reduce the negative ones (less noise, less fuel use, and less emission of harmful substances). For *inter*generational equity, this is precisely what is desired, since reducing the negative effects that have a long term effect (like resource use and climate change) give a more equal spread of these negative effects over the different generations. However, for *intra*generational equity it does not seem plausible that technological changes will influence the distribution of the positive and negative effects of aviation; that is a matter of politics and power.

Concluding, the indicators for intergenerational equity will be addressed by the environmental outcomes of interest PL2 through PL4, while for the intragenerational equity no indicators could be identified.

PE5: Fairness

While in the EU adopted definition of Sustainable Transport the word ‘fair’ is used, in other publications of the EU, and, also in publications of the UN-CSD, the term is almost absent. On one particular page, the UN-CSD hits at the term and states (UN-CSD, 2001, p.20): “Equity involves the degree of fairness and inclusiveness with which resources are distributed, opportunities afforded, and decisions made.” Fairness seems to be related to a certain level of access to and influence on resources, opportunities and decisionmaking. In that light, the addition by INFRAS (2000) that a transport system should offer people choice and that they should be able to have influence on decisions made about that transport system makes sense.

The difference between fairness and equity, according to the UN-CSD statement, seems to be that fairness accounts for the fact that different people (groups, societies, generations) have access to and influence on something. Equity then relates to this access and influence as it requests access and influence in a comparable way. UN-CSD (2001, p.20) states: “[Fairness and inclusiveness] includes the provision of comparable opportunities of employment and social services...” Though, given this statement, it seems that fairness is somehow included as a prerequisite for equity, some specific notions need to be further discussed here.

Fairness in terms of the possibility that people have access to resources, opportunities, and decisionmaking in the light of transport and aviation means that the transport system must be accessible. This issue is covered in the outcome of interest ‘Access’ (both PL1 and PR1).

Fairness in terms of the possibility to influence decisions around the transport system is related to how a society organizes itself. In very hierarchically-led countries, leaders might (or should) take the interest of the people into account, but no direct influence is present. In the UN-CSD statement, this is unfair. In liberal countries, people can have influence via the free market forces. This is then called fair, although equity is not served, as not everyone in a free market will have the same opportunities to have influence. For this study, it is not likely that the introduction of innovative aviation technology will influence the way a society organizes itself, so for this particular issue no indicators will be included in the list.

Fairness in terms of offering choice in an aviation system will be applicable to people who make use of that system: the passengers. Offering choice can then be described within the system, but also in between systems. The last one meaning that passengers can for their trip choose among different modes of transport. This issue is covered in the outcome of interest ‘Competitive economy’ (PR4). Within the system, choice is provided to people if they can choose among different airlines and/or different types of aircraft flying the same routes. Different airlines as well as different types of aircraft may have a different effect on ticket price, comfort, environmental burden, etc. The number of airlines in operation is also covered in outcome of interest PR4, but the different technologies are not. This is precisely an issue that the introduction of innovative aviation technologies can and will have influence on. Therefore, as an issue related to fairness, an indicator measuring the different types of aircraft flying around is introduced here (Table 3.8).

Fairness as described above also appears to have strong links with the term openness or transparency, since offering choice and influencing decisionmaking requires a certain level of transparency for anyone involved. Seen in that light, regulatory issues that are currently important in aviation, such as open skies agreements requiring regulatory transparency, are also part of the outcome of interest “fairness”. As discussed earlier in this chapter, that part of the system technology can influence is outside the part in which decisions are made about regulatory issues, so no indicator for regulatory transparency is included in the list.

Code	Outcome indicator	Unit	Desired direction of change
PE5-1	Different type of aircraft in service	#	increase

Table 3.8. Indicator as a result of the outcome of interest “Fairness” (PE5).

3.5.2 Environmental criteria (“Planet”)

PL1: Ecosystem health

According to the EU definition of what sustainable transport is, the EU is very clear on the ecosystem health issue: “[Sustainable Transport should] limit emissions and waste within the planet’s ability to absorb them”. INFRAS (2000) adds to this the issue of climate change and air pollution.

Aviation activities produce emissions and waste of different types. According to Tempelman, by far (>97%) the most ecosystem burdening activity is the actual flying due to the production of gas emissions (Tempelman 1998). So, in this analysis, measuring ecosystem health when it comes to the aviation system is limited to the emission of gases.

Aircraft emit gases with local effects near airports, during their LTO cycle. Locally, it is specific emissions that can be very harmful for organisms. CO is an example, as are NO_x and VOCs. CO_2 is also emitted, but from a local perspective, close to the ground, CO_2 is more a nutrition than something hazardous.

Because aircraft in LTO cycles have very low power settings, the engines run far from optimal revolutions per minute and have relatively bad burning characteristics. This means that the percentage of non-CO_2 gasses in the emissions is relatively high.

Indicators measuring the exhaust of these types of gases are well covered in the outcome of interest “Human health” (PE3). What is covered there is that less of each of these harmful gases is contributing to Sustainable Development. What is not covered is the notion that the emissions should stay within “the planet’s ability to absorb them”. As ecosystems have a very dynamic character, also their ability to absorb harmful gases differs in time, and, differs due to earlier emissions of gases in that ecosystem. Ecosystems can build more ability to absorb unfamiliar and hazardous substances over time, but usually at the cost of reductions in biodiversity. It is therefore hard to define strict constraints with respect to when an ecosystem becomes uncapable of absorbing the emitted gas. No indicator for this particular issue is therefore included in the list.

Aircraft also emit gases with global effects. In fact, most aircraft emissions take place high up in the atmosphere and have only global effects. The big global issue that aircraft in cruise flight influence with their gas emissions is climate change. INFRAS (2000) already added climate change directly as an issue for sustainable aviation, but it is also related to the issue of ecosystem health, since climate change is expected to have severe effects on ecosystems (IPCC 1999).

According to the IPCC (1999), CO_2 is the most important gas emitted by aircraft that has influence on climate change. With respect to other gases, the quantity is much smaller, the effects are not well-known yet, or, the effects on climate change are not very large. For the issue of emitting CO_2, an indicator is added to the list (Table 3.9).

Code	Outcome indicator	Unit	Desired direction of change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	decrease

Table 3.9. Indicators related to the outcome of interest "Ecosystem health" (PL1).

PL2: Resource use

A rough material and energy flow analysis for aviation reveals that the aircraft system uses the following resources (Tempelman 1998): construction materials, maintenance goods, and crude oil products flowing into the system, while old aircraft are scrapped and gas emissions are produced in flight operations, resulting in waste production coming out of the system.

The most used material for construction is aluminum. Plastics and hybrid materials such as GLARE (glass fiber reinforced) metals, are used more often, although their total share is still very small. In aircraft engines, more expensive and rarer materials are used, since specific material behavior is required in high temperature, high pressure, high air speed surroundings. The interior of aircraft require different metals, plastics and glass fibers for the wiring and flight instruments. The cabin interior is mainly composed of plastics with fire resisting or fire delaying characteristics. For aircraft maintenance all kind of products are used, ranging from crude oil (like oil in engines' moving parts) to de-icing fluids to clear the wings from ice prior to take off.

The use phase of aircraft (that is flying them) requires energy that nowadays is taken out of the crude oil product kerosene. Kerosene is burned in engines, either to rotate propellers that produce thrust or to create a backward directed high speed stream of air (in jet engines) to get thrust. Either way, gas emissions are produced, mainly CO_2, but also smaller quantities of H_20, CO, NO_x, and VOCs.

Categorizing these issues into renewables and non-renewables, there is not much material and resource use within aviation that can be categorized as "renewable". All crude oil products are non-renewable, as are the plastics and hybrid materials. The aluminum that is used in the construction can be used for other purposes after its use in aircraft, but the other way around is not possible. For safety reasons, only non-recycled, "virgin" material is allowed to be used in aircraft construction. This is to avoid voids and encapsulated "foreign" materials in the aluminum (or other construction material) that could reduce its static and/or fatigue strength. In addition, recycling is by far not renewable, as serious effort (and thus energy) has to be put into wasted material to make usable recycled material from which new products can be made.

Studies indicate that more than 97% of the environmental non-sustainability of aircraft is not caused by energy and material use in the construction phase, but in the use phase (Tempelman 1998). During this phase, energy from the non-renewable crude oil source is converted into kinetic energy due to burning fuel. As systems analysis is about the larger changes (for several reasons, the small differences are of less interest), it seems plausible to focus the discussion on renewables to the use of fuels, and to abandon any further analysis of construction materials.

Kerosene contains energy that has been accumulated by plants via photosynthesis and then fossilized over millions of years. This energy is released when kerosene burns, but there are also other products of this chemical oxidation reaction, among others CO_2. In principle, plants use this CO_2 from the atmosphere to grow. In a very slow process of fossilization, the remains of these plants can form crude oil again if the right circumstances are present. As the process by which plants take CO_2 from the atmosphere and fossilize is billions times slower than the current rate at which crude oil is burned, crude oil cannot be called a renewable resource. Bringing much more carbon into the atmosphere than the plants subtract from it will reduce the size of the source of crude oil (and also cause other undesired effects, such as climate change).

The EU takes the use of hydrogen as a serious candidate to replace crude oil. Hydrogen acts as an energy carrier (as oil is too), but without the negative effects of non-renewability (and pollution and climate change). In principle, the problem of non-renewability can be solved using hydrogen. Releasing the energy from hydrogen by burning will produce water, and water can be used to produce hydrogen. When solar, wind, or tidal energy is used to convert water into hydrogen, it really can be a renewable resource of energy. However, when, as is currently the case, fossil fuels are used for this conversion, the production of hydrogen uses up another resource (fossil fuel) and thus makes it non-renewable.

Using hydrogen in combination with solar, wind, or water energy sources seems very promising for down-to-earth processes, like driving cars, in which mobile energy sources are required. Water is all around us and in large enough quantities that human use of it for energy carrying activities will not change this situation.

However, using hydrogen for aviation activities might have some effects that are undesired. The problem might be that water is emitted at high altitudes where there is currently not much. Also water molecules are, just as CO_2 molecules, capable of capturing radiated heat from the Earth's surface. Water at such altitudes may therefore contribute to climate change.

Also, other options than hydrogen may be considered. To indicate the usage of renewable fuel resources, a percentage indicator will be used in the analysis. Every type of fuel will have its own score on renewability. For crude oil products, this is practically 0%. For hydrogen it is potentially very high (depending on what process is used for the generation of hydrogen).

In a sense, more abstract outcomes, such as silence and clean air, can also be seen as resources. At least their presence in today's industrialized world is scarce and aviation generally reduces the amount of silence and clean air. It is debatable whether these two issues can be seen as renewable or not. Indeed it is true that, in the absence of aircraft noise, silence recovers quickly to its full potential and also local air quality might quickly increase. That, however, may not be a reason to make infinite use of it, since it is clear that less noise and better air quality are desired from a sustainability point of view. As both issues are further covered under PE3 Human health and PL4 noise, they are not considered any further in this section.

The indicator resulting from the outcome of interest "Resource Use" in the technological aviation system is listed in Table 3.10.

Code	Outcome indicator	Unit	Desired direction of change
PL2-1	Percentage of renewable fuel of the total amount of fuel used	% (ton renewables / total tons of fuel)	increase

Table 3.10. Indicator related to the outcome of interest "Resource use" (PL2).

PL3: Impact on land

In contrast to road and rail transport, aviation does not need an elaborate infrastructure on land linking all geographic places of interest. Its land use is concentrated in specific areas, usually not too far away from major cities. Despite ideas like in the Netherlands to build airports further away from the city (to reduce noise hindrance) and have fast train connections, only some of these ideas have been realized (e.g. Oslo). Airports require valuable land that can not be used anymore for other purposes. Airports require many square kilometers of land on which runways, aprons, etc. are built, but they also lay a claim on the surrounding area. Due to heavy noise disturbances, no houses can be built close to the airport and high buildings (skyscrapers for offices and international headquarters of firms, for instance) form obstacles for landing and take off routes.

It is therefore important to measure the amount of land that, due to aviation activities, cannot be used for other purposes. For several reasons less land use is positively contributing to Sustainable Development (Table 3.10).

Code	Outcome indicator	Unit	Desired direction of change
PL3-1	Land unavailable for other than aviation purposes	km^2	decrease

Table 3.10. Indicator representing the outcome of interest "Impact on land" (PL3).

PL4: Noise

Aircraft produce noise that seriously deteriorates the quality of life near airports. Aircraft not only produce noise when flying, but also when taxiing or standing at the gate and using their auxiliary power unit to run different aircraft systems. This last part is called apron noise. When flying, aircraft noise originates from the airframe itself and the engines.

Aircraft noise has negative effects on humans. Sleep is disturbed. The human body is generally more aroused when exposed to periodic noise resulting in higher heart rates and higher blood pressure with long term health consequences. Also, negative effects on the body's ability to defend itself against intruders like bacteria or viruses are found.

The hindrance people perceive from being exposed to noise is not the same for everybody and is influenced by several factors, such as culture and lifestyle. European citizens are among the most sensitive to aircraft noise, partly because of their relatively high standard of living and their demand of a nice and comfortable living space, and partly because Europe is among the most densely populated areas in the world with a lot of air traffic that disturbs a lot of individuals.

Noise hindrance is an important reason why a lot of airports cannot grow in terms of aircraft movements while their physical capacity of runways and terminals could easily handle many more passengers. Many airports have noise contours specifying exactly how many aircraft movements can be made per year at what times of the day. Sometimes this has been a reason to rebuild the airport at a place further away from densely populated areas, which happened in, for instance, Oslo, Norway. Also in the Netherlands there have been plans to close down Amsterdam Airport Schiphol and build a completely new airport some kilometers from the coast in the North Sea.

Technology has brought a considerable improvement in the noise performance of aircraft. Varying from new designs for airframes and engines, to so-called hush kits that can be applied to existing aircraft, thereby improving their noise performance. While the noise performance of individual aircraft has drastically improved, the total amount of flight movements has also grown significantly. Therefore, nowadays, noise hindrance is also seen as how often a person is disturbed instead of how much noise each disturbance actually exposes that person to.

The human ear responds differently to different frequencies. Noise measures are, therefore, often expressed in so-called A-weighted decibels. The weight factors stress those parts of the spectrum that the human ear is sensitive to and deemphasizes the rest. The decibel scale is a logarithmic scale; a rise of 10 dB(A) is actually a doubling of the noise level.

The experience of noise is determined by several factors; two important factors are the maximum sound level and its duration. For aviation purposes, a sound exposure level method is introduced that measures all of the sound energy of an event that someone is exposed to. The European standard methodology for measuring aircraft noise is L_{DEN}. L_{DEN} measures the average noise level over a specified time (in dB(A)) with an extra 5 dB(A) for evening noise (e.g. between 19:00h-23:00h) and an extra 10 dB(A) for night noise (e.g. between 23:00h-6:00h).

Geographical places around an airport that exceed a certain chosen level of L_{DEN} dB(A) can be drawn on a map to give a so-called noise contour.

All places outside the contour are exposed to less noise. The contour is often fixed by governmental regulation. Back calculation then gives the opportunities for the airport to operate. Many combinations of numbers of flights, noisiness of aircraft, and timing of flight movements produce the same noise contour. Technology that can reduce noise from aircraft operations can, therefore, be used to reduce the noise contour, increase the number of flights or a combination of both.

The actual noise can be determined in several ways. One that at first glance looks the most obvious is putting microphones around an airport and directly measuring the noise. However simple, this method has its shortcomings. It is for instance not easy to distinguish among noise from aircraft and other traffic. Putting the microphone in the middle of densely populated areas, it is not easy to distinguish the noise from someone shutting the door very hard from real aviation-originated noise. Lots of research has been done to overcome the problems of measuring, and today's technology has improved dramatically using arrays of microphones and sophisticated software technology to analyze the measured data. Another option is to model the noise with programs like the FAA's Integrated Noise Model (INM), which is popular all over the world. Standard patterns of noise for each aircraft type are stored in a data base and, using information on flight schedules, departure routes, and flight altitudes, the software can calculate the noise contour. More elaborate software models have also been developed and applied world wide.

A good indication for noise around an airport is not easy to give, as the use of aircraft play a substantial role in what the noise contour around an airport will look like. Technology studies usually give a percentage of how much more silent a new design is compared to what it replaces. Compared to each other, it is then known how much more or less noise a new design makes. Although it is very likely that this figure will be related to the actual noise contour around an airport, the exact relationship between the two depends on many more factors than this test figure.

Therefore, for this study, the indication for noise will be based on the expected outcome of the given technological design on a standard static noise test, to have a comparison between the different designs and the current technology that is flying around today (Table 3.12).

Code	Outcome indicator	Unit	Desired direction of change
PL4-1	Noise production of specific innovative aviation technology	dB(A)	decrease

Table 3.12. Indicator representing the outcome of interest "Noise" (PL4).

3.5.3 Economic criteria ("Profit")

PR1: Access

Already in the outcome of interest PE1 Access, this issue has been covered for individuals and society in general. The question is whether companies have different interests when it comes to access. Also here, access can be split into economic and physical parts: the money it costs to use the system and the geographic distance to a point from which the system can be entered. While for leisure travelers it might be desirable to have fast connections to and within the aviation system, for business this can be vital to stay in a competitive business economy. Time could sometimes outweigh price. In essence, the objectives for business and leisure travelers are not very different, so the indicators representing this outcome of interest are all already covered under that part of this outcome of interest that has been covered under "Planet" with code "PL1 Access", in Table 3.2.

PR2: Affordability

In the third part of the EU transport policy White Paper (European Commission 2001) it is clearly stated that "users ... need to be put back at the heart of transport policy", as "...everyone should enjoy a transport system that meets their needs and expectations". The European Commission states that it is necessary that everybody involved in the transport system should be aware of the complete costs of the use of infrastructure, tackling pollution, and congestion. Behind this is no doubt the idea of "users and thus polluters pay".

Affordability has several aspects: the price users pay for transport, but also affordable for the providers of transport and for society as a whole who experience the negative effects of congestion and pollution. The European Commission states that all these interests can best be obtained by the "transparency and coherence" that is the result of "say[ing] exactly what these costs are".

The influence that innovative aviation technology has on the issue of affordability lies in the costs that the use of these technologies will have. Directly, for the transport provider (airline) via the Direct Operating Costs (DOC) (Table 3.13). More indirectly, the end user (traveler) will experience a certain ticket price (Indicator PE1-3) that will partly be influenced by DOC, in combination with issues like crude oil price. Whether aviation is affordable to society in terms of pollution and congestion is covered under outcome of interest PE3 Human health and PL1 Ecosystem health.

Code	Outcome indicator	Unit	Desired direction of change
PR2-1	Direct operating cost	€/year	decrease

Table 3.13. Indicator representing the outcome of interest "Affordability" (PR2).

PR3: Competitive economy

References to competitiveness in the literature often point to GDP as the measure for competitiveness of the economy. The competition element of competitiveness then seems to be between economies (who has the highest GDP) rather than within. However, it is also argued that internal competition for the customer in a free, liberal economy will boost the quality of products and services while reducing prices at the same time. Within the EU region a clear goal is set to reach number 1 in the ranking of most competitive economies in the world by 2010. Boosting GDP is suggested to be done by stimulating certain activities in the region, among which innovative technology development is one. New technologies are expected to deliver product and services of higher quality at lower cost and less environmental burden.

The world economic forum (WEF) periodically publishes a ranking of most competitive economies in the world. Indeed, their ranking has a correlation with GDP, but it is not GDP that determines the ranking. The “Growth Competitive Index” used by the WEF is composed of three parts: a technology index, a public institutions index, and a macroeconomic environment index. Parts of these indices are determined by using publicly available hard data, other parts are determined by survey questioning among experts around the world.

While the non-technological indices are composed of factors such as contracts, law, corruption, stability, investments, and governmental spending (on which technology has no direct influence), the technology index is composed of innovation, transfer, and information/communication. Within the technology index, a lot of attention is paid to the amount of innovation through expenditures on R&D, both from within the country, as from so-called foreign investment, and from collaboration with research institutes, such as universities.

The combination of these several figures are used as representatives of the competitiveness of an economy compared to other economies. The WEF also clearly indicates the importance of internal competition in order to keep quality and reliability of products and services high at affordable prices.

Relating to innovative aviation technology it seems that more innovations is positively contributing. However, it should be noted that competitiveness is made up out of many indicators. Technology alone influences especially this particular indicator of innovation. Also, competition for the customer appears to have positive effects, for instance on prices (indicator PE1-3).

Competitiveness within the aviation industry cannot be expected between the several aircraft manufacturers. There are only two major manufacturers for civil aircraft left, and both are very cautious when it comes to new projects, since one mistake could put the whole company out of business. In addition, the governments see an aircraft industry as an important contributor to overall knowledge and to the economy. Subsidizing is forbidden by international agreements, but there is still money flowing from the governments to the industry, though under another label. The US sponsors military research programs that have also application possibilities in the civil area and the EU stimulates overall research and development under their “Framework” programs.

In their white paper the European Commission describes that an important part of competitiveness is offering choice to customers. It is not likely that offering choice to aircraft passengers is offered by the different number of aircraft type that fly around, nor that the different services that different airlines offer their passengers are highly influenced by introducing new technology in the aviation system. A choice that a traveler has is the modal choice. Intercontinental flights don’t have much modal choice as the ship is not replacing aircraft and also long train rides (like the famous 7 day trans Siberian trip) are not a replacement for the aircraft. Continental flights, however, are much shorter and their there is a possibility for modal choice as high speed trains may be an alternative. The issue then is that the existence of other modes than aircraft are influenced by technology, but not by innovative aircraft technology. Therefore, no indicator for model choice will be included in the list.

Code	Outcome indicator	Unit	Desired direction of change
PR3-1	Number of innovative aviation technologies in use worldwide	#	increase

Table 3.14. Indicator representing the outcome of interest “Competitive economy” (PR3).

PR4: Regional developments

Within the EU region, there is a policy to stimulate local development, as a force to support the competitiveness of the whole region. The three themes the EU supports by funding suggested projects are technological innovation, ICT, and energy/waste management. The idea is that local people on a small scale can best organize projects that are perfectly in line with local habits, culture, needs, and possibilities.

Here, also, a region’s competitiveness is measured in local GDP. This measurement is not very useful to determine the contribution of innovative aviation technologies, as there are many non-technological factors influencing this figure.

Local aeronautical developments happen in very specific regions spread over Europe and as not many institutes are involved it will contribute more to the EU’s overall competitiveness rather than a spreading of competitiveness equally over Europe. However, the services provided by a working aviation system through local air fields immediately make more local developments possible. All over the world, regional airfields attract activity, and developments of all kind usually take place around airports. Increasing the number of local airports will positively influence regional development. It is the EU policy to especially promote this in the poorer regions of the EU. Both issues are well covered in outcome of interest PE1 Access, so no additional indicators are included in the total list for the outcome of interest “Regional developments”.

3.5.4 Summarizing the set of outcome indicators for the problem owner

In the following Table 3.15, the indictors for each of the three elements of Sustainable Development (social, environmental and economic) are summarized for the actor problem owner, based on the discussions in the previous sections 3.5.1, 3.5.2 and 3.5.3.

Code	Outcome indicator	Unit	Desired 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

Table 3.15. Indictors specified for the concept of Sustainable Development as objective of the problem owner.

3.6 Other system actors and stakeholders, and their objectives

3.6.1 Introduction

So far in this chapter, we have paid attention to the objective of the problem owner only. In a systems analysis, the problem owner is the central actor and determines the perspective of the analysis. The problem is formulated from the perspective of the problem owner and all his or her objectives are translated into measurable indicators. That does not mean that other actors or stakeholders in the system are neglected. Ethics requires all actors' and stakeholders' objectives to be included in the analysis. In addition to moral reasoning, there are very practical reasons why other than the problems owner objectives should be included in the analysis and presented to the problem owner. The problem itself, for instance, is often determined by the desire of the problem owner to make changes, but has the dilemma that other actors than the problem owner will experience so much negative consequences that the initially proposed "solution" can not be implemented, will elicit lots of protest or several parties end up in court for years of legal fights.

In order not to forget actors and stakeholders the following general questions on actors and stakeholders have been answered (Enserink et al. 2002).

- What actors are actively involved in the problem?;
- What actors can be involved in either the origin or the solution to the problem?;
- What actors have resources that can be important for the problem?;
- What actors can be expected to have the desire to be involved in the problem?, and;
- What stakeholders, not actively participating in the problem, will be influenced by the problem?

Answering these questions resulted in the following list of actors and stakeholders who are involved in or influenced by the problem:

- Governments;
- Airlines;
- Aircraft Manufacturers;
- Airports;
- Air traffic control;
- Persons living near airports, and;
- Air travelers.

For each of these actors, their objectives and the relation of these objectives with the already discussed concept of Sustainable Development will be discussed in a separate section.

3.6.2 Governments

Governments have had enormous influence on their particular flag carrier in the past. The national airline was long seen as “the pride of the nation”. Some of that is left today, as one can see for instance during the discussions in the Netherlands about the merger of the Royal Dutch Airline KLM with Air France. Governments sponsored their airline and in return the airline served routes to for instance (former) colonies of that particular nation (Dierikx 1999).

Nowadays, airlines (as well as airports) are more and more privatized and a direct relation with the national government is not that well present anymore. However, governments still have some influence on aviation in general within their territory via their National Aviation Authorities. In addition to that there is still something left of the pride for the national flag carrier. Though international regulations on the concept of free markets forbid any support from the government to a national flag carrier, still a desire to keep the national flag carrier literally in the air exists.

Any direct stakes that the government officially might have, are the preservation of safety and environment in its airspace. Governments like to support the development of their main airports into even larger hubs, for instance through making their airports more attractive by reducing congestion. There is a strong general belief that large hub airports are a necessity within a country’s territory, as they are believed to have a net positive effect on a nation’s economy.

These two objectives however are in conflict: growth in the sector normally increases the environmental burden in terms of gas emissions and noise. This contradiction lies at the heart of the problem formulation for this research, in which the benefits of aviation should be kept or even enlarged, while reducing the negative, undesired effects.

For a government, also the general issue of preserving (or even increasing) the total amount of jobs can be a stake, though that is not typical for the aviation industry. This job preservation is however often mentioned when discussions in politics take place about the growth desires of airports in relation to the negative consequences (noise, air quality deterioration, external safety) that has on the surroundings.

Comparing the content of governmental publications (of EU member states) with European publications (e.g. by the European Commission), it appears that, in general, the objectives of European countries are not so much different when it comes to aviation than the overall vision of the European Union. The need for growth of the aviation sector is elaborately stressed in many documents. However, there is no clear description of what exactly the size is of the net benefits of that growth to national economies.

The concerns for safety and environmental issues like noise and air quality are also present in both national and European publications. The issue of climate change and aviation, also related to gas emissions, like local air quality, is however not so elaborately addressed.

Differences between national objectives and European objectives lie in typical national interests, like local industry support or the existence of a national flag carrier. This research assumes that issues like these are of a political kind and not directly influenced by the introduction of innovative technology in the aviation system.

As a result of this section, for the actor “governments”, no extra objectives could be identified that can be influenced by innovative technology and are not already covered in the existing list of criteria of the problem owner as listed in Table 3.15.

3.6.3 Airlines

What today’s commercial airlines want to achieve, might be summarized by the mission statement of Royal Dutch Airlines KLM:

> *“By striving to attain excellence as an airline and by participating in the world's most successful airline alliance, KLM intends to generate value for its customers, employees and shareholders”* (KLM 2003).

Other airlines have similar statements. For example, British Airways states that

> *“’The BA way’ is the active engagement and support of all our stakeholders – investors, employees, customers and the communities in which we operate”* (BA 2005).

Under the heading of “Shouldering Responsibility – Keeping a Balance”, Lufthansa Group states an excerpt of their mission statement on their Website:

> *“Service is our vocation. Our staff constitute our most important asset. As an attractive employer of present and future staff, we endeavour to offer our employees job security, good working conditions, career opportunities and convincing corporate ethics. Our staff honour that endeavour with customer-friendly service and thereby underpin future growth.*
>
> *We are committed to creating sustainable value for our investors. The norms are set by the capital market. We aim at a performance level that stands as a benchmark for the European airline industry.*
>
> *Business success does not rule out a corporate policy geared to sustainable development and care for the environment. We are fully committed to keeping a balance between them. Protecting the environment is therefore a prime corporate objective, to which we subscribe with total conviction.”* (Lufthansa 2006)

“Generating value” as in KLM’s mission statement is indeed, as also the Lufthanse statement shows, much different for the different groups mentioned: customers, employees, and shareholders. Customers would like many good connections, good service, not too high ticket prices, and no delays. Employees would like good working conditions, security in their jobs, and good pay. Shareholders might be interested only in the final result of the company, (“return on investment”) related to the level of profit the company makes.

The issues of good working conditions, good pay, and attention for the environment are policy decisions that might be possible through the application of new technologies. Companies in general have as main goal to stay in business. This is determined by their net profit result at the end of the year. This result is, in turn, influenced by the mentioned issues like working conditions, good services to customers, ticket prices, etc.

Making profit is directly related to some more detailed objectives, such as (de Neufville and Odoni 2003; KLM 2003; Upham et al. 2003; BA 2005):

- Low congestion at airports: making it possible to fly according to schedule;
- Low direct operating costs (DOC): costs that are inevitably related to the type of aircraft the airline is flying;
- Low airport fees;
- High load factors: maximizing the number of passengers in each aircraft to make use of the available seats as much as possible;
- Small turnaround times: all the time an aircraft is not flying, it is not earning money; small times between landing at an airport and taking off again highly influence the overall profit. Low cost carriers have appeared to be masters in reducing turnaround times to the minimum, and;
- No dramatic changes in aircraft operations and maintenance.

Comparing these issues to what has been covered already by the objectives of the problem owner, clearly the issue of cost has been covered. New are the issues related to congestion at airports and changes in the design. Load factor and airport fees are seen as issues that cannot be influenced by the introduction of aircraft related technology in the system, but more that of an airline’s and airport’s policy to attract customers.

Table 3.16 summarizes the indicators that relate to the objectives of airlines and are not yet covered by the existing list of indicators of the problem owner.

Code	Outcome indicator	Unit	Desired direction of change or desired value
ASI2-1	Percentage of flights leaving the airport according to schedule	% (# flights on time / total # flights)	increase
ASI2-2	Average turn around time	minutes	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

Table 3.16. Indicators related to objectives of airlines in addition to the existing objectives of the problem owner. *(ASI = **A**dditional **S**takeholder **I**ndicator.)*

3.6.4 Aircraft Manufacturers

Only two major manufacturers of large civil aircraft are present today: in Europe Airbus Industries and in the United States the Boeing corporation.

Airbus defines its mission as:

> *"Our mission is to provide the aircraft best suited to the market's needs and to support these aircraft with the highest quality of service"* (Airbus 2004)

While Boeing sees it's strategy more as:

> *"Running healthy core business, leveraging our strengths into new products, and opening new frontiers"* (Boeing 2001)

These are clearly statements that could hold true for all kinds of commercial activities, though Airbus is more focused and concrete on what its market is (aircraft, aviation). Central theme is delivering what the market wants to have and constantly improving what is available. This all seems to be the means to the end objective of having a profitable company.

There is a dilemma between making a good profit and "opening up new frontiers" or "delivering the best suited aircraft". Most profitable would be simply selling what is already available off the shelves. If markets change, new product development will be necessary to keep up the sales, but new product development definitely is not a goal in itself if one has profit as a higher goal. New designs require investments and include risks for the manufacturer; the manufacturer that tries to increase profit will only take that risk if the market requires new products. Therefore, as outcomes of interest to the manufacturers, the criterion "No big changes to existing designs" is included.

A tricky item has always been governmental support for large companies. Officially, this is not allowed, as it is seen as an unfair intervention in a free market economy. But some industries (and the aviation industry is one of them) have to invest so much money for developing new products, that the corporation might be bankrupt if the project fails.

Through the European Commission's Framework Projects, enterprises from Europe can get money for research that contributes to reaching the goals the EU has for its member states. It can be either supporting new policy measures that the Parliament wants to take, or research on topics that the Parliament wants to be seen achieved in the EU, like no air travel congestion or safe tunnels for road transport. Officially this is not governmental support, but it can help companies in reducing risk.

In the United States, Boeing receives governmental orders for defense materials. Research done for defense can later be used in civil products for the free market. This also is not officially governmental support, but again, the company gets help in spreading risks for new developments.

Support for risky projects is definitely an important interest for the manufacturers, although care has to be taken in which form it appears to the companies. International law prohibits direct supports and watches very carefully if research funding and defense orders are really meant that way, or are used to strengthen market position at the cost of the other players.

Code	Outcome indicator	Unit	Desired value
ASI3-1	Design risk of innovative technology	small/medium/substantial	small

Table 3.17. Indicators related to additional objectives of aircraft manufacturers in addition to the existing objectives of the problem owner.

3.6.5 Airports

Airports depend upon passengers for their income and depend upon local and national governments for their environmental capacity, as governments tend to set boundaries for noise. To a certain extend they are responsible for their physical capacity. However, building extra buildings or runways usually requires extensive negotiations between government and the airport.

Strangely, at first sight, airports appear to generate more money with selling goods in tax-free shops than with the actual handling of aircraft. In addition to shops and airport fees for handling aircraft, real estate is generating income for airports as well (de Neufville and Odoni 2003).

A group of passengers called transfer passengers fly into an airport only to change planes. There are different opinions on the role of airports that serve the highest amount of transfer passengers, namely the big international hub airports. To some, hub airports are the pivots of the aviation activities now and in the future (the so-called hub-and-spoke system); given the ideas for very large aircraft, Airbus would be among these. To others, like Boeing, the big hubs will gradually disappear and most people will travel directly from the airport of origin to the airport of final destination (the so-called point-to-point system). If the point-to-point system would indeed take over the nowadays outside the US widely spread hub-and-spoke system, large hub airports will have to reconsider how they will maintain their income if the amount of transfer passengers decreases substantially.

Congestion is a special topic for airports, lots of air travelers experience it on many flights each day. Congestion can be influenced using different aviation technology and can be measured by the time aircraft need to stay at the gate for unloading, refueling, safety checks and loading. The objective to reduce congestion is of special interest to airports, since it is a main reason for passengers to choose for a specific airport.

Summarizing, airports would like to have a higher passenger flow. They would like to have fewer restrictions from governments, in order to match their supply much easier with the demand for air travel. A special topic for airports is to reduce congestion. As for all stakeholders, also airports value a high external safety in and around their territory.

The passenger flow is not directly influenced by new technology, but, for instance, by reducing congestion with new technology, also passenger flow will be influenced. In this research however, demand for aviation (number of potential passengers) is a scenario variable. Measuring it would result in measuring preset numbers chosen for these scenario variables, instead of measuring a real effect. Restrictions from government are political issues. It is not the restrictions that change due to new technology, it is the space to operate that new technology can create within the restriction. Setting restrictions itself is a political process, rather than being influenced by new technology. However, new technologies that clearly can perform better can sometimes be the reason to make regulations even stricter, as to increase human well being due to the possibilities of new technology. The issue of safety is well covered already in the list of indicators from the problem owner. What remains is an indicator for congestion. The average turn-around-time is an indicator that represents congestion (indicator AS2-2), as well as is the indicator AS2-1 measuring how many flights leave the airport according to schedule.

3.5.6 Air traffic control

The Dutch Air Traffic Control (LVNL: Luchtverkeersleiding Nederland) defines its mission as being “Safety, Efficiency and Environment,” meaning that air traffic control should contribute to a safe operation of aircraft, that ATC should generate low costs for airlines, contribute to less congestion, and that ATC should also contribute to a smaller impact on the environment (in noise and gas emissions) by aviation activities (LVNL 2006).

Assuming that other air traffic control institutions in the world have comparable objectives, each of these objectives have already been well covered in the list of indicators of the problem owner.

3.5.7 Citizens living near airports

Worldwide, people living close to airports experience direct adverse effects of flying, mainly in the presence of noise. Continuous presence of noise makes conversations less easy, leads to concentration problems and sleep disturbances and to an overall raise in stress level (IPCC 1999; Upham et al. 2003).

In addition to noise, the fear of crashing aircraft is present too. The take-off and landing phases are the most critical procedures in a flight cycle and both happen near and on airports around which many people live. High levels of external safety, that is safety for the people on the ground, are highly welcomed in the surrounding of airports (de Neufville and Odoni 2003).

A third issue is the local air quality. Around airports, one can experience the typical smell of burned kerosene. Apart from the bad smell, the direct surroundings of airfields have higher quantities of potentially harmful substances in the air. No doubt these quantities should be lower than those maximally allowed, but, from the people living close to airports, preferably as low as possible (de Neufville and Odoni 2003).

The issues of noise, safety and local air quality are already well covered in the list of indicators of the problem owner.

3.6.8 Air travelers

Easily the most preferred elements of a flight from the perspective of the traveler can be formulated: no delays, lots of possible connections to choose from, low fares, high safety, and simple and fast handling at the airport.

Considering the issues that can be influenced by introducing innovative aviation technology, the congestion, connections, fares, and safety issues are all covered already in the list of indicators of the problem owner. This research assumes that the handling at the airport is influenced by other factors than aviation technology, for instance the vision of the CEO of an airport on how the airport should develop in the future and in what projects money should be invested.

3.5.9 Summarizing the list of indicators for additional actors and stakeholders

In the following figure (Table 3.18), the indictors for all other than problem owner major actors and stakeholders are specified.

Code	Outcome indicator	Unit	Desired direction of change or desired value
ASI2-1	Percentage of flights leaving the airport according to schedule	% (# flights on time / total # flights)	increase
ASI2-2	Average turn around time	minute	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

Table 3.18. Indicators specified for the other than problem owner actors and stakeholders.

In two tables (Table 3.15 and Table 3.18), the concept of Sustainable Development, being the major objective of the problem owner, has been operationalized regarding the influence of new, aircraft related technologies. In chapter 4, the identified aircraft related technologies are presented, each in an own section. Their effects will be explained on the issues that are of importance to the concept of Sustainable Development, by using the indicators identified in this chapter. In chapter 6 the actual modeling of the effects of new aircraft technology on the identified indicators for Sustainable Development will take place.

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4. Technologies as Policy Measures

4.1 Introduction

Chapter 3 identified the different actors in the aviation system and their interests. It also translates these interests into outcome indicators. Now that we know what indicators are important, we need to score alternative technologies on these indicators.

This chapter identifies several aircraft related technological developments that are expected to come, that are expected to have large influence on either the aviation system as a whole, or Sustainable Development in particular.

In order to have any chance of making a real contribution to Sustainable Development, the technologies will have to be more innovative than those recently implemented. For example, emission models used to estimate future aviation emissions by incorporating a historical trend in technological developments, since technology has shown substantial efficiency increases in the past. Typical values used are a 1 to 1.3% reduction in emissions per flown seat kilometer per year (IPCC 1999; Upham et al. 2003). Although these emission reductions are substantial, given average air travel demand growth expectations of roughly 5% per year (Airbus 2004), they imply that technology in its normal pace of development will not be sufficient to keep up with the growth of the sector. Given normal (i.e. historical) technological improvements, the situation from an emissions point of view, will every year deteriorate, resulting in negative effects on local air quality and an increasing contribution to climate change.

The task of selecting technologies for the analysis in this research is not an easy one. Definitely, the technologies giving only small increases in performance of the system on the Sustainable Development indicators are of no use. Within a year or so, their benefits are overtaken by air travel demand growth. On the other hand, very radical and extreme ideas (“Beam me up Scotty”) might promise substantial improvements but are technically not (yet) feasible.

Our research has chosen to divide aircraft technology into several categories (airframe, propulsion, etc., see Figure 4.3) and to examine in detail promising technologies in each category for which a serious preliminary design exists. This approach leads to the consideration of a variety of technologies that are promising and technically feasible within the time frame of the research. In making the choice for certain technologies, the research relied on literature and expert interviews.

This chapter starts by discussing radical and incremental changes within a categorization scheme that identifies those places in the aviation system where aircraft technology can be introduced. Second, after a literature scan and interviews, each new selected type of technology (i.e. each possible alternative in the systems analysis) is presented in a separate section, including a short description of its expected positive contribution to elements of Sustainable Development and its expected adverse effects.

4.2 Technological changes: radical or incremental.

In many systems, there is a general tendency to make incremental improvements in existing products and processes. Since the 1950s, when the current civil aircraft design (a cigar-like fuselage with two wings in the middle, and a tail section) was introduced, aircraft have become faster, larger, less noisy, and more fuel efficient (Anderson 1989; Upham et al. 2003; Airbus 2004).

Most of the changes to processes or products have not been large changes. The essence stays the same, but there are some minor modifications. This is similar to the hard-to-tell differences between succeeding versions of software, such as the word processor Microsoft Word. The current aircraft paradigm, is as old as the 1950s. For more than half a century it has been optimized for safety, comfort, and direct operating costs. But every new improvement costs more than the former; the optimization curve will eventually reach a horizontal ceiling (Figure 4.1).

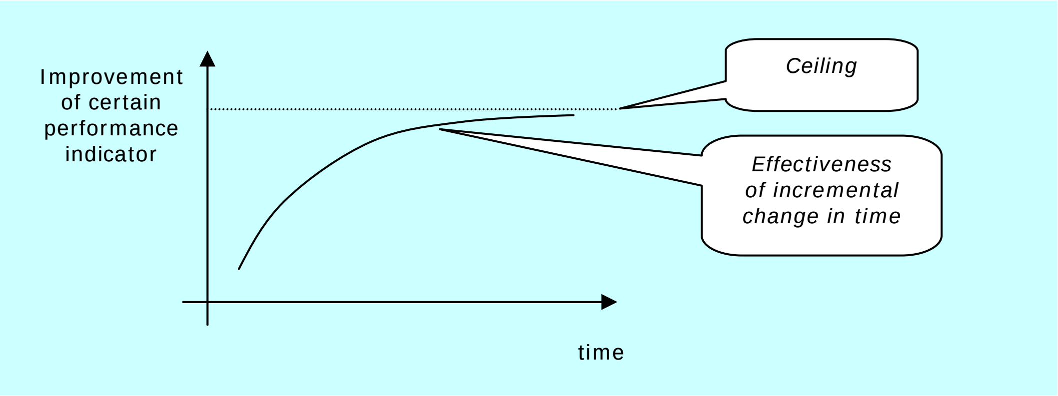

Figure 4.1. For every new development more effort is needed.

If this ceiling is being reached, new paradigms (radical technology changes) might be able to start challenging the status quo in aviation technology, since they may promise improvements within time and cost frames that the current paradigm may never be able to reach (Figure 4.2).

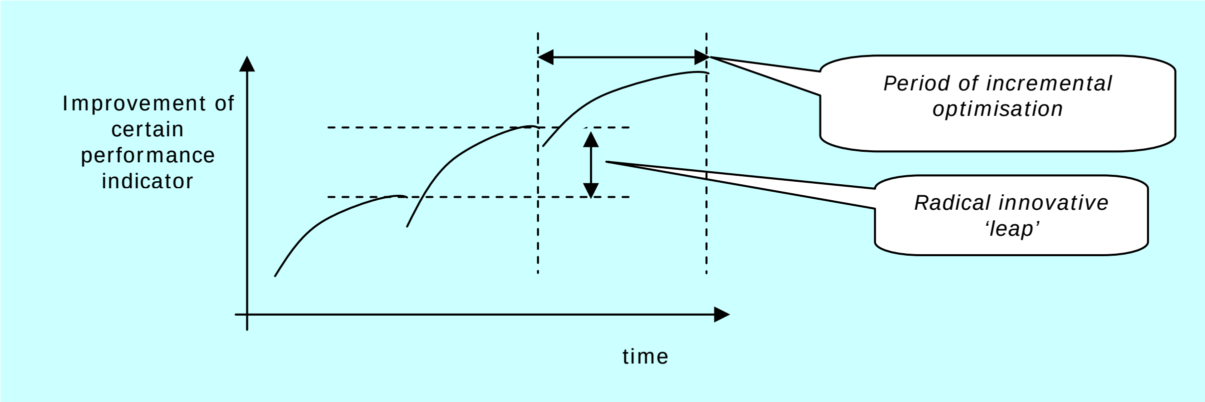

Figure 4.2. Radical innovations can leap technology forward.

Both kinds of changes will be able to contribute to Sustainable Development. However, in the long run more can be expected from radical innovative changes, as it might well be that optimizing current technology is hardly possible anymore since the optimization curve (see Figures 4.1 and 4.2) gets steeper: more and more effort has to be put into the optimization process (de Haan and Mulder 2002). On the other hand, although more radical changes might be more effective, it is by no means clear that these changes can actually be achieved. The risk taken is larger in innovative technologies (Tempelman 1998; Moors 2000). They might pay off more, but at a higher risk. This research therefore, does not focus exclusively on radical technological changes, but also on the less radical ones as well as it pays attention to the problems that occur in the implementation phases of these technologies (see chapter 7).

4.3 Categorizing technologies

In chapter 3, we have used de Neufville and Adoni's distinction between landside and airside to explain the aviation system (de Neufville and Odoni 2003) and identify that part of the system that is studied in this research. Now, some more detail on that system is needed in order to identify categories of technology in which changes can or might occur in the future that are of importance for Sustainable Development.

In the system description in chapter 3 (Figure 3.1) we have shown the parts of the aviation system that aircraft can influence and thus, in which parts of the aviation system technological changes to the aircraft would have their effects.

An aircraft itself can also be characterized as a system consisting of many subsystems. For instance, Moir and Seabridge subtitle their book on aircraft systems "mechanical, electrical, and avionic subsystems integration" (Moir and Seabridge 2001). They further decompose these three subsystems into many sub-subsystems, including the fuel sub-subsystem, the hydraulic sub-subsystem, et cetera.

Anderson makes the distinction between aerodynamics, aircraft performance, stability and control, and propulsion (Anderson 1989). Each of which he elaborates on in different chapters.

It seems that a subsystem called "aircraft structure", combines the mechanical, electrical and part of the avionics susbsystem that Moir and Seabridge write about. Aircraft performance as such does not seem to be a technical subsystem in which one can make technical changes, it is rather a result of the combined outcomes of other subsystems. Anderson however, comes up with three subsystems, aerodynamics, stability and control and propulsion, that in their turn also cover parts of Moir and Seabridge's electrical and avionics subsystem.

Therefore, four subsystems in aircraft in which substantially different technologies can be implemented, are identified in this research. These are:

- Structure;
- Aerodynamics;
- Stability and Control, and;
- Propulsion.

Technologies implemented in any of these four subsystems might have a substantially different focus; it will however still be unavoidable that they influence other subsystems in an aircraft. Applying shark skin on wings might change the aerodynamics of an aircraft, but with it, will also influence the structural components and the way the aircraft is controlled. The main focus however is the aerodynamic change in reducing drag. Therefore applying shark skin on wings would be categorized under aerodynamics.

Some technologies are not of a small scale but change the complete appearance of the aircraft, like Blended Wing Bodies or Flying Cars. These technologies not only influence all four subsystems at once, they are focused on changing the complete aircraft paradigm as it currently exists. These technologies are not categorized in a subsystem of the aircraft system, they are considered to change the aircraft system as such. They are categorized under the label "aircraft system" (see Figure 4.3). Some authors see a shift in paradigm, thus in the whole aircraft system, as a serious option for the not too far future (Torenbeek 2000).

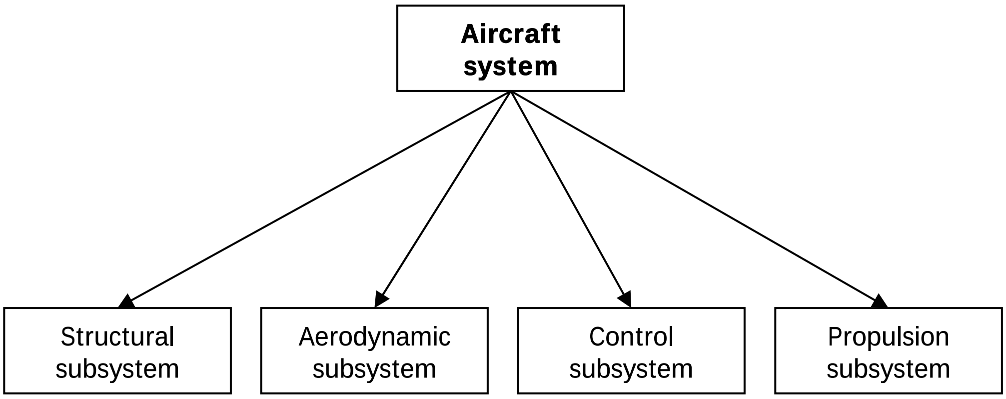

Figure 4.3. Subsystems of the aircraft system

4.4 Technologies influencing the structural subsystem

4.4.1. Introduction

In this section we describe two technologies, the ultra high capacity aircraft and the use of composite materials. Each of these technologies will affect the structural subsystem, as identified in the last paragraph and illustrated in Figure 4.3.

4.4.2 Ultra high capacity aircraft

The starting point for a study on Ultra High Capacity Aircraft is the idea that benefits in cost, noise, and emissions can be gathered by enlarging the scale of aircraft. This study took the largest civil aircraft now being constructed, the Airbus A380, as a starting point. The goal was to design an aircraft for at least 1000 passengers and investigate the benefits, problems, and drawbacks of such a design. The author of this thesis, two colleagues, and ten of our students carried out the design process. The report has been published as the result of a design exercise at the faculty of Aerospace Engineering of Delft University of Technology in June 2001 (Blok et al. 2001).

Four concepts, all scaled-up variants of the A380, were studied:

- Concept 1: Lengthening of the fuselage,
- Concept 2: scaling up of the fuselage,
- Concept 3: making the fuselage circular, and,
- Concept 4: making the fuselage higher to fit three passenger decks.

Enlarging the fuselage of the aircraft gives higher stresses. These stresses do not rise with an equal amount for all four concepts. As a result, the total weight of the aircraft is not equal for all four concepts. In addition, there are huge differences in some important aspects, such as stability, aerodynamics, and safety. In Table 4.1 the masses of the fuselages of each concept are compared when constructed in traditional Aluminum or in the new glass fiber reinforced aluminum GLARE.

concept	Frontal surface	Diameter	Mass fuselage Al2024 [kg]	Mass fuselage Glare III [kg]
A380-100	46,23 m2	24,28 m	23738	19100
Concept 1	46,23 m2	24,28 m	37453	30135
Concept 2	84,28 m2	32,78 m	45003	36210
Concept 3	56,35 m2	26,61 m	34957	28127
Concept 4	67,08 m2	30,28 m	34714	27931

Table 4.1. The masses of the 4 concepts and the current A380-100 design when constructed in Aluminum and Glare.

A comparison of the four concepts mass shows that the three-passenger deck configuration, concept 4 drawn in Figure 4.4, is the most favorable (Blok et al. 2001). This concept was therefore further designed in detail.

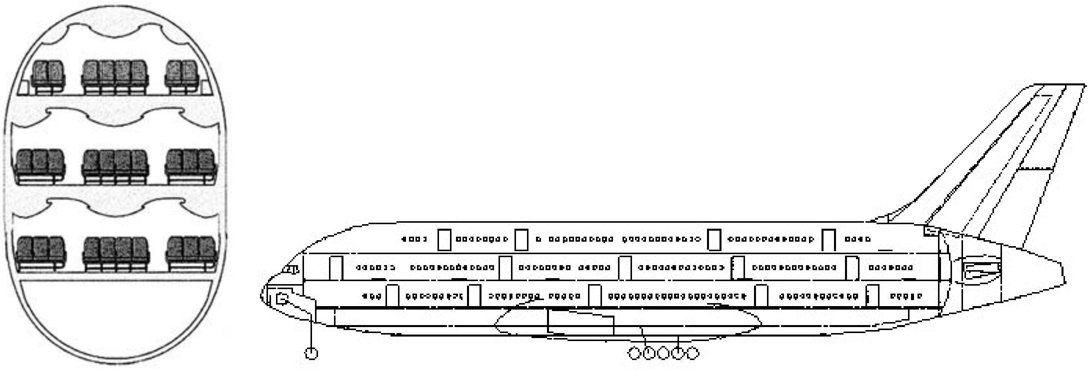

Figure 4.4. The three-passenger deck configuration for 1001 passengers: the A3XL. Left a cross section of the fuselage, with the chair configuration, right an impression of the complete aircraft.

The A3XL is basically a conventional design, with a wing on each side at the middle of the fuselage, and a tail section at the end. Its dimensions however, are non-conventional. It has a length of 76 meters and a maximum take-off weight (MTOW) of 1.1 million kilograms. With a wing span of slightly over 106 meters, it does not meet by far the standard of a maximum size of 80 times 80 meters on which current airfields are designed (ICAO Airport identification code letter F). For its propulsion, the A3XL needs 5 conventional engines of 500 kiloNewton or 4 new 625 kiloNewton producing engines. In its tanks the A3XL can take 357 tons of fuel to give it and its 1001 passengers a range of 17300 km or 19 hours of flight with a speed of 900 km/h. A comparison between the A3XL, the current new A380 and the traditional high capacity aircraft, the B747 is made in Table 4.2. An artistic impression of the aircraft can be seen in Figure 4.5.

	A3XL	A380	B747-8
Length	76 m	73 m	76.4
Wing span	106 m	79.8 m	68.5
MTOW	1100 ton	590 ton	440 ton
Number of Passengers	1001	555	467

Table 4.2. A comparison between the A3XL, the A380 and the B747 on some general aspects.

Figure 4.5. Artistic impression of the A3XL.

For the A3XL (or any type of ultra high capacity aircraft) to operate, the network of the aviation system would have to consist of a few routes carrying lots of passengers. Airbus expects the market to move further toward a hub-and-spoke network in the future, especially on routes within, and connecting to Asia. Cunningham and De Haan found some evidence for that as well (Cunningham and Haan 2006), by identifying 5 super hubs in the aviation system of 2050 (see Figure 4.6).

In their paper, Cunningham and De Haan perform a regression analysis on air travel demand data from the years 1985 to 2002 from the sources Airbus, Boeing, and the World Bank. The air travel demand data is specified per region of the world. The distinguished regions are: Africa, Central America, China, CIS region, Europe, Middle East, North America, North East Asia, Oceania, South America, South East Asia and South West Asia.

Cunningham and De Haan combine this regression model with a model based on the strong link between air travel demand and GNP that has been observed for many years in the past. Future expectation about the development of the GNP for each of the mentioned regions are then assumed to have a strong correlation with air travel demand.

Both approaches (the regression model and the GNP-model) are in moderate agreement in their numerical outcomes. However, both models give a comparable picture about the distribution of air travel demand around the world in the year 2050. This distribution, including the five main super hubs that are predicted by both models, can be seen in Figure 4.6.

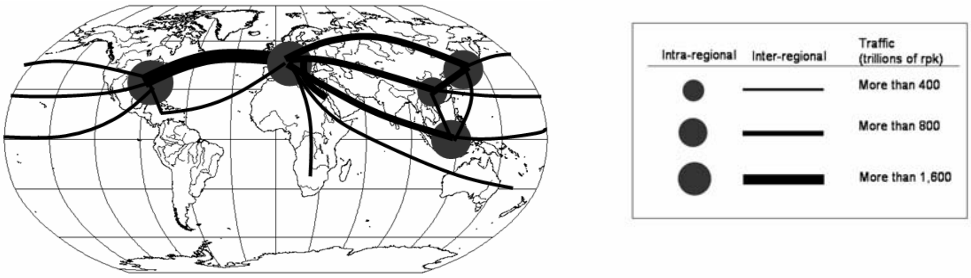

Figure 4.6. World travel network as suggested by Cunningham and De Haan (2006).

As these large routes (with lots of passengers) require a lot of small "feeder routes" (with less passengers to and from central hubs where these passengers can transfer) it is likely to suggest that more places on Earth will be connected than in a system in which there are only point to point connections. However, at the same time, large routes with lots of passengers can also be fed by increasing the number of passengers on existing feeder routes, without introducing new routes. Two major manufacturers of civil aircraft (Airbus and Boeing) differ strongly in their opinion about how the aviation market will develop. Either more direct connections, like Boeing thinks, and which requires lots of mid-size aircraft, or more hubs with feeder lines, as Airbus claims, and which will require ultra high capacity aircraft like the A3XL. This research will therefore not make a final conclusion on this issue. Besides, it is not the technology that will determine the market; it is the market that will determine if such a technology will be operated in it.

Due to scale enlargement, our study predicted a decrease in cost per seat kilometer flown as the number of passengers transported was increased, but the size of the crew does not increase linearly with it. The same holds true for maintenance, catering, air traffic control, apron occupancy, et cetera. Since costs can be cut by roughly 15% compared to the direct operating costs of the A380, a decrease in ticket prices is also possible.

The emissions of one A3XL compared to one A380 will increase, since the A3XL is larger and heavier and thus requires more fuel. The need for fuel increases, but the number of seats increases faster. That means that, per seat kilometer flown, there is a reduction in fuel use of roughly 10% compared to the A380. Measured per landing and take of cycle (LTO), the comparison of emission numbers between the A3XL and the A380 is assumed to be the same as in flight. This means that also here the emissions of the A3XL are larger, but it also contains more seats, making it per seat kilometer flown a net positive effect of 10% less emissions. The A3XL is designed to be burning traditional kerosene and in its current design cannot make use of any renewable energy carriers.

The A3XL is much larger than the A380 and thus will require more space on the airfields. At the same time, fewer aircraft are needed, given the higher capacity of the A3XL. Still however, a small increase in land use is assumed since for airfields to facilitate the A3XL, there is a need for widening taxi paths and aprons, and maybe enlarging flyovers to withstand the weight of the A3XL, which is much heavier than the A380.

The preliminary study performed by Blok, El bouzidi et al. (Blok et al. 2001) suggests that the noise characteristics of the A3XL are comparable to the A380. If four new engines could be designed with higher thrust, it could well be that the specific noise (per kiloNewton thrust) is less (as it will be new designs), but that due to the increased power output of the engine, the total amount of noise produced will still be comparable.

The A3XL is not considered a paradigm shift and thus cannot be counted as a radical innovation in the aviation system, though there are challenges in the design and lots of adaptations will be necessary to accommodate this aircraft. The A3XL is not expected to have any direct influence on the number of airlines operating, nor on the number of transport modes for continental transport. Due to the fact that, given the same number of travelers, fewer aircraft are necessary, it can be expected that a less occupied schedule leads to more flights leaving the airport without delay. A drawback of implementing such a large aircraft is that adaptations at the airport might require large investments. Aprons should be made accessible for this aircraft and runways should be strengthened (due to its weight). The effects of the A3XL on the indicators designed in chapter 3 are summarized in Table 4.3. If the column A3XL contains the label “No Change”, this means that that particular indicator will not change in value when the A3XL will be implemented instead of the current high capacity aircraft.

Code	Outcome indicator	Unit	A3XL
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	-5%
PE2-2	Number of internal incidents in aviation per year.	#/pax km	-5%
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	-5%
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	-10%
PE3-2	Average emission of NO_x per LTO cycle	ton/year	-10%
PE3-3	Average emission of CO per LTO cycle	ton/year	-10%
PE3-4	Average emission of VOCs per LTO cycle	ton/year	-10%
PE5-1	Different type of aircraft in service	#	No change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-10%
PL2-1	Percentage of renewable fuel of the total amount of fuel used	% *(ton renewables/ total tons of fuel)*	0
PL3-1	Land unavailable for other than aviation purposes	km^2	Slight decrease
PL4-1	Noise production of specific innovative aviation technology	dB(A)	Equal to A380
PR2-1	Direct operating cost	€/year	-15%
PR3-1	Number of innovative aviation technologies in use	#	No change
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)*	Increase
ASI2-2	Average turn around time	h	Equal
ASI2-3	Changes in design and maintenance of aircraft	small/medium/ substantial	Medium
ASI3-1	Design risk of innovative technology	small/medium/ substantial	Small

Table 4.3. The effect on the indicators representing Sustainable Development of introducing the A3XL in the aviation system.

4.4.3 Use of high tech composite materials

For radical and innovative changes, a first thought is often about completely new sizes and shapes of the airframe, such as a C-wing aircraft or the Blended Wing Body. However, keeping roughly the current shape of the airframe, there are still substantial improvements possible if, where possible, the conventional aluminum alloys are replaced by new materials like composites.

This usage of new materials is not just a one-on-one replacement of the current piece of aluminum alloy with an equal sized panel of composite material. Each material has its own fatigue and static strength. So, tensions can be higher in one material than in another. But simple high tension resisting material is not enough. This would give such thin material that buckling would be a serious problem. For this reason, steel is not used as skin material in aircraft. An aircraft must be completely (re)designed for the specific characteristics of a composite material for the full potential of that material to be achieved.

However, designing aircraft using new and modern materials can have substantial benefits. Serious weight reductions have been achieved in the design of the Airbus A380 by applying the aluminum glass fiber composite called Glare. Redesigning certain sections of the Airbus A340 fuselages from aluminum to Glare gave a 26% weight saving (Tempelman 1998). An overview study by Lee (Lee 2003) gave a 15 to 30% possible weight reduction when using composites compared to traditional material. This is assumed to give a 10% to 15% fuel use reduction. Additional gains are possible, since composites can provide much smoother surfaces resulting in better aerodynamic performance, less drag, less required thrust, and thus less fuel use. Smoother surfaces can also give better noise performance, especially in descending stages of a flight when traditionally air frame noise dominates engine noise.

A serious disadvantage of the use of modern composites is the long design and testing phase before they get certified for aeronautical use. The many tests require lots of time, effort, and money. Designing using composites might be very promising but requires specialist skills and tools. Fabricating composites is complex, requires much effort, and special protecting measures have to be taken to keep a healthy working environment in the production plant.

The possible scoring of implementing new composite materials in the aviation system is summarized in Table 4.4.

Code	Outcome indicator	Unit	Composites
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	No change
PE2-2	Number of internal incidents in aviation per year.	#/pax km	No change
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	No change
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	-15%
PE3-2	Average emission of NO_x per LTO cycle	ton/year	-15%
PE3-3	Average emission of CO per LTO cycle	ton/year	-15%
PE3-4	Average emission of VOCs per LTO cycle	ton/year	-15%
PE5-1	Different type of aircraft in service	#	No change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-15%
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	No change
PL4-1	Noise production of specific innovative aviation technology	dB(A)	No change
PR2-1	Direct operating cost	€/year	Decrease
PR3-1	Number of innovative aviation technologies in use	#	No change
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	Medium
ASI3-1	Design risk of innovative technology	small/medium/ substantial	Medium

Table 4.4. The effect on the indicators representing Sustainable Development of using new composite materials in aircraft.

4.5 Technologies influencing the aerodynamic subsystem

4.5.1. Introduction

In this section we describe one technology, high aspect ration wings for large aircraft. This technology will affect the aerodynamic subsystem, as illustrated in Figure 4.3.

4.5.2 High aspect ratio wings for large aircraft

Wings of aircraft need a certain amount of surface in order to generate enough lift to carry the total weight of the aircraft. In principle, for generating lift, there is no limitation on wing length or width, as long as the product of both (which is the wing surface) meets a certain required number.

Relatively short wings must have a higher width to reach the specified wing surface. These kinds of wings have a so-called low aspect ratio (ratio between wing length and wing width). Low aspect ratio wings are easier to construct and, thus, lighter than high aspect ratio wings. This weight saving is positive, but low aspect ratio wings also have a drawback. Their aerodynamic characteristics are worse than the characteristics of high aspect ratio wings. They induce more drag, which leads to higher fuel consumption.

In a study co-supervised by the author (Dalhuijsen 2003), a parametric design model was built and used to determine optimal points for the trade-off between weight of the wing and fuel use of the aircraft. As an illustrative case, the new Airbus A380 was chosen. The model is based on two widely used preliminary design methods, the Roskam (Roskam, 1989) and Torenbeek (Torenbeek 1982) methods.

The A380 was taken as a case because its aspect ratio breaks sharply with the historical trend line of Airbus to increase aspect ratios (see Figure 4.7). In addition, the wingspan of the A380 is 79.75 meters, just 25cm less than the upper boundary of the ICAO code F aerodrome reference. Code F means that the airport is capable of handling aircraft with a wingspan between 65 and 80 meters. Based on the historical trend line and the wingspan of almost 80 meters, it looks like Airbus has chosen code F as a limiting factor rather than optimizing for fuel use.

As final output, the parametric design model plots direct operating costs (DOC) and global warming potential GWP (a relative indicator for the influence on climate change, in this case due to CO_2 emissions) against aspect ratio for a specific situation in flight altitude and speed.

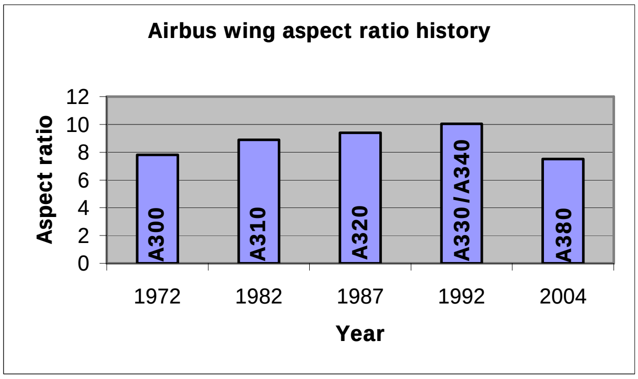

Figure 4.7. Airbus aspect ratios throughout history.

The graph in Figure 4.8 indicates that for cruise flight condition (speed approximately 0.85 Mach and an altitude of almost 11km) around aspect ratio 10 and 12 there is minimum DOC and GWP (As GWP is determined here by CO_2 emissions, in this case GWP is directly related to fuel use) respectively. Compared to the actual aspect ratio of the A380 of 7.5, this would mean a possible 2.4% DOC reduction and even a 7.6% reduction in fuel use. For a typical A380 flight this would save approximately 15 thousand kilograms of fuel.

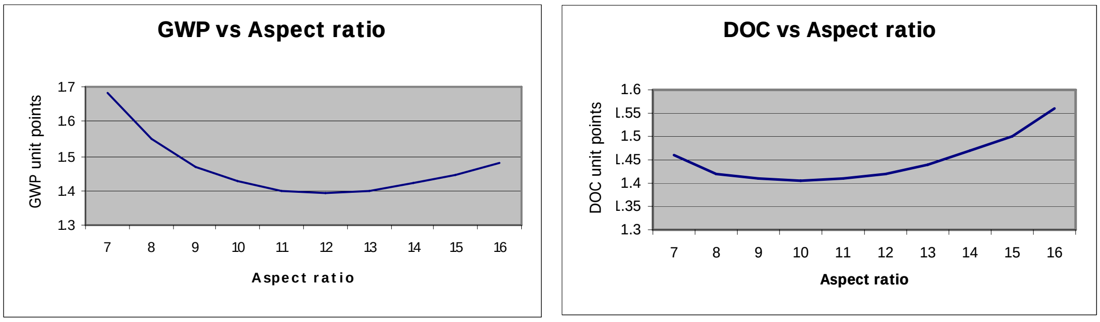

Figure 4.8. Direct operating costs and GWP versus aspect ratio. Source: Dalhuijsen, 2003.

Direct operating costs are influenced by fuel price. But fuel price itself is also changing. The aspect ratio around 10 is an optimum for a fuel price of around $0.28 per kilogram. Lower fuel prices would give an optimum lower than 10 and higher fuel prices an optimum higher than 10 (see Figure 4.9). Higher fuel prices are to be expected in the future, since higher demand for crude oil is foreseen while at the same time the capacity of production cannot be set much higher (Deffeyes 2001).

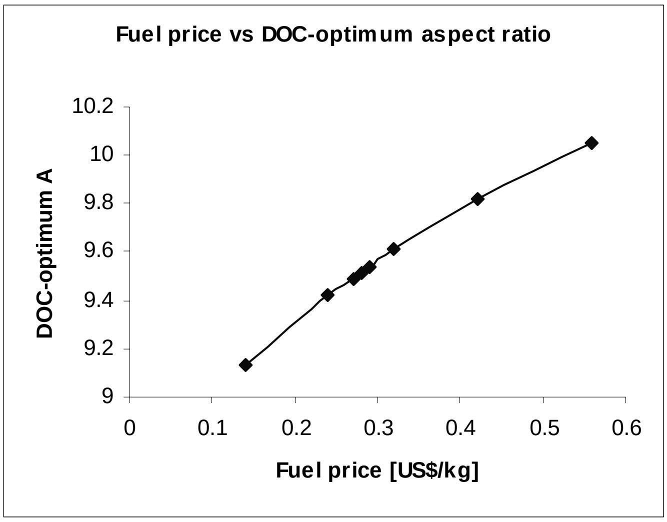

Figure 4.9. The relation between DOC optimum for aspect ratio and fuel price. Source: Dalhuijsen, 2003.

Given the indicators for sustainable development as identified in chapter 3, the introduction of high aspect ratio's wings on the larger aircraft, which would otherwise fall outside the 80m x 80m box to which current airfield are designed (aerodrome code letter F), will have several effects on different factors of the system.

It can not be expected that these wings will make changes in the number of places connected through air, nor in the frequency, as nothing in the seat capacity of the aircraft will change. The same reasoning holds true for the number of operated airports, and thus the average distance towards them.

When high aspect ratio wings are introduced, the fuel costs will go down, giving the airline the possibility to reduce ticket prices. It can be expected that market forces will indeed enforce such a reduction in ticket price. The direct operating costs (DOC) will decrease by roughly 3% (Dalhuijsen 2003).

There are in this preliminary study no indications found that anything in terms of safety might change. Again, only the wing configuration changes, everything else in and around the aircraft stays the same.

Fuel savings take place in cruise conditions, since it is there that the induced drag is lower. No savings in gas emissions during the landing and take off cycle therefore can be expected, however the amount of CO_2 emission during cruise flight can be reduced by a maximum of roughly 8% (Dalhuijsen 2003).

This technology has no influence on the type of fuel that is being used, only on how much of it will be used in cruise flight conditions.

It can be expected that with larger wing spans, more space is needed at airports to facilitate the different aircraft. Apron size will have to be increased to make sure that aircraft can pass each other.

The noise characteristics of this new technology have not been studied. However, it can be expected that only very small changes occur. In the take off phase, no change can be expected, since the engine noise forms the majority of the total noise of an aircraft then. In the landing phase a small change might be possible, since the aircraft casco has a different configuration. However, the flaps and landing gear are in this phase the largest source of noise, not the wing itself.

No paradigm shifts will occur if the wings of aircraft get higher aspect ratios. Also, neither the number of airlines operating nor the number of transport modes will be influenced by the described changes to wings. The new design of high aspect ratio wings is only slightly different from the conventional wings, so there are no large design risks or changes in maintenance. Also no changes can be expected in turnaround times and flight delays.

Table 4.5 summarizes the scoring of the introduction of high aspect ratio wings on ultra high capacity aircraft.

Code	Outcome indicator	Unit	High aspect ratio wings
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	No change
PE2-2	Number of internal incidents in aviation per year.	#/pax km	No change
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	No change
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	No change
PE3-1	Average fuel use per LTO cycle	ton/year	No change
PE3-2	Average emission of NO_x per LTO cycle	ton/year	No change
PE3-3	Average emission of CO per LTO cycle	ton/year	No change
PE3-4	Average emission of VOCs per LTO cycle	ton/year	No change
PE5-1	Different type of aircraft in service	#	No change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-8% compared to A380 when number of chairs are kept constant
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)	No change
PR2-1	Direct operating cost	€/year	-3% compared to DOC of equal capacity aircraft without high aspect ratio wings
PR3-1	Number of innovative aviation technologies in use	#	No change
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	Small
ASI3-1	Design risk of innovative technology	small/medium/ substantial	Small

Table 4.5. The effect on the indicators representing Sustainable Development of introducing high aspect ratio wings on ultra high capacity aircraft.

4.6 Technologies influencing the control subsystem

4.6.1. Introduction

In this section we describe two technologies, Free Flight and new landing and take off (LTO) cycles. Each of these technologies will affect the control subsystem, as illustrated in Figure 4.3.

4.6.2 Free Flight

Free Flight (or Free Route Airspace) refers to a concept that has been discussed for some years that promised a more efficient and less congested air transport system. Besides this, the concept also promised reduced fuel use, since, in general shorter routes would be flown than in the traditional system.

In essence free flight means that aircraft choose their own optimal route from origin to destination and are not restricted to the traditional air route network used by the ATC system nowadays. The individual aircraft is capable of doing that, since it has enough information, not only on what happens around it in the nearby airspace, but also on the long haul to its final destination. Today, air traffic controllers have this information and guide the aircraft over certain prescribed paths. Leaving these prescribed tracks gives more airspace to be used and with it more capacity. It usually also gives shorter connections, faster travel times, and less fuel use.

Eurocontrol has studied the free flight concept thoroughly. For direct environmental benefits, Eurocontrol has concluded that fuel savings up to 2% are possible. With it, the exhaust of water vapor, CO_2 and SO_x emission can be reduced by a maximum of 2%. Exhausts of NO_x can be reduced by a maximum of 1.6%, while emissions of unburned hydrocarbons and CO will hardly change (Jelinek et al. 2002).

Since the study has based its findings on European continental cases, no very long haul flights in complete free air space were included. The study therefore suggests that savings can possibly be higher if the dimensions of the free flight air space were increased.

Direct financial benefits are expected mainly for the operators of aircraft, since Air Traffic Control costs will be able to go down. But on the other hand, operators must invest in new equipment for their aircraft and train their crews. In addition, other actors in the aviation system, like governments or the military, must make large investments without getting a net financial benefit (McFarlane and Church 2002). It is not unlikely to expect that the net direct financial benefits will be spread more equally over those who invest and those who do not have to invest, leaving only marginal direct financial benefits for the airlines themselves.

Apart from direct environmental or financial benefits, it is expected that some important other effects will occur when the concept of free flight is introduced, like greater capacity of the air space, greater flexibility in planning, and greater predictability of flight times (McFarlane and Church 2002). These effects will undoubtedly benefit airports, airlines and the traveler.

Table 4.6 summarizes the scores of introducing Free Flight into the aviation system.

Code	Outcome indicator	Unit	Free Flight
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	Small reduction
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	No change
PE2-2	Number of internal incidents in aviation per year.	#/pax km	No change
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	No change
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	No change
PE3-1	Average fuel use per LTO cycle	ton/year	No change
PE3-2	Average emission of NO_x per LTO cycle	ton/year	No change
PE3-3	Average emission of CO per LTO cycle	ton/year	No change
PE3-4	Average emission of VOCs per LTO cycle	ton/year	No change
PE5-1	Different type of aircraft in service	#	No change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-2%
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	No change
PL4-1	Noise production of specific innovative aviation technology	dB(A)	Possible reduction
PR2-1	Direct operating cost	€/year	Small reduction
PR3-1	Number of innovative aviation technologies in use	#	No change
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)*	Increase
ASI2-2	Average turn around time	h	No change
ASI2-3	Changes in design and maintenance of aircraft	small/medium/ substantial	Small
ASI3-1	Design risk of innovative technology	small/medium/ substantial	Medium

Table 4.6. The effect on the indicators representing Sustainable Development of introducing the control concept of Free Flight into the aviation system.

4.6.3 New LTO cycle

Noise hindrance from aircraft takes place near airports especially when the aircraft are flying relatively low to the ground. Experts think that changing the current procedures for landing, taxiing, and take off might give benefits for noise and gas emissions near airports, thus influencing the quality of life for citizens living near airports.

Landing

During descent and landing, aircraft noise mainly stems from two sources. One is the changes in aircraft engine thrust settings, needed for the maneuvering to line up the aircraft for the runway. The other source is the airframe, especially due to flap setting changes and the landing gear.

In a traditional approach to an airport, an aircraft descends to 2000 feet (approximately 670 meters), and then maneuvers till it intercepts the instrumental landing system (ILS) glide slope that will further guide the aircraft to the ground.

A way to reduce noise in the landing procedure is to abandon the maneuvering at low altitudes. In a procedure called Continuous Descent Approach (CDA), this maneuvering takes place at much higher altitude and also horizontally further away from the airport. After the maneuvering, the aircraft continuously descends until it intercepts the ILS slope at 2000 feet, after which the landing is the same as in the standard approach.

A case study for some individual flights at Amsterdam Schiphol airport (co-supervised by the author) revealed a reduction of 10% in noise and 4.5% in fuel use when CDA was compared to the standard approach (Aarts et al. 2002). However, the study also warns for a decrease in capacity of the runway system of 50% as different aircraft with low idle thrust settings will have different approach speeds. An option the study suggests is to use CDA in the late evening, when noise is most critical and capacity is not a problematic issue.

An MIT study by John-Paul Clarke showed a redesign of the CDA approach in which the maneuvering takes place even further away form the airport (70km instead of 17km) and at higher altitudes. This study gives much better noise reductions (up to 50%), which is equivalent to 10dB (Marks 2003).

In addition to capacity problems, from which CDA suffers badly, there is another issue. Current airspace design around airports is very complex to avoid too many flights over populated areas. This way of airspace design requires lots of maneuvering close to the runway, so close to the ground. With current airspace design, a continuous descent approach is possible for some flights, but not for all. An optimized CDA is not possible at all with such an airspace design.

If airspace would have to be redesigned in order to make application of CDA possible, this would need more routes over populated areas. Though CDA would then reduce overall noise, an increase in noise over populated areas would also be the result.

Because CDA reduces the capacity so much, it is not considered to be implementable. Given the scenarios for air travel demand in 2050, it appears impossible to reach those amounts of air travel demand while also implementing CDA. Therefore no scoring for CDA is presented here in this section.

Taxiing

When aircraft taxi, the thrust setting of their engines is very low. This makes the engines run in a very inefficient part of the power curve and thus emitting relatively large amounts of CO and black smoke. Ideas for improvement have been pulling trucks, a central pulling cable systems to which aircraft can attach, and taxiing on less than all engines.

When engines are not in use during taxiing, there is a problem with the warming up (before departure) and cooling down (after landing) of the engines. Implementing systems that do not require running engines during taxiing would also require cooling down and warming up periods during which the engines would have to run on low thrust settings for 2 to 3 minutes. The complexity of the procedure, including large investments for the extra pulling systems without having serious benefits, has meant that these systems have not been studied very much.

Running on less than all engines has been studied several times. It still requires cooling down and warming up periods, but not for all engines. And, it also does not require extra systems and extra handling. The idea behind taxiing on less than all engines is that the remaining engines can run on higher thrust settings, letting them operate in a more efficient part of their power curve.

However, a study by KLM (Huiskamp and Bouwmeester 2001) and a re-study of this study by the author and his students (Aarts et al. 2002) revealed that taxiing on less than all engines does not give real benefits. Though overall fuel consumption decreases, the specific emission of NO_x increases, making it not favorable from an environmental point of view. Also, compared to aircraft fuel use in flight, the fuel reduction in taxiing on less than all engines is marginal (and increases the complexity of the procedures), which also makes it unattractive from an economic point of view.

It appears that other taxi procedures do not make any improvements on the indicators for Sustainable Development. No further scoring of this technique on the indicators designed in chapter 3 is done in this section.

Take off

The International Civil Aviation Organization (ICAO) has defined two standard take off procedures, the so-called ICAO A and ICAO B take-off procedures. The ICAO A procedure focuses on reduction in noise at a certain distance from the airport, while the ICAO B procedure focuses on reduction of noise close to the airport. ICAO allows other procedures, as long as they do not counteract other flight rules.

Interviews that we conducted revealed that some pilots are hardly aware of these two standard procedures (Aarts et al. 2002). It appears that it is common practice that pilots follow their own take-off procedure, which they adapt to any specific situation. Their main goal with these adaptations is a continuous optimization of the total safety during a take-off procedure.

Combining the advantages in noise of the ICAO A and B procedures would be very beneficial. This can be done by reducing flap use and thrust settings much earlier in the take-off procedure than prescribed by ICAO A or B. The idea of combining characteristics of the ICAO A and B procedures led to the design (by the author and his students) of some alternative procedures to maximize a reduction in fuel use. It appeared that reductions of 25-30% in fuel use and 6-13% in noise could be obtained in this way. Horizontal and vertical displacements (climb) are still comparable in equal time frames as with both ICAO procedures. Even one lost engine (reducing 25% thrust in a four engine 747) still gives positive climb speeds throughout the whole take off procedure (Aarts et al. 2002).

Compared to a standard trip, the fuel savings are negligible, so no global benefits are present. However, local air quality can be improved substantially.

It is clear that reducing flaps and thrust so early in the take off procedure reduces the level of safety, since a pilot has fewer margins in which he or she can operate in case something goes wrong. However, the benefits of using a different take off procedure are substantial. With ever increasing safety levels due to new technologies, a discussion about the trade-off between safety and noise/gas emissions during take off would be a worthwhile effort. By determining the effects of implementing this combined ICAO A and B take off procedure on all indicators representing Sustainable Development (as identified in chapter 3), this thesis can support such a discussion (see Table 4.7).

Code	Outcome indicator	Unit	Reduced thrust take-off
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	No change
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	No change
PE2-2	Number of internal incidents in aviation per year.	#/pax km	No change
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	No change
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	No change
PE3-1	Average fuel use per LTO cycle	ton/year	-35%
PE3-2	Average emission of NO_x per LTO cycle	ton/year	-35%
PE3-3	Average emission of CO per LTO cycle	ton/year	-35%
PE3-4	Average emission of VOCs per LTO cycle	ton/year	-35%
PE5-1	Different type of aircraft in service	#	No change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	No change
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	No change
PL4-1	Noise production of specific innovative aviation technology	dB(A)	-10%
PR2-1	Direct operating cost	€/year	No change
PR3-1	Number of innovative aviation technologies in use	#	No change
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	Small
ASI3-1	Design risk of innovative technology	small/medium/ substantial	Small

Table 4.7. The effect on the indicators representing Sustainable Development of introducing a combination of ICAO A and B take off procedures into the aviation system.

4.7 Technologies influencing the propulsion subsystem

4.7.1. Introduction

In this section we describe two technologies, Propellers for high flying speeds and hydrogen powered flight. Each of these technologies will affect the propulsion subsystem, as illustrated in Figure 4.3.

4.7.2 Propellers for high flying speeds

What propellers essentially do is pressurize air, as a result of which the air accelerates as its pressure reduces to free stream pressure again after the aircraft has passed. According to Newton's law, this results in an opposite force that accelerates the aircraft. In order to make that pressure difference, the propeller needs the power delivered by the aircraft's engine. The more power delivered by this engine that is turned into a certain amount of thrust per unit of time, the more efficient the propeller is. A propeller is capable of translating up to 80% of the power of the engine into thrust (Ruijgrok 1990).

At low airspeeds (under 200km/h) propellers perform with less than 80% efficiency; in the range 200-700km/h, 80% efficiency can be reached. At higher speeds, the efficiency drops dramatically due to shock waves at the tips of the rotor blades when they approach the velocity of sound and compressibility effects occur (Ruijgrok 1990).

For higher speeds, the turbo jet engine was initially used. It produces thrust by accelerating a much smaller amount of air compared to the propeller, to a much higher velocity. The turbo jet engine can produce much more thrust than the propeller, but at a much lower efficiency.

In trying to combine the efficiency of the propeller and the large possible thrust of the turbo jet, the turbo fan engine was designed. Nowadays all large civil aircraft fly with turbo fan engines. Of all the air that a turbo fan engine accelerates, a substantial part is accelerated with a fan to lower speeds than the turbo jet would do. The power is generated by a conventional turbo jet engine that, with its high velocity exhaust stream, also generates some of the total thrust a turbo fan engine delivers. Typical turbo fans need only 60% of the fuel a typical turbo jet needs for equal amounts of thrust (Anderson 1989).

Turbo prop engines, in which a propeller is driven by a turbo jet engine are even more efficient engines, and very silent compared to turbo fans, though they are limited to speeds up to 750km/h (Anderson 1989), while modern large civil aircraft cruise at higher speeds.

Torenbeek expects that with considerable design effort it is possible to develop propellers for higher flying speeds than 750km/h to make propellers suitable for operating within the current flying speed range of large modern civil aircraft (Hidding 2002). So far, two problems remain: (1) the limited amount of engine power that one propeller can transform in thrust, and (2), the decreasing efficiency at flying speeds over 750km/h.

Some tests by NACA (the later NASA) in the 1950s indicated the possibility of propellers for high flying speeds. Their tests showed propellers in operating test aircraft at speeds slightly higher than Mach 1 (Aiken 2004). Testing the efficiency of these propellers was however not an item in these experiments.

Other NASA tests, performed in 1981 (Jeracki and Mitchell 1981), revealed options to improve the propeller to keep an acceptable efficiency, but to be able to function with flying speeds up to Mach 0.80-0.90. Among other things, the blade number was increased, the thickness of the blades reduced, and other curvatures for the blades introduced. Still, efficiency levels decrease with increasing flying speed, but these efficiency levels keep being higher than with more conventional turbo prop engines. At flying speeds of Mach 0.8, turbo props reach efficiencies of roughly 65%, while the improved propeller still has almost 80% efficiency. At lower speeds, these propellers can reach even higher efficiencies. The study concludes that between 15 and 30% reduction in fuel use can be achieved if such improved propellers would be implemented.

Implementing such propellers in that aviation system would have a large impact on noise characteristics and fuel use, and, related to that, DOC and ticket price. Since only the propulsion system is changed, other indicators are not expected to change. However, the design risk of this technology is high, since this technology is not currently used and is not completely proven. The scoring of this technology is summarized in Table 4.8.

Code	Outcome indicator	Unit	High Speed Propeller
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	No change
PE2-2	Number of internal incidents in aviation per year.	#/pax km	No change
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	No change
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	No change
PE3-1	Average fuel use per LTO cycle	ton/year	No change
PE3-2	Average emission of NO_x per LTO cycle	ton/year	No change
PE3-3	Average emission of CO per LTO cycle	ton/year	No change
PE3-4	Average emission of VOCs per LTO cycle	ton/year	No change
PE5-1	Different type of aircraft in service	#	No change
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-30% compared to aircraft with turbo props -50% compared to aircraft with turbo fans
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	No change
PL4-1	Noise production of specific innovative aviation technology	dB(A)	Decrease
PR2-1	Direct operating cost	€/year	-10% compared to DOC of aircraft with turbo props -15% compared to DOC of aircraft with turbo fans
PR3-1	Number of innovative aviation technologies in use	#	No change
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

Table 4.8. The effect on the indicators representing Sustainable Development of introducing propellers for high flying speeds into the aviation system.

4.7.3 Alternative fuels

Current aircraft use kerosene as their source of energy, refined from crude oil. Though there is discussion among scientists about the exact moment until which crude oil is available, there is agreement that the first half of the 21st century will be the last time frame in history in which society can use cheap oil products (Deffeyes 2001). Some expect already a sharp decline in cheap oil availability after the year 2025. This means uncertainties about fuel type for aircraft that are being put into service today.

After research showed that burning fossil fuels was changing the climate, with all its devastating consequences, a drive for research on so-called alternative fuels emerged.

But already from the first oil crises in 1973 on, people have been thinking of alternative energy sources for crude oil. Car manufacturers, for instance, have introduced engines running on alcohol, electricity, and hydrogen. There have also been studies on hydrogen-powered aircraft. The current problem with hydrogen is that any large scale generation needs electricity, which eventually comes from fossil fuel use or direct generation from natural gas.

Uncertainties about the availability of crude oil already for the year 2025 (Deffeyes 2001) are important for the aviation system, as, for aviation, this is not a far away time horizon. As mentioned in earlier chapters, designing, certifying and operating a new aircraft design usually takes place in a time span of around 40 years. Taking 2025 as a horizon, this would mean that new aircraft designs from the late 1980s onwards could suffer from extremely high oil prices or no availability at all during their operating life times.

Hydrogen - Hydrogen as an alternative source of energy is mentioned quite often. It is storable, can (in principle) be generated in an environmentally friendly way, and is infinite, since there is enough water available. Also, burning hydrogen produces only water vapor.

The largest problem with hydrogen nowadays is its generation, for which 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.

A study by Boeing (Daggett 2003) shows that hydrogen aircraft will be approximately 8% heavier in empty weight due to heavier constructions for the hydrogen storage. Also, around 10% more drag is expected because of larger frontal surfaces, since the storage of hydrogen needs much more space than an energy equivalent amount of kerosene. This rise in drag will roughly need an equal higher amount in fuel of 10%.

On the positive side, the study expects a 5 to 10% more efficient fuel use by the engines together with lower NO_x emissions. Using hydrogen automatically reduces CO_2, CO, black smoke, and hydrocarbon emissions to zero.

In general, safety is improved, since the heavier hydrogen storage tanks are more resistant to impact. In addition, hydrogen flames quickly move upward and radiate much less than kerosene flames would do. Kerosene, if leaking, will pool under the aircraft, making a perfect supply of fuel for the flames, while hydrogen will not pool at all.

Compared to today’s prices for fossil fuels, generating hydrogen using nuclear or wind power will cost roughly 2.5 times as much as an energy equivalent amount of Jet-A fuel out of crude oil. Future changes in oil price due to taxes or scarcity can dramatically change this picture, of course.

An earlier Airbus study (Klug 2001) comes to comparable results and stresses slightly more two important issues. One is the amount of water vapor that will be introduced into higher layers of the atmosphere. Though water will remain for a much shorter time in the upper atmosphere than CO_2 (6 months versus 100 years), lots of water at such heights will still contribute to climate change. How much precisely, is still a matter of debate (IPCC 1999). The second issue the Airbus study stresses is the required storage capacity for the hydrogen near airports. As hydrogen in energy equivalent amount takes up more than 4 times the volume of kerosene, and should be stored either pressurized or cooled, this storage near airports will require considerably more land than kerosene does.

The Airbus study also pinpoints the problem of transition from kerosene to hydrogen. It does so by showing that today's capacity of hydrogen generation worldwide is less than 200 tons per day, while for current aircraft fleet every day an amount of 30000 tons is needed. In addition, these 200 tons would today be generated using fossil fuels, which usage is one of the reasons to transit to hydrogen.

A recently finished European Commission Fifth Framework study on hydrogen fueled aircraft (Airbus 2003) gives numerical clues to the overall change in direct operating costs (DOC) of such an aircraft compared to a kerosene operated aircraft. It should be mentioned that this study also concludes that cheap oil will be available until 2050. With that as taken for granted, the study comes to approximately 5% increase of DOC for hydrogen aircraft.

The client for this research supports research for a transition from crude oil to hydrogen as energy carrier. Although today hydrogen cannot be produced in large quantities from sustainable resources, it has the promise that in the future that might be the case. It is also a good mobile carrier of energy to be transported and used everywhere, in contradiction for instance to heavy batteries, in which electrical energy must be stored.

The scores on the outcome indicators of introducing hydrogen powered flight into the aviation system are summarized in Table 4.9.

Bio fuel – Another option is to exchange kerosene for bio-fuels, although this can not be a simple "exchange", since the characteristics of burning bio-fuel will require that storage facilities and engines to be drastically adapted if not completely redesigned. Though at first glance bio-fuels are promising because they can almost be CO_2 emission neutral (by burning the fuel, the same amount of CO_2 is emitted as the plants took up from the atmosphere during their growth), bio-fuels have some negative sides. One is the increased prices of foods, since plants can serve as foods or as basis for fuels; especially the poor in the developing countries are expected to suffer from these price increases. Large scale use of bio-fuel requires large intensive mono cultures with potential dangers for diseases and collapses and thus uncertainty about the availability of fuels.

The Renewable Aviation Fuels Development Center of Baylor University in the U.S. has developed and tested procedures to run aircraft piston engines (general aviation only) on bio-ethanol (Shauck and Zanin 1996). Nine test aircraft have accumulated up to 2500 hours of flight time on this bio-fuel. However, piston engines are not used for large scale civil air transport transport;

those aircraft are equipped with gas turbine engines. No serious preliminary designs could be found to show that large scale usage of a bio-fuel in aircraft gas turbine engines is possible.

Code	Outcome indicator	Unit	Hydrogen powered flight
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	Increase
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	No change
PE2-2	Number of internal incidents in aviation per year.	#/pax km	No change
PE2-3	Number of aircraft crashes per year involving aircraft >150 passengers.	#/pax km	No change
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	# ton	No change
PE3-1	Average fuel use per LTO cycle	ton/year	-10%
PE3-2	Average emission of NO_x per LTO cycle	ton/year	Decrease
PE3-3	Average emission of CO per LTO cycle	ton/year	-100%
PE3-4	Average emission of VOCs per LTO cycle	ton/year	-100%
PE5-1	Different type of aircraft in service	#	Increase
PL1-1	Total emission of CO_2 during flight operations	Ton/year	-100%
PL2-1	Percentage of renewable fuel of the total amount of fuel used	% *(ton renewables/ total tons of fuel)*	100%
PL3-1	Land unavailable for other than aviation purposes	km^2	Increase
PL4-1	Noise production of specific innovative aviation technology	dB(A)	-10%
PR2-1	Direct operating cost	€/year	+5%
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

Table 4.9. The effect on the indicators representing Sustainable Development of introducing hydrogen powered flight into the aviation system.

4.8 Paradigm shifts

4.8.1 Introduction

In this section we describe several paradigm shifting technologies that seriously would influence the appearance of the modern civil aircraft as it is currently flying around. The considered technologies are: airships, the SkyCar and Blended Wing Bodies.

4.8.2 Airships

In the 1920s and 1930s, airships were widely used as luxury modes of transport. The space an airship provided its passengers was enormous, much more than what today's aircraft offer in their economy class or even business class. In addition, travelers enjoyed very good comfort, since their enormous size make airships relatively insensitive to turbulence and downbursts.

The success of the airship was disrupted by several incidents in which the hydrogen that provides the lift for these vehicles caught on fire. The disaster with the Hindenburg Zeppelin in 1938 is still well known. It is for this reason that modern airships use helium instead of hydrogen as a way of generating lift.

In the late 1990s, interest in the airship increased again. For one or other reason, airships also got the reputation of being very environmentally friendly; they got a 'green image'. So green, even, that after publication of their first annual environmental report, the airline KLM received letters from readers in which they asked KLM why it would not replace its entire fleet by airships for environmental reasons.

In addition to their green image, people also tend to believe in the possibility of marketing newly designed and constructed airships in certain niche markets. Millions of Euros have been invested in new companies. For instance, in Germany, two large companies were set up; Zeppelin Neuer Technologie (Zeppelin NT) and CargoLifter. In the United Kingdom, AirTrain was established and SkyCat (whom humorously called their initial small prototype 'SkyKitten'). In the Netherlands there has been the initiative of Rigid Airship Design in Lelystad.

From the beginning of the renewed interest in airships in the 1990s, it has never been the intention to replace part of the fleet of aircraft that is in service. The airship is simply not capable of offering something comparable to what an aircraft can offer. Speed is the main issue. Being 6 to 10 times slower than civil aircraft, it cannot fulfill the role aircraft are playing.

However, there might be the possibility that airships can play a role in certain small parts of the market. From a Sustainable Development point of view, creating new niche markets, and with it more new transport, is not favorable. But, if after some maturation in an uncompetitive niche market, the airship would be able to replace certain parts of civil aviation in a much more sustainable way, this could be interesting.

In order to investigate the possibilities and the impact of airships, the author and his students designed a 100-passenger airship for operating on the route Amsterdam-Barcelona (Adriaensen et al. 2001). The airship, quickly called LTAB (with a blink to a large aircraft manufacturer meaning Lighter Than Air-Bus), was intended to have minimal noise and gas emissions. The LTAB's cabin measures 50m x 6m x 2.5m, giving space for up to 100 passengers. It has five 480 horsepower diesel engines, driving propellers with a diameter of 6 meters. It needs between 36000 and 52000 m^3 of helium for its lift.

While in operation between Barcelona and Amsterdam, and compared to other modes of transport like aircraft, busses, and trains, the airship only outperformed the airplane on noise. On gas emissions (the airship uses diesel as fuel for its propulsion, thereby emitting CO, CO_2, SO_x, etc.), no significant advantage could be found for the airship. As the travel times are by no means comparable to aircraft flight times, the airship could replace only trains and buses on this route, which it does not outperform in terms of noise, gas emissions, and costs.

Comparable results were also found in another study, supervised by the author, of passenger transport by airship between Amsterdam and London (Schuitemaker 2002). Especially on noise, there is an advantage for the airship over the airplane, but in terms of time and costs, it is by far not comparable to what an airplane can offer. Airships may be alternatives for the boats over the channel (between Calais, France and Dover, UK), but not for aircraft.

Schuitemaker (2002) could identify only two niche markets for airships in which they could operate and have benefits from a market (economic) point of view. These are pleasure cruises and sight seeing trips. Both of these niche markets are not part of the market that civil aviation is serving today.

Since neither studies co-performed by the author, nor other studies found that airships can take over the role airplanes have today, no further scoring pattern for introducing airships into the aviation system is made.

4.8.2 SkyCar

An idea that has already existed for a long time is to introduce car-like aircraft into the system, which have the size of an automobile, but that can both fly and drive. This concept, referred to as the SkyCar (popularized in the TV show “The Jetsons”), has been studied by several institutes. Firms in the United States are actually working on designs, and parts or small scale prototypes are being tested. An example is the Flying Car, which is being developed by the company “Moller”.

Mollers Flying Car is slightly larger than a high-end automobile. It is assumed that the owner can drive from and to a good take off and landing place, using normal roads. The Flying Car can be certified as a three-wheel motor vehicle. After taking-off, it cruises with a speed of 285 miles per hour and is designed to fly up to 10km altitude.

The designer suggests that the flying car will cost slightly more than a high-end automobile, and thus be available for the wealthy only. Maintenance is expected to be not more expensive than a high-end automobile, since much less moving parts are in the Flying Car. There might, however, be a problem with the certification of who is allowed to maintain such a vehicle. This could make maintenance costs rise substantially.

Not everybody who has a driving license will be allowed to use the vehicle; in principle a pilot’s license is needed. However, the designer suggests a fully automatic system in which the driver becomes passenger, and the vehicle finds its way automatically. In that way, no licenses will be needed, but, also the idea of freedom that people have driving (or flying) their own cars will then be gone for this Flying Car.

The company expects that flying cars will not take over any part of the current aviation system. It is expected that these cars will, as their name suggests, serve as cars. Maximum operating distances that can be reached will be only a few hundred kilometers.

Following the same reasoning as with the Airship, for purposes of this research, the SkyCar does not seem to be a technology that is worth studying in further detail, since it will not be able to serve as a replacement for current existing aircraft. It might serve a niche market and be very successful there, but that would be an addition more to the existing short haul commuting car transport system, than to the aviation system. Thus, no further scoring pattern for introducing SkyCars into the aviation system is made.

4.8.3 Blended Wing Bodies

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 4.10.

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

Table 4.10. The effect on the indicators representing Sustainable Development of introducing blended wing bodies (BWB) into the aviation system.

After the description of the different technological developments in this chapter, these developments will serve as the alternatives (policy measures) to be further analyzed in chapter 6. However, first, the uncertainty in the analysis due to the long time frames (of up to 2050) has to be managed using scenarios. This is done in the next chapter.

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5. Uncertainty; Air Traffic Demand in 2050

5.1 Introduction

In the last chapter, technologies were reviewed that have the promise to increase the level of sustainability in the aviation sector compared to what it is today. However, a big factor determining the outcome of the system on the indicators for Sustainable Development is the amount of flown kilometers. This is a factor that is determined by many subfactors that the problem owner can not necessarily control.

This chapter deals with the uncertainty of air travel demand in the future of 2050. It creates scenarios of plausible values to manage this uncertainty. In the next chapter, for each of these scenarios a score card will be created. These score cards will show what effects the different possible new aircraft technologies (described in chapter 4) will have in that particular scenario on all indicators for Sustainable Development (as identified in chapter 3). With all these score-cards, a picture exists on the effects of the possible new technologies in a range of different, plausible air travel demand futures.

5.2 Scenario approach

When, in chapter 6, the consequences of implementing new technologies in the aviation system are determined, it is necessary to know the future state of the system under study. This necessity stems from the fact that the consequences (i.e. the effect on the indicators) will be influenced by this future system state. As there is no well-established and objective way to predict exactly the future state of a complex, multi-actor, socio-technical system (as the aviation system is), also the results of the system analysis (the filled in score-cards) are uncertain.

The daily weather forecast is an example of a possible future state of a system. By experience we all know about the accuracy of it, and thus about the difficulty of creating plausible future weather system states. The weather forecast can be based on several techniques: implicit experience of people (who can judge what clouds mean for the weather half a day later), explicit interpretation of satellite images (with which speed and direction of violent storms can be determined) or very elaborate statistical models. With all these techniques, the forecast is based on past and current data. People add, implicitly or explicitly, assumptions on how that data is connected to the future (Miser and Quade 1985).

If one is interested in the effects of certain policy measures implemented in a system, one must know something about the context in which the policy measures will have to be implemented and function. This context usually lies quite some time in the future. In this particular research, a time horizon is chosen of 2050, since the policy measures address changes in aircraft designs. The full implementation (and thus full potential outcomes) of a new aircraft design, replacing all older technology, might take that long (see chapter 1, section 5.2 and chapter 6).

Implementation of a potential policy measure in the aviation system of 2004 will give different changes in that system, and thus different outcomes from the system, than implementing that potential policy measure in the aviation system of 2050. Since we are interested in what outcomes the system of 2050 produces when the policy measures would be implemented, there is a need for a description of the possible context of the aviation system in 2050.

As there is quite some uncertainty about the future state of the aviation system, especially when a description of the state of that system in 2050 is needed, a single prediction of that future state is of not much use. The future state of the system will for sure be much different from that prediction. In order to manage this uncertainty, a systems analysis can make use of a range of possible futures (i.e. different scenarios) and determine the outcomes from the aviation system when certain policy measures are implemented for these different possible futures.

This study has chosen to determine a range of possible futures for the demand for air travel (in terms of available number of seats) in the aviation system and chose the most extreme scenarios in terms of demand size. For these extreme scenarios, the outcomes of the system are determined (chapter 6) when the innovative technologies (see chapter 4) are implemented.

Findeisen and Quade advise to not take a too sophisticated technique to construct possible future states of the system under study (Miser and Quade 1985). In the case of this research, the time horizon to suggest some plausible picture for is 2050. Although lots of data are available to make short term forecasts for the aviation system, it is very doubtful whether this data extrapolation will be very valid for long time future projects. It seems appropriate to make, based on literature and expert opinion, some assumptions about a plausible causal chain of events to get a possible future picture of the system. Making some variation in the assumption (i.e. assuming different values for certain factors) gives a range of possible futures. This is a technique called scenario writing, which will be applied in this research.

Using this technique gives insight into the concrete factors that drive changes in the system. When knowledge about these factors and their causality increases over time, assumptions made on their numerical values can easily be adjusted leading to a different set of plausible future scenarios.

In dealing with scenario uncertainty in a policy analysis study, six steps can be described (Walker 2000a; Walker 2000b):

1. Develop the system diagram of the system to analyze (chapter 2)
2. Identify possible external forces (section 5.4)
3. Identify system changes due to these external forces in relation to the outcomes of interest (section 5.4)
4. Select relevant (that is high impact on outcomes and highly uncertain) external forces as candidates for scenario development (section 5.5)
5. Develop scenarios (section 5.6)
6. Quantify scenarios (section 5.6)

In the indicated subsequent sections, each of the mentioned steps is carried out in order, as the overall goal of this chapter is to come up with air travel demand scenarios for the year 2050. These scenarios will be quantified in terms of number of seats needed to fulfill the demand. This figure, number of seats, is needed in chapter 6, when, for each of the chosen scenarios, innovative aircraft related technologies (tactics) will be scored on their merit to Sustainable

Development in order to see if any of them would contribute to Sustainable Development in any of the scenarios.

5.3 Forecasting approaches in aviation

Over the last couple of decades aviation has shown tremendous growth rates, well over the GDP growth rates. After the outbreak of the SARS disease and the 9/11 incident in the United States, this growth suddenly stopped and even turned negative. In 2003 the demand for air travel is still lower than before both incidents, but 2006 shows that the historical growth trend lines, with a little delay, have been picked up again. The demand for air travel is rising again; the long-term trend line of growth has not been broken.

Predicting long term air travel demand contains on one hand huge uncertainties, as information about the future becomes less certain the further in the future it tries to develop certain forecasts. On the other hand, incidents like SARS influence air travel demand only on the short term, general trend lines do not have to be broken, not meaning that they never will (Mowford 2003). Any specific future predicted by models, educated guesses or whatever way, will occur with probability zero: it will always be different than expected.

Reaching sustainability (a sustainable state) via the process of Sustainable Development, takes time. If one would like to change the current state of the world into a sustainable state, it cannot be done in a short time frame, as the world as it is today was not created in such a short time frame, but slowly developed to its current state over many years. A Sustainable Development, if it would be, as expected (WCED 1987), a development towards organizing the world dramatically different than today, needs a long time span (see also chapter 3).

Sustainable Development in aviation by means of technological changes will have to take place during aircraft design and replacement. It makes sense to expect that technological changes to the aviation system that may contribute to Sustainable Development will need at least one new generation of aircraft design, and replacement of the old aircraft still flying around.

It might be possible that in an emergency situation suddenly a leap in technological development might take place and aircraft can suddenly be replaced much faster. However, in a situation that is not recognized as such, things like certification, safety regulations and high competitiveness between the remaining two aircraft manufacturers make the aviation industry very slow to change. To answer questions on the contribution of technological designs in aviation to Sustainable Development, the time span under study must at least be 2050, that is, roughly a new aircraft design away, in full operation and replacing all older technology.

A clear distinction has to be made between *forecasts* and *scenarios*. Forecasts aim at *predicting* a future state of the system. For aviation forecast predict, for instance, how many travelers there will be in the year 2050. Scenarios, on the contrary, *do not predict* anything. A scenario is one possible and plausible future state of the system. More scenarios together form a range of these possible futures. An analyst can then show, for a range of possible futures, what the effects of certain policy measures are. In this chapter, we do not try to make any predictions about future air travel demand. This chapter develops some plausible futures for air travel demand for the year 2050.

Forecasts, however, for air travel demand can be widely found. Most well-known probably are the market forecast published every year by the civil aircraft manufacturer companies Boeing and Airbus.

These two periodically published forecasts have a time horizon of 20 years. That seems enough for planning slightly adapted versions of existing aircraft (e.g. larger range, different seat capacity, etc.). However, for bringing complete new designs on the market, a 20 years forecast seems a little too short. As, ideally, a new design would only be commercially in service for roughly ten years by then and might not have passed the economic break even point. It seems likely that both aircraft manufacturers therefore have, kept internally in their organization, models of the aviation market that have a time horizon much further than 20 years.

At first glance, one might think that it is vital for commercial firms to have a good and precise prediction of the future state of the market in order to be able to make accurate investment decisions for new products. Still, uncertainty is always present, even with the most elaborate and sophisticated procedures.

The uncertainty increases with an increase in the time horizon about which a forecast is made. For models that try to say something about certain factors in a system way in the future, it might be wise to only partly make investment decisions where possible. This includes for instance postponing the full investments decision as long as possible (in the given problem) in the hope that with increasing time also the uncertainty decreases.

Such an approach to policy making usually does not focus on one single possible future with some range of uncertainty. On the contrary, for such an approach to function most effectively, the decision maker would like to have a range of plausible futures. This gives the opportunity to choose for the most robust option that, in as much plausible future scenarios as possible, has reasonable good outcomes.

What this particular research on aircraft technology and Sustainable Development does, is finding out if the aircraft technologies considered can give a more sustainable system state of the aviation system in any of the plausible scenarios of the aviation system for 2050. The broader the range of scenarios in which this is the case, the better instrument aircraft technology is for the problem owner to make a more sustainable aviation system state possible in 2050.

Before revealing the approach this research takes to create its range of plausible 2050 aviation system scenarios, first an overview is given of past attempts to make scenarios or predict future air travel demand.

Forecasts come from Airbus and Boeing, the two large civil aircraft manufacturers, and from ICAO, the international Civil Aviation Organization. The forecasted periods are between 10 and 20 years. The most important factor steering these forecasts is the GDP. But also travel behavior plays a role, as well as market maturation. Airbus and Boeing substantially differ in their ideas about whether the aviation system will develop further mainly as hub-and-spoke or as a point-to-point system. This does not lead to a substantially different insight in the total market development (in that, Airbus, Boeing and ICAO hardly differ), but it does make a difference in the amounts of the different types of aircraft the prediction models forecast to fly around in 20 years from now. Airbus, for instance, forecasts many more very large aircraft (A380 size and larger, so more than 550 passengers) to be flying around in 2020 than Boeing does. Boeing expects many more mid-size aircraft (200 to 300 passengers) that typically operate in a point-to-point system.

For these relative short term forecasts (up to, roughly, 2020), the assumptions made about what influences air travel demand can be done with some confidence. Many historical data, and thus trend lines, are available. Possible current changes in these trends can be observed today and explained. These explanations then also form a basis on which to make further assumptions about the future.

The mentioned forecasts roughly expect an annual 5% growth rate in air travel, thus a rough 2½ times growth of air travel demand in 20 years. For 2015 or 2020 this forecasting approach might be sufficient, but also 20 year forecasts contain uncertainty. Since, for the purpose of this research, ideas about the state of the aviation system in 2050 are necessary, it faces the problem of fast increasing levels of uncertainty. This research therefor adopts the scenario approach to manage this uncertainty. This is not different from existing approaches to get insight into how large air travel demand might be in 2050.

Several attempts at developing scenarios have been taken in the literature and a very well known (and widely cited) attempt is the FESG 2050 scenarios (FESG 1998). This study comes up with several possible curves along which air travel demand might develop itself between now and 2050. Historical data are used to make assumptions about how fast the different geographical markets in the world will mature. By assuming a range of possible values for a series of subfactors, FESG comes up with a high, medium and low growth scenario. Their scenarios for 2050 range from a three to eight fold increase in air traffic compared to the year 2000.

The FESG, and other, 2050 scenarios assume that there are no factors like limiting infrastructure, noise contouring or emission restrictions that might reduce air traffic growth. However, given past experience with extending air transport infrastructure (e.g. Schiphol Amsterdam’s fifth runway) and given fast increasing resistance against expanding airports or increasing traffic, it seems at least debatable whether these growth figures can be reached.

This research attempts to add two things to the discussion of air travel development till 2050. First, in contrast to complex and detailed existing models, it develops a very simple causal factor model that can easily be programmed in any spreadsheet program, so decision makers can quickly and roughly discover what possible influences certain factor value assumptions have on the 2050 air traffic size. Second, this research makes particular assumptions about the constraints to air travel development due to resistance within society against unlimited expansion of air travel infrastructure to always meet unrestricted air travel demand. Most existing models assume unrestricted growth of different speeds and sizes.

The factors driving this research’ model are based on factors used by existing models (FESG 1998; Boeing 2001; Airbus 2004), from literature and from experts. The different values for these factors stem from literature review and expert interviews. The next section covers this in detail.

5.4 Parameters driving air travel demand

External forces are forces that are beyond the control of the problem owner, but have effect in the system to analyze and thus on the outcomes of interest. The goal of this section is to identify those external forces that will lead to such changes in the aviation system that the demand for air travel (measured in available seats) will get influenced. We assume that there is a strong correlation between the number of available seats and the actual demand, especially given the long time frame till 2050.

The forces described in this section are based on a process that began with a literature review (covering the description of existing models that either predict future states of the aviation system or produce scenarios (FESG 1998; Boeing 2001; Airbus 2004)), which produced an initial list of forces. This list was then presented to experts working on the future of aviation or compared to publications of those experts reflecting their opinions (among others: Upham et al. 2003). With this information, the list of possible external factors influencing air travel demand was reduced to a list of relevant external forces which form the basis for scenario building (section 5.4).

GDP – Over the last 50 years, aviation growth has paralleled GDP growth. This correlation is almost perfect, so it makes sense to extrapolate it to the future, even to 2050.

Some authors disagree on using GDP as a basis for aviation growth forecasts in the future. GDP might predict unrestricted demand for air travel very well, but not restricted demand (Humpreys 2003). The unrestricted demand for air travel as predicted by GDP will require a lot more capacity of airports around the world than today. With examples of how long these enlargements of capacity nowadays take, due to a lot of pressure from people living nearby airports and a declining political will to let aviation grow unrestricted, Humphreys argues that the forecast based on GDP can never be realistic and must be much lower.

In addition to issues of capacity, there can also be unforeseeable issues, often referred to as trend breaks. The crude oil market, for instance, has shown that oil consumption and GDP were in perfect correlation until the 1973 oil crises, since when even the most conservative scenarios do not fit the real figures anymore. This trend break scenario was hardly predicted by anyone.

Related to GDP, for the general growth of air travel demand in the mature markets, an average 2.3% is assumed for the period 2004-2020 (Airbus 2004). After that period, on average over the remaining 30 years of the scenario 2% is assumed.

As some authors (Humpreys 2003) see the figures produced by Airbus and Boeing to be unreachable for Europe and North America in 2020 due to problems with capacity in noise, landside and airside, a low growth scenario for these areas will have a 2.3% growth between 2004 and 2010, after which no substantial further growth will take place (Table 5.1).

For Asia, for the next 20 years, enormous growth figures, of up to 9% per year, are assumed by the existing models. Indeed, the economic developments in Asia are such that a huge increase in aviation activities can be expected. No signs of forces that could reduce these high growth rates are yet there (like the political and societal resistance in Europe).

Areas outside Europe-North America and Asia are assumed to have growth percentages in between those of Europe-North America and Asia.

GDP driven growth is taken as a basis for the growth figures on which other factors will be imposed. Given no further change on other factors, this is the extrapolated growth, given the growth figures produced by Airbus and Boeing. However, factors like network, tourist focus et cetera will influence these numbers to a certain extent. Those effects will be discussed in the remainder of this section.

Maturation of markets – Especially the North American market, but to a lesser extent also the European air transport markets show signs of maturation, as they do not grow faster anymore than GDP. However, the Asian markets still show large growth figures.

As the relative (and absolute) number of people living in Asia is expected to increase dramatically in the next 50 years, any air travel demand growth figure in this area will have a substantial effect on the total world demand for air travel.

The issue is how long it takes before the market in Asia matures and the growth figures drop till a number closer to GDP growth.

For the Asian market, both Airbus and Boeing expect growth figures of around 9% until 2010 and 7% in the period 2010-2020. Linear extrapolation of this (a decrease of 2% every ten years) would result in a market maturation like the US and Europe of the Asian market (growth figures around 2%) around the year 2045.

However, markets that have joined the industrialized economy later have shown a much faster maturation than markets that joined earlier. Therefore, a more conservative scenario is also assumed in which the Asian market will have matured in 2025 (See Table 5.1).

Region	GDP driven % growth of air travel demand				
Year →	2004-2010	2011-2020	2021-2030	2031-2040	2041-2050
Europe and North America	2.3	2.3	2.3	2.0	2.0
Europe and North America Low growth	2.3	0.5	0.5	0.5	0.5
Asia - fast maturation	9.0	7.0	3.0	2.0	2.0
Asia - slow maturation	9.0	9.0	7.0	5.0	3.0

Table 5.1. Market maturation for air travel demand in the period 2000-2050.

Low cost carriers – Recently, low cost carriers have been the fastest growing and best performing airlines in the world. By introducing a different organizational culture and reducing what traditional airlines call “service level” and these airlines call “unwanted side issues” (like broad catering facilities and scheduled transfers), low cost carriers have been able to offer ticket prices affordable to almost everyone, even people with the lowest income. The no-frills approach appears to be very successful (Schiphol Group 2005).

While for airports, Low Cost Carriers might require a lot of changes (de Neufville 2006), recent developments of low cost carriers have changed air travel demand slightly, but not dramatically. It is expected that low cost carriers and their organizational culture will set a new trend in aviation, which gradually will spread out over the current market.

Network structure – Currently, the hub-and-spoke network structure is clearly the main way in Europe along which aviation networks are structured; several large hub airports connected by very thick passenger lines, and a star-like network (the spokes) that feed the big lines. This system effects the fleet of aircraft needed in a way that it needs a lot of small feeder aircraft, but also some very large aircraft on the main lines connecting the different hub airports.

The US network is currently more a point-to-point network, where smaller aircraft fly to many airports, even those further away, without the need for passengers to transfer. This system requires a lot of middle-sized aircraft. During flights it is more convenient for the passengers, but the network has less connections, as not all cities can easily be reached directly from every airport.

Changes in any of these networks, either more focus on point-to-point or hub-and-spoke, will largely effect the market for type of aircraft.

Although the hub-and-spoke system is still widely in use for flights arriving or departing from the European continent, signs show, that a change might be at hand. Overcrowded airports are not in the travelers advantage, the upcoming low cost carriers fly on relative small, cheap and flexible airports instead of the big ones. Hensgens (2003) foresees a big take over by the small airports in the world, which could mean the end of the hub-and-spoke system. On the contrary, Airbus, still forecasts a market for the very big aircraft. Not only 600 seaters, like their new A380, but even larger ones for 800 and 1000 passengers. While at the same time Boeing predicts a market for new very large aircraft of only 33 of these aircraft in 2020 and even those will be 'of the size of a 747 or larger'.

Thus, the network type is not assumed to have an influence on the number of seats flying around, but on their spreading among the different aircraft size categories. The assumed division of the growth figures among type of aircraft for the two different systems is presented in Table 5.2.

System	% growth of overall aviation growth for aircraft seats per category		
Aircraft type → ↓ Network system	<175 seaters	176-350 seaters	351< seaters
Hub-and-spoke network	50%	25%	25%
Point-to-point network	15%	75%	10%

Table 5.2. Division of total growth per category aircraft for hub-and-spoke and point-to-point network.

Focus of the tourist industry – Tourists form a large part of air travelers. Figures for Amsterdam Schiphol Airport (1999) show that around 50% of the passengers are tourists going on vacation trips. Although the business class passenger is the passenger the airline really earns money from, tourists in economy class determine for a large part which flights will be scheduled and which will not.

Therefore, the focus of the tourist industry on where the beautiful or 'hot' places in the world are where everybody should spend their holiday, has influence on which flights get scheduled (Geisler et al. 2003). The current focus on holidays far away from the home country (for example Europeans spending their holidays in Brazil or Thailand) increases the demand for long-range air travel. It also increases the modal share for air travel, since spending holiday within Europe is done often with the car or by train.

In this study, the focus of the tourist industry is assumed to be either long distance or short distance holiday destinations. Based on expert opinion this focus is assumed to result in an additional 0.5% overall growth per year in the case of a long distance focus and an additional –0.5% per year in the case of a short distance focus.

Travel Time Budget - All over the world a travel time budget appears to be almost constant, meaning not depending on GDP, technological development of the population or physical and spatial properties of the country. This means the total transport demand will increase proportionally to the increase of the average transport speed of the total transport system, but under the restriction of travel money budget (TMB) (Schafer and Victor 2000; Lee et al. 2001).

Though Travel Time Budget as a concept might predict the air transport demand very well, it cannot be used to understand the system in terms of causal relations and can therefore not be used in a scenario approach to cope with uncertainty in a policy analysis study.

The possible values for the main drivers for market development are presented in Table 5.3.

Scenario variable	Possible values	
GDP driven demand	See Table 5.1	
Maturation of Asian market	Around 2025	Around 2045
Substantial amount of Low Cost Carriers	Yes	No
Network	Hub-and-spoke	Point-to-point
Focus tourist industry	Long distance	Short distance

Table 5.3. Scenario variables and their possible values

5.5 Selection of relevant scenario variables

With expert opinion, as described under each external force in section 5.3, the external forces identified in the previous section have been grouped in the following 2x2 matrix, organizing them in order of uncertainty and impact (Table 5.4).

	Highly certain	Highly uncertain
Low impact on outcomes	Low cost carriers	
High impact on outcomes		GDP driven demand Maturation of Asian market Network (HaS/PtP) Focus of tourist industry

Table 5.4. Categorizing external forces.

GDP will be the basis for every scenario, as in their forecasts Airbus (2000, 2004) and Boeing (2001) make predictions for 2020 and 2023 based in GDP growth. However, one has to take into account the capacity problem, so also a “low growth scenario”, (a standstill in growth of restricted air travel demand after 2020) is included. In addition to this, the scenario variables that will be varied to get the different scenarios are the maturation of the Asian market (fast or slow), the type of network that is operational (Hub-and-spoke versus Point-to-point), and the focus of the tourist industry (either short haul or long haul).

5.6 Modeling equations and calculation

To start calculating several plausible scenarios for air travel demand in 2050, this research starts with the most recent available data about air travel as available from Airbus (2004). This data gives number of seats flying around in the different geographical locations of the world. It also gives data about the type of aircraft flying around.

The first step taken is a categorization of regions (Europe and North America, Asia, and the rest of the world). Europe and North America are taken together, because the prediction of Airbus and Boeing is that these two regions will have comparable growth figures in the next decades (the markets in both regions are assumed to have or almost have fully matured). Asia is predicted to have higher growth figures and assumed to develop in a different way than Europe and North America. The same holds true for the category 'rest of the world'.

A second step is to categorize aircraft in aircraft size (< 175 seats, 175-350 seats, >350 seats). Some technologies will be applicable to for instance only smaller aircraft, while others replace old technology in all three size categories. As no detailed information about the spread of aircraft sizes around the world could be found, it is assumed that the worldwide valid numbers for amount of aircraft in each category are comparable valid also for the three geographic regions Europe andNorth America, Asia, and the rest of the world).

The input for the calculations is, summarizing, number of aircraft seats in three aircraft size categories (< 175 seats, 175-350 seats, >350 seats) in three geographic regions (Europe and North America, Asia, rest of the world). Given the data from Airbus, roughly 50% of the market is currently in the region Europe and North America, 25% in Asia and 25% in the remaining rest of the world. In number of seats this results in the following Table 5.5.

Market area	Share (%)	Aircraft (#)	Seats (#)
Europe – North America	50	5419	1049028
Asia	25	2710	524514
Rest of the world	25	2710	524514
total	*100*	*10838*	*2098056*

Table 5.5. Number of aircraft and aircraft seats per region in the year 2004

When all aircraft are counted (situation in 2004: (Airbus 2004)) in the three mentioned categories, it turns out that 46% of the seats is in small aircraft (<175 seats), 40% is in medium sized aircraft (175-350 seats) and 17% is in large aircraft (>350 seats). Applying this to the table above gives the following Table 5.6.

Market area	Year 2004 situation in seats (#)
Europe-North America	*1049028*
<175 seat category	480378
175-350 seat category	414596
>350 seat category	154054
Asia	*524514*
<175 seat category	240189
175-350 seat category	207298
>350 seat category	77027
Rest of the world	*524514*
<175 seat category	240189
175-350 seat category	207298
>350 seat category	77027
Total all regions	*2098056*

Table 5.6. Number of seats specified per region and per aircraft size category (in 2004).

Now the total number of seats in each category of aircraft size and each market region in the world is known, the growth figures need to be determined. Each region has different growth figures per year for different 10-year periods, as can be seen in Table 5.1. Upon this growth figure, the effect of the focus of the tourist industry has to be superimposed. Basically, that is not more than the assumed growth percentage value for a year's period due to the focus of the tourist industry adding to the growth figures given in Table 5.1. If the focus of the tourist industry would be on long haul, adding 0.5% growth per year, the growth figures for the different regions in the different time intervals would be the following (Table 5.7). As explained earlier, for the region 'rest of the world', as growth percentage the average of the two other regions is assumed.

Region	GDP driven % growth of air travel demand				
Year →	2004-2010	2011-2020	2021-2030	2031-2040	2041-2050
Europe and North America	2.8	2.8	2.8	2.5	2.5
Europe and North America Low growth	2.8	1.0	1.0	1.0	1.0
Asia - fast maturation	9.5	7.5	3.5	2.5	2.5
Asia - slow maturation	9.5	9.5	7.5	5.5	3.5

Table 5.7. Growth figures for long haul tourist industry focus.

Given the growth figures for the period 2004-2010 for Europe and North-America (2.8% per year), and given the total number of seats available for this area in 2004 (926321, see Table 5.6) in 2010 (6 time periods), the total number of seats would then be:

$$1049028 \cdot (1.028)^{6} = 1238072$$

This is, however, the total growth. Given the network structure (hub-and-spoke or point-to-point) this growth must be spread over the different aircraft size categories given the values of Table 5.2. If the network is assumed to develop as hub-and-spoke network, the smallest aircraft category (<175 seats) should increase with 50% of the growth (that is 50% of 1238072-1049028 equals 94522 seats), the medium sized and large aircraft category should both increase with 25% of that growth (47261 seats). For the year 2010 this would then lead to the following figures (Table 5.8).

Market area	Year 2004 situation in seats (#)	Year 2010 situation in seats (#)
Europe-North America	*1049028*	*1238072*
<175 seat category	480378	574900
175-350 seat category	414596	461857
>350 seat category	154054	201315
Asia	*524514*	*904153*
<175 seat category	240189	430008
175-350 seat category	207298	302208
>350 seat category	77027	171937
Rest of the world	*524514*	*750373*
<175 seat category	240189	353118
175-350 seat category	207298	263763
>350 seat category	77027	133492
Total all regions	*2098056*	*2892597*

Table 5.8. Market development scenario for 2010, assuming hub-and-spoke system, long haul focus of tourist industry, normal growth in Europe-North America and slow market maturation in Asia.

The most interesting scenarios, from the point of view of this research, are the ones with the most seats and least seats. This is because the research seeks to find out in what future scenarios aircraft related technology can contribute to Sustainable Development.

If, in the largest growth scenario, the situation as reflected by the values on the indicators of chapter 3 improves, then we conclude that in all plausible futures given the knowledge of today, aircraft technology can contribute to Sustainable Development. If the situation deteriorates in the largest scenario, but improves in the smallest growth scenario, one knows that there is a possibility for aircraft technology to contribute to Sustainable Development, but that it is unlikely that it will happen always. If even in the smallest growth scenario the situation deteriorates, then it is likely that the expert selected aircraft technologies can not contribute to Sustainable Development in the aviation sector.

The question then would be what will happen if no new technology is implemented. The difference between the effects for implementing new technology and not implementing it, is a measure for how much aviation technology can make the situation ‘less bad’. It gives an idea about the value of implementing technology as one of the measures to reach sustainability. Maybe it turns out that technology, though not improving the situation, can still almost maintain current sustainability levels. In that case, it might be wise to make use of this technology and combine it with other, non-technical, measures to increase sustainability levels. If, however, implementing technology would hardly make a difference, then it would probably be wise to invest all available time and money in other than technology measures to reach sustainability.

To get the smallest and largest growth scenarios, the calculations as shown above are repeated for the whole time period till 2050 and also for all possible combinations of factor values. All the possible combinations and their numerical results in terms of seats are presented in the next Table 5.9.

Growth in Europe-North America due to GDP	Maturation Asian market	Network type *(no influence on number of seats)*	Focus tourist industry	Number of seats according to these assumptions
Normal	Fast	HaS	Short distance	6789983
Normal	Fast	HaS	Long distance	10602103
Normal	Fast	PtP	Short distance	6789983
Normal	Fast	PtP	Long distance	10602103
Normal	Slow	HaS	Short distance	12348471
Normal	Slow	HaS	Long distance	**19131827** *scenario A*
Normal	Slow	PtP	Short distance	12348471
Normal	Slow	PtP	Long distance	**19131827** *scenario A*
Low	Fast	HaS	Short distance	**5220388** *scenario B*
Low	Fast	HaS	Long distance	8161396
Low	Fast	PtP	Short distance	**5220388** *scenario B*
Low	Fast	PtP	Long distance	8161396
Low	Slow	HaS	Short distance	10480860
Low	Slow	HaS	Long distance	16235090
Low	Slow	PtP	Short distance	10480860
Low	Slow	PtP	Long distance	16235090

HaS = Hub-and-Spoke network
PtP = Point-to-point network

Table 5.9. Numerical results in terms of seats for all possible scenarios given the selected external forces.

In the next two sections, the two most extreme scenarios in terms of numbers of seats are examined in more detail. In each case, two cases are examined. The situation with a dominant point-to-point network and the situation with a dominant hub-and-spoke network

5.7 Highest number of seats

Scenario A1: Point-to-point network system

The expected large and long-lasting growth of air transport in Asia has become reality, as it took until 2045 until that market matured. After the maturation of the Asian market around 2045, no further significant growth over GDP growth has taken place in air transport demand worldwide; aviation continues to grow slightly at a 2% rate per year. On all the airports, people have found ways to cope with the ever bigger getting problem of congestion and environmental capacity, therefore it had been possible to achieve this large growth and it is still possible for aviation to grow at mild rates.

The tourist industry has been booming over the last half century; together with it the operators that fly on long haul holiday destinations, this has boosted extra the demand for air travel. “The further away, the better holiday” has become the motto. Aviation is the only way to get there within an acceptable amount of time.

In scenario A1, the point-to-point has worldwide taken over from the in earlier days more common hub-and-spoke system to become the most dominant system in the world. Large aircraft, comparable to the Airbus A380, are not very successful. Smaller aircraft of 200 to 300 seats are booming business.

This scenario A1 is numerically summarized in Table 5.10.

Scenario A1 Point-to-point year→ ↓market	2004	2010	2020	2030	2040	2050
Europe – North America						
<175 category	480378	574900	771783	1031284	1332492	1718065
176-350 category	414596	461857	560298	690049	840653	1033439
>351 category	154054	201315	299756	429507	580111	772897
total	*1049028*	*1238072*	*1631838*	*2150840*	*2753257*	*3524401*
Asia						
<175 category	240189	430008	1098280	2287005	3922162	5541658
176-350 category	207298	302208	636344	1230706	2048285	2858032
>351 category	77027	171937	506073	1100435	1918014	2727761
total	*524514*	*904153*	*2240696*	*4618146*	*7888460*	*11127452*
Rest of the world						
<175 category	240189	353118	659403	1103936	1644693	2217919
176-350 category	207298	263763	416905	639171	909550	1196163
>351 category	77027	133492	286634	508900	779279	1065892
total	*524514*	*750373*	*1362941*	*2252007*	*3333521*	*4479974*
Total all categories	*2098056*	*2892597*	*5235475*	*9020993*	*13975238*	*19131827*

Table 5.10. Numerical values for seats for each geographic region, for each aircraft size category for several years, representing the high growth scenario A1 (point-to-point).

Scenario A2: Hub-and-Spoke network system

In scenario A2, the Hub-and-Spoke system is the most dominant system in the world. Large aircraft, comparable to the Airbus A380 and larger, are very successful. The long lasting growth figures and the focus of the touring industry are the same as in scenario A1.

Scenario A2 is numerically summarized in Table 5.11.

Scenario A2 Hub-and-Spoke year→ ↓market	2004	2010	2020	2030	2040	2050
Europe – North America						
<175 category	480378	508735	567799	645650	736012	851684
176-350 category	414596	556379	851703	1240955	1692768	2271126
>351 category	154054	172958	212335	264235	324477	401591
total	*1049028*	*1238072*	*1631838*	*2150840*	*2753257*	*3524401*
Asia						
<175 category	240189	297135	497616	854234	1344781	1830630
176-350 category	207298	492027	1494435	3277522	5730258	8159501
>351 category	77027	114991	248645	486390	813422	1137321
total	*524514*	*904153*	*2240696*	*4618146*	*7888460*	*11127452*
Rest of the world						
<175 category	240189	274068	365953	499313	661540	833508
176-350 category	207298	376692	836118	1502918	2314053	3173893
>351 category	77027	99613	160870	249776	357928	472573
total	*524514*	*750373*	*1362941*	*2252007*	*3333521*	*4479974*
Total all categories	*2098056*	*2892597*	*5235475*	*9020993*	*13975238*	*19131827*

Table 5.11. Numerical values for seats for each geographic region, for each aircraft size category for several years, representing the high growth scenario A2 (hub-and-spoke).

5.8 Lowest number of seats

Scenario B1: Point-to-point network system

The Asian market, much faster than expected, has matured around 2025, after which no further significant growth higher than GDP growth has taken place. Aviation hardly grows anymore, definitely not in the old matured markets in Europe and North-America. As the adverse effects of congestion and noise have become so substantial it is not possible anymore for aviation to grow, even not at mild rates.

The tourist industry is focusing on short haul holiday destinations, as it has become very popular to spend holidays on the own continent, preferably where it is sunny and usually not more than an approximate 8 to 13 hour drive by car. Aircraft hardly play any role in this, other than flying people to some holiday islands that remain popular, but not to a large extent.

In scenario B1, the point-to-point has worldwide taken over from the in earlier days more common hub-and-spoke system to become the most dominant system in the world. Large aircraft, comparable to the Airbus A380, are not very successful. Smaller aircraft of 200 to 300 seats are booming business.

This scenario is numerically summarized in Table 5.12.

Scenario B1 Point-to-point year→ ↓market	2004	2010	2020	2030	2040	2050
Europe – North America						
<175 category	480378	498156	498156	498156	498156	498156
176-350 category	414596	503484	503484	503484	503484	503484
>351 category	154054	165906	165906	165906	165906	165906
total	*1049028*	*1167545*	*1167545*	*1167545*	*1167545*	*1167545*
Asia						
<175 category	240189	289871	402460	469945	519462	576927
176-350 category	207298	455708	1018651	1356080	1603661	1890988
>351 category	77027	110148	185207	230198	263209	301519
total	*524514*	*855728*	*1606318*	*2056223*	*2386331*	*2769434*
Rest of the world						
<175 category	240189	267854	307933	327301	340163	354023
176-350 category	207298	345621	546020	642856	707168	776469
>351 category	77027	95470	122190	135101	143676	152916
total	*524514*	*708945*	*976143*	*1105258*	*1191007*	*1283408*
Total all categories	*2098056*	*2732218*	*3750006*	*4329026*	*4744883*	*5220388*

Table 5.12. Numerical values for seats for each geographic region, for each aircraft size category for several years, representing the low growth scenario B1 (point-to-point).

Scenario B2: Hub-and-Spoke network system

In scenario B2, the Hub-and-spoke network has stayed the most dominant system in the world. Large aircraft, newer and larger versions comparable the Airbus A380 are very successful.

This scenario is numerically summarized in Table 5.13.

Scenario B2 Hub-and-Spoke year→ ↓market	2004	2010	2020	2030	2040	2050
Europe – North America						
<175 category	480378	539637	539637	539637	539637	539637
176-350 category	414596	444225	444225	444225	444225	444225
>351 category	154054	183683	183683	183683	183683	183683
total	*1049028*	*1167545*	*1167545*	*1167545*	*1167545*	*1167545*
Asia						
<175 category	240189	405796	781091	1006044	1171097	1362649
176-350 category	207298	290101	477749	590225	672752	768528
>351 category	77027	159830	347478	459954	542481	638257
total	*524514*	*855728*	*1606318*	*2056223*	*2386331*	*2769434*
Rest of the world						
<175 category	240189	332405	466003	530561	573435	619636
176-350 category	207298	253406	320205	352484	373921	397022
>351 category	77027	123135	189934	222213	243650	266751
total	*524514*	*708945*	*976143*	*1105258*	*1191007*	*1283408*
Total all categories	*2098056*	*2732218*	*3750006*	*4329026*	*4744883*	*5220388*

Table 5.13. Numerical values for seats for each geographic region, for each aircraft size category for several years, representing the low growth scenario B2 (hub-and-spoke).

The scenarios as discussed in the section earlier in this chapter will serve as a basis for the further analysis in the next chapter. In there, for each of the scenarios a scorecard will be constructed in which the effects of aircraft related new technology will be represented by scores on the outcome indicators designed in chapter 3.

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6. Scoring technology in future scenarios

6.1 Introduction

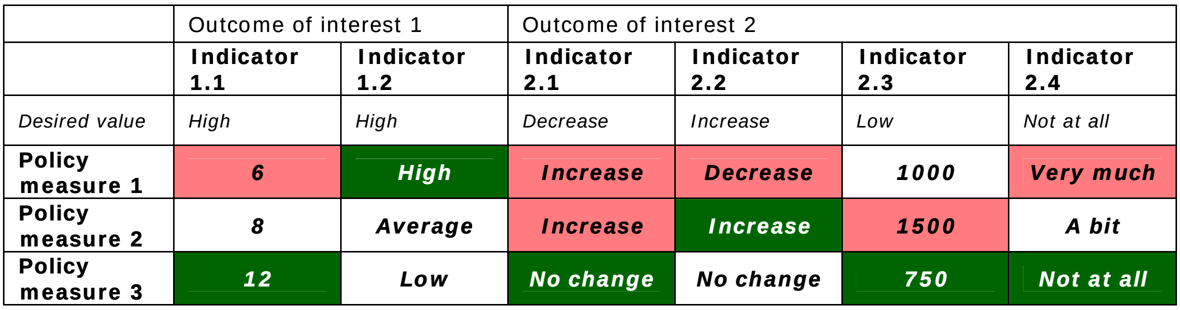
In the last five chapters, all elements have been collected to perform the scoring step (‘analyzing the alternatives’) in a systems analysis: in chapter 1, the problem has been identified, in chapter 3 the actors, their interests and the indicators representing these interests have been identified, in chapter 4 the alternative policy measures have been identified and in chapter 5 the possible future states of the aviation system in 2050. Now, in this chapter, the alternatives can be analyzed.

This chapter has as its goal to assign values to the several indicators for Sustainable Development (designed in chapter 3) for the several situations (with or without implementation of new technologies) in the several designed plausible scenarios (see chapter 5). These scoring patterns will be compared to each other (to show the difference technology can make) and to the situation in the year 2004 (to see if any improvements can be made with respect to Sustainable Development). This analysis result can then answer the research question to what extent the expert selected aircraft related technologies are capable of contributing to Sustainable Development.

This chapter starts explaining what scorecards are (section 6.1). After this, the base case is introduced. This case describes the situation as it is in the year 2004. This case is introduced for comparison to other possible future cases. Then, in section 6.3, the reference case is introduced about possible situations in the year 2050. Neither in the base case, nor in the reference case new technology is implemented. In section 6.4 the new technology cases, in which the new aircraft related technologies are implemented in the several scenarios of chapter 5, are introduced and scored. Finally, section 6.5 draws conclusions out of all the scoring patterns by comparing them to each other.

6.2 Scorecards

As mentioned in chapter 2, this research uses scorecards to present the results of its analysis. A scorecard has all the alternatives that have to be analyzed in rows. The columns each represent an indicator that measures a certain performance that is of interest to a decision maker. To illustrate this, the figure of a scorecard as presented in chapter 2 is repeated here (Figure 6.1). Note that the scores in the scorecard do not necessarily have to be numerical.



	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***

Figure 6.1. An example of a scorecard (repeated figure from chapter 2).

In the last chapter, several plausible scenarios were designed for the possible future state of the aviation system in 2050 in terms of air travel demand. Introducing new technology into the aviation system will change that system. As a result from this, the system will produce different values for the outcomes of interest. It is these values (values on the indicators representing the outcomes of interest) that are of interest to the problem owner. This is the reason why the analysis is done in the first place.

However, the system can also change because external factors acting on the system beyond the control of the problem owner change in value. The changes in the external factor values will also make changes in the system and also produce different outcomes. Since it is unknown how the external factor values will develop over time, several possible scenarios are constructed. For decision makers it is important to know the effect of the alternative expert selected aircraft technologies in each of the plausible future scenarios. Each scenario, therefore, has one scorecard.

This set of scores on the indicators for Sustainable Development is the final product of the research, which is then presented to the problem owner. Here is where the analysis ends and decisionmakers can now make use of these results in their decisionmaking process; in this case on what to do with the undesired effects of aviation.

It is possible to take the analytical process one step further. What is done then is to try to rationalize the implicit ideas in the decisionmakers' thoughts about the relative importance of the different indicators. These implicit ideas are explicitly translated into weight factors. As long as the scores on the criteria are all numerical and normalized, introducing weight factors (and multiplying and adding up scores) leads to a ranking of alternatives. However, lots of speculation is introduced when weight factors are determined. In addition, in a lot of cases, if not most, the scores on the scorecard are mixed forms of numerical and non-numerical (e.g. 'larger than', 'good', 'blue'). This makes weight factors use impossible. But maybe the most important reason of all is that making decisions is the job of the decision maker. It is not an easy task. It is very complex and requires lots of experience and skills. A policy analysis, as this study is, can be of help in a decision making process, but can not replace it.

6.3 Base case: the situation in 2004

In every policy analysis study there has to be a case to which the possible new situations (given the external forces), with new instruments implemented can be compared. This study tries to find out whether implementing certain expert selected promising aircraft related technologies can contribute to Sustainable Development. Time of full implementation of these technologies is the year 2050. This situation then has to be compared to the situation in the year 2004. These two moments in time differ so much from each other since it takes so long before new innovative aircraft related technology is developed, certified and has fully replaced the old technology (as described in the chapters 1, 4 and 5).

All indicators have specified units (e.g. ton/yr or km^2). In principle the 2004 base case could be scored with pure raw data given in their particular units. There are two reasons for not doing this. One is that for a lot of indicators the absolute numerical values cannot be found or the values found are (very) speculative. The second reason is that, for this study, there is also no need to score the 2004 base case in absolute numerical numbers. This research does not measure the state of sustainability in absolute terms. It only wants to compare several possible future aviation system states to each other and to the situation in the year 2004. It is all about relative change. Does the situation improve or deteriorate, and, if so, to what extent? What is needed are the *differences* in scoring patterns (rather than the absolute values) on the indicators representing Sustainable Development due to the effects of implementing aircraft related technology and the effects of the external factor air travel demand.

For the base case, the aviation system state in the year 2004 regarding Sustainable Development, all scores on the indicators are therefore set to 1. Needless to say this does not give any information about the sustainability level of the system in 2004.

6.4 Reference case: the system in 2050 without new technology

In the reference case (in the year 2050) no new technology is implemented in the system. It is therefore a hypothetical case, as, of course, the aviation system will for sure undergo some technical changes in the next years until 2050. The values of the outcome indicators for the reference case are different from those for the base case only due to the effects of changes in the external factor air travel demand. No other effects are taken into account, as, see chapter 2 and 5, no other effects out of the problem owner's span of control are assumed to act upon the aviation system that can cause changes in the outcomes of interest.

The objective of the research is to get a clear picture of what difference new aircraft related technology can make in the system with respect to Sustainable Development. First, therefore, a clear picture must be constructed about the aviation system in 2050 without the effect of new technology, so there is something to compare the effects of technology to. This comparison opportunity is the reason to create the reference case.

Air travel demand models function as the basis for many emission models in the literature (IPCC 1999). These demand models give some idea about the total air travel demand in a possible future state of the aviation system. From these ideas of air travel demand, the required number of flights to fit that demand is constructed. This number of flights is then an indication for the size of the total emissions from aviation activities. Emission models usually take technological development into consideration, especially when they want to generate emission information about times far in the future. Usually they take into account a certain percentage efficiency gain per certain time span due to technological developments. It is important to note that this percentage efficiency gain per unit of time is not included in the reference case. This research focuses on what certain expert selected technologies can contribute to Sustainable Development; including this increased technological efficiency in the reference case would make this impossible.

Since the reference case is based exclusively on the effects of the external factors, assumptions have to be made about the relations between the external factors and the indicators representing the outcomes of interest. This section addresses these relations one by one.

6.4.1 *Capacity coverage and area coverage* *(indicators PE1.1, PE1.2 and PE1.6)*

A lot of airports around the world have a noise contour to prevent citizens living close to airports from experiencing too much aircraft noise. There are constant political fights about the boundaries of the noise contour, the way the amount of noise is determined (either measured or modeled) and the type of aircraft being allowed to land and take-off at that airport. It seems obvious (given the political fights) that current air travel demand is higher than what can actually be achieved. In other words, the restricted air travel demand is smaller than the unrestricted air travel demand. It is the restricted air travel demand that we can actually measure by counting the number of actual air travelers. We can only make assumptions and educated guesses about how this restricted demand will rise when restrictions like noise contours are removed, and thus when restricted air travel demand becomes unrestricted air travel demand.

Nevertheless, in both the smallest and the highest growth scenario, many more seats are flying around than today. So, in one or another way it must be assumed that the just mentioned problems around the extension of air transport infrastructure must, at least partly, have been resolved.

All these extra, new seats that are flying around compared to the situation in 2004 can be there due to extra flights between cities that were previously already connected. It is, however, likely that also new city pairs will have been added to the existing list. More travelers also mean that it is economically feasible to fly now between city pairs and make a profit where that was impossible in 2004.

Because of the earlier mentioned maturation of existing markets, the growth is expected to be especially in the new markets (Boeing 2001; Humpreys 2003; Airbus 2004). This research therefore assumes no new large European airports (PE1.5 equals 1 in both scenarios A and B) and that roughly two-third of the increase in seats in aircraft in a particular region of the world can be attributed to newly connected places (indicator PE1.1, EU area only), while one-third is attributed to an increase in flight frequency (indicator PE1.2, EU area only). Parallel reasoning gives an increase in EU remote area airports (indicator PE1.6). These increases are for 2050:

PE1.1: (Scenario A High Growth, table 5.10, column 2 row 6 divided by column 6 row 6)
$1+2/3*(3524401/1049028)=1+2.24$

PE1.1: (Scenario B Low Growth, table 5.11, column 2 row 6 divided by column 6 row 6)
$1+2/3*(1167545/1049028)=1+0.74$

PE1.5 (Scenario A High Growth) = 1

PE1.5 (Scenario B Low Growth) = 1

The values for indicator PE1.2 and PE1.6 are half of these, as 1/3 instead of 2/3 of the growth is attributed to this indicator. For the low growth scenario, simply the appropriate values for number of seats from Table 5.10 have to be substituted in the above equations. The average distance to a large international airport (worldwide, not in EU area only) will decrease, only by what amount exactly can not be determined.

PE1.2: (Scenario A High Growth, table 5.10, column 2 row 6 divided by column 6 row 6)
$1+1/3*(3524401/1049028)=1+1.12$

PE1.2: (Scenario B Low Growth, table 5.11, column 2 row 6 divided by column 6 row 6)
1+1/3*(1167545/1049028)=1+0.37

PE1.6: (Scenario A High Growth, table 5.10, column 2 row 6 divided by column 6 row 6)
1+1/3*(3524401/1049028)=1+1.12

PE1.6: (Scenario B Low Growth, table 5.11, column 2 row 6 divided by column 6 row 6)
1+1/3*(1167545/1049028)=1+0.37

6.4.2 Safety *(indicators PE2.1, PE2.2, PE2.3 and PE2.4)*

Historically, since the start of commercial aviation, the safety record of aviation has improved dramatically, though over the last couple of decades no further improvement has been signaled. Taken over the last two decades, Figure 6.2 shows that there is no clear tendency in US domestic flights; the number of incidents and fatalities is between 0.0065 and 0.0070 per 1 million flown miles, which means around 1 fatality per 166 billion flown passenger miles.

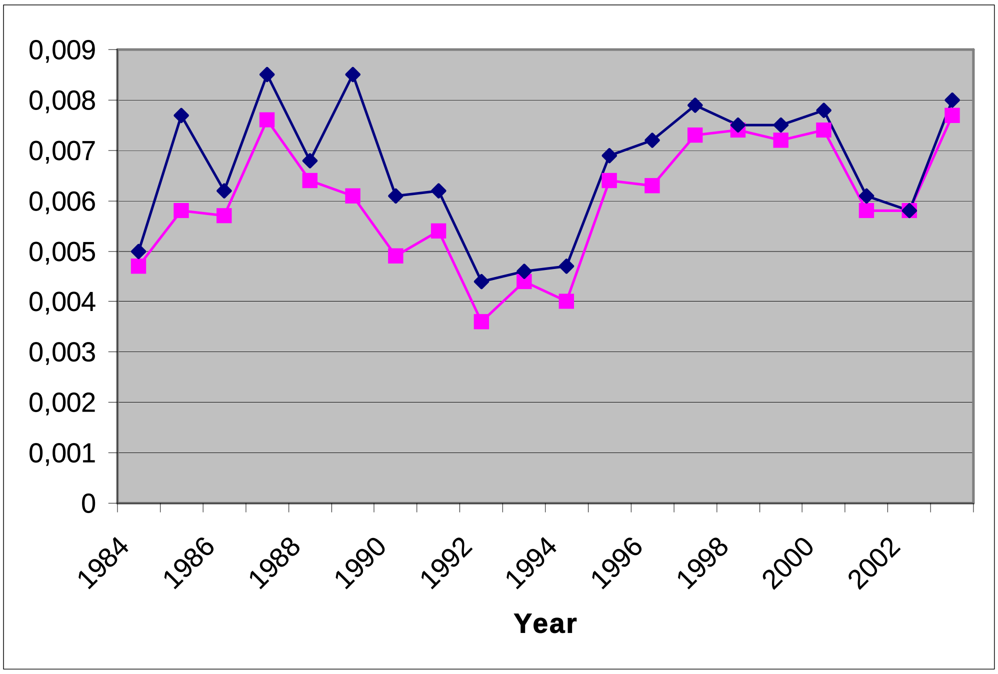


Figure 6.2. Aviation incidents (dark grey or blue) and fatalities (light grey or purple) both per 1 million miles flown in US domestic flights for the period 1984-2003. Source: NTSB (United States)

For this study, no increasing or lowering trend in this figure will be assumed due to increases in traffic (as is the case in all scenarios). It is very unlikely that the growth of air travel will be accepted at a cost in safety, meaning more casualties per unit of flown distance. Only the used safety indicator PE2.4 “External safety weight of risk” will linearly increase with traffic growth, as by definition this indicator is a linear function of, among other things, number of flight movements (see chapter 3). The value of indicator PE2.4 is determined by the total growth in seats for both scenarios considered (Table 5.10 for scenario A high growth and Table 5.11 for scenario B low growth): 19131827 and 5220388 respectively compared to the number of seats in 2004 (2098056). Dividing both numbers gives:

PE2.4: (Scenario A High Growth, table 5.10, column 2 last row divided by column 6 last row)
1+(19131827/2098056)=1+9.12

PE2.4: (Scenario B Low Growth, table 5.11, column 2 last row divided by column 6 last row)
1+(5220388/2098056)=1+2.49

6.4.3 Fuel use and emissions *(indicators PE3.1, PE3.2, PE3.3 and PE3.4)*

The International Air Transport Association calculated a decrease of 70% in fuel use per seat kilometer flown over 100km since 1970. They expect in the next 10 years a further decrease of fuel use per seat kilometer. However, they expect this decrease to happen due to the introduction of technology. As this study tries to find out what role certain technologies can play in contributing to Sustainable Development (and fuel use is part of that concept), it should not in its reference case assume reduction in fuel use due to technological improvements. This research, thus, assumes for the reference case a linear increase in fuel use with the growth of air travel demand. Traditionally, fuel use is measured in amount of fuel used per landing and take-off cycle (LTO cycle). Although the number of LTOs increases in both scenarios, nothing in either the technology or anything else changes, so each LTO still requires the same amount of fuel. As no new technology is implemented, and current technology does not make use of renewable fuels, also in the reference case no renewable fuels will be used. The indicators PE3.1, PE3.2, PE3.3 and PE3.4 will therefore all be scored equally 1:

PE3.1 (Scenario A High Growth) = 1
PE3.1 (Scenario B Low Growth) = 1

PE3.2 (Scenario A High Growth) = 1
PE3.2 (Scenario B Low Growth) = 1

PE3.3 (Scenario A High Growth) = 1
PE3.3 (Scenario B Low Growth) = 1

PE3.4 (Scenario A High Growth) = 1
PE3.4 (Scenario B Low Growth) = 1

6.4.4 Ticket price and direct operating costs *(indicators PE1.4 and PR2.1)*

The final price of a ticket (indicator PE1.4) is determined by a set of market forces that technology is hardly capable of influencing. However, technology can make flying more efficient in terms of cost per flown seat kilometer, thereby reducing the direct operating costs (indicator PR2.1) for the airlines (for instance by improving an aircraft's fuel economy). A reduction in direct operating costs can be used by the airlines for several purposes. The airlines may decide, for instance, to have a more competitive pricing strategy, by lowering its ticket prices. This is, of course, no fixed rule; airlines can use the margins they receive from lower direct operating costs for anything. It is not expected that current technology, without any substantial changes, is capable of seriously lowering current direct operating costs. So:

PE1.4 (Scenario A High Growth) = 1

PE1.4 (Scenario B Low Growth) = 1

PR2.1 (Scenario A High Growth) = 1

PR2.1 (Scenario B Low Growth) = 1

6.4.5 Number of airlines (indicator PR3.2)

In a larger market, more airlines will be able to make a profit. It is therefore likely that in any (substantial) growth scenario, more airlines will be operating. However, so many variables will influence the development of the exact number of airlines, that scoring this indicator in this study is done qualitative (i.e. non numerical). For the reference case in both the high growth and low growth scenario, this indicator is scored with the label 'increase'.

PR3.2 (Scenario A High Growth) = increase

PR3.2 (Scenario B Low Growth) = increase

6.4.6 Noise generation (indicator PL4.1)

Over the last couple of decades aircraft have become much more silent. This happened mainly by the introduction of new technologies as the turbo fan engine and the turbo prop engine. IATA documents that jet aircraft are nowadays around 80% less noisy than 40 years ago. IATA projects another 50% reduction in the generation of noise to be reached by 2020. However, this 50% reduction is said to be possible only with research on new technologies and introducing them. Therefore, no further noise reduction from current technologies is assumed in this study. For the different scenarios, proportionally more noise is assumed as traffic increases. However, noise is perceived and interpreted by humans. The result of this is that the same measured energy level of noise (in dB) can be disturbing for one person in a certain context, while it gets hardly noticed by another. Therefore this study uses only one indicator (see chapter 3) for specific technology compared to older technology (for more details and discussion, see section 3.5.2). As no new technology is introduced in the reference case, indicator PL4.1 will be scored equal and unchanged (as 1) in both scenarios.

PL4.1 (Scenario A High Growth) = 1

PL4.1 (Scenario B Low Growth) = 1

6.4.7 Land use *(indicator PL3.1)*

Land use of an airport is determined by the total of all aviation related activities. It will however not be completely proportional to the growth of air travel (if no substantial technological changes will be implemented) as every airport has some equipment (e.g. fire department), buildings (e.g. control tower), infrastructure (e.g. safety escape routes, car parking places) that it needs, being either small or large. However, as all this equipment and infrastructure gets used more heavily, it will also have to increase in size, and thus in use of land, with increasing traffic. For simplicity, this study therefore assumes a linear growth of land use by aviation activities, parallel to traffic growth (for calculation details see indicator PE2.4 under “Safety”).

PL3.1 (Scenario A High Growth) = 1+9.12

PL3.1 (Scenario B Low Growth) = 1+2.49

Based on the assumptions made in this section and the previous, the scores for the base case (in 2004) and the reference case (with two scenarios for 2050) are summarized in Table 6.1.

Code	Outcome indicator	Desired value or direction of change	Score Base Case I (2004)	Score Base Case II Low Growth (2050)	Score Base Case II High Growth (2050)
PE1-1	Number of connected geographical places via operated air routes in the EU.	increase	1	1+0.74=1.74	1+2.24=3.24
PE1-2	Average frequency of flight between two airports within the EU area.	increase	1	1+0.37=1.37	1+1.12=2.12
PE1-3	Average ticket price for flight.	decrease	1	1	1
PE1-4	Average distance to larger, international airport.	decrease	1	Decrease, <1	Decrease, <1
PE1-5	Number of operated larger, international airports in EU area.	increase	1	1	1
PE1-6	Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.	increase	1	1+0.37=1.37	1+1.12=2.12
PE2-1	Number of internal fatalities in aviation.	decrease	1	1	1
PE2-2	Number of internal incidents in aviation.	decrease	1	1	1
PE2-3	Number of aircraft crashes involving aircraft >150 passengers.	decrease	1	1	1
PE2-4	External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)	decrease	1	1+2.49=3.49	1+9.12=10.12
PE3-1	Average fuel use per LTO cycle	decrease	1	1	1
PE3-2	Average emission of NO_x per LTO cycle	decrease	1	1	1
PE3-3	Average emission of CO per LTO cycle	decrease	1	1	1
PE3-4	Average emission of VOCs per LTO cycle	decrease	1	1	1
PE5-1	Different type of aircraft in service	increase	1	1	1
PL1-1	Total emission of CO_2 during flight operations	decrease	1	1+2.49=3.49	1+9.12=10.12
PL2-1	Percentage of renewable fuel of the total amount of fuel used	increase	1	1	1
PL3-1	Land unavailable for other than aviation purposes	decrease	1	1+2.49=3.49	1+9.12=10.12
PL4-1	Noise production of specific innovative aviation technology	decrease	1	1	1
PR2-1	Direct operating cost	decrease	1	1	1
PR3-1	Number of innovative aviation technologies in use	increase	1	1	1
PR3-2	Number of airlines operating	increase	1	Increase, >1	Increase, >1
PR3-3	Number of transport modes for continental transport (including aviation)	increase	1	1	1
ASI2-1	Percentage of flights leaving the airport according to schedule	increase	1	1	1
ASI2-2	Average turn around time	decrease	1	1	1
ASI2-3	Changes in design and maintenance of aircraft	small	1	1	1
ASI3-1	Design risk of innovative technology	small	1	1	1

Table 6.1. Scores for the base case and reference case.

6.5 Policy case: Scoring the aviation system in 2050 with new technologies

6.5.1 Introduction

This section's goal is to determine what all promising technologies (identified in chapter 4) will do in the two scenarios for 2050 (see chapter 5) on the indicators designed to measure the contribution to Sustainable Development (see chapter 3). In the last section such an exercise has been performed for current implemented aviation technology both for the 2004 situation (base case) and two different scenarios (reference cases) in 2050. The aim is to compare those outcomes with the result of this section to see what difference expert selected innovative aviation technologies can make in contributing to Sustainable Development.

As discussed earlier, changes in aviation technology, especially the larger innovative changes, do not occur easily. The system is very resistant to change. Changes take place at a slow pace, making it last a long time before new technologies are widely implemented. It is for this reason that this study took 2050 as time horizon. Within the remaining years from now till 2050, it is assumed that some large and innovative technologies can find a place in the aviation system and mature.

6.5.2 Assumptions related to the analyzed technologies

In Chapter 4, the aviation system was broken down in several subsystems. From these subsystems, a few were influenced by new aircraft technology. The aircraft itself was also broken down in several subsystems. For each of these subsystems some technological developments were chosen that are promising in terms of some indicators for Sustainable Development. These technologies are listed in Table 6.2. Of these technologies some are seen as additional to the current aviation system (and thus creating a new niche) rather than as a possible replacement for current aircraft technology. These technologies, airships and the skycar, are not further analyzed.

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

Table 6.2. Identified technologies in the overall aircraft system and its four subsystems.

In the analysis in this research, for each of these technologies it is assumed that in 2050 the technology is fully implemented in the aviation system. This means that no ‘old’ aircraft will be flying around with ‘old’ technology that can be replaced by the ‘new’ technology under study.

That does, however, not necessarily mean that all aircraft in the total fleet operate with that particular technology. For instance, smaller aircraft already today have a wing aspect ratio of 10, compared to 7.5 for the A380. Large aircraft (like the A380) will have smaller aspect ratios for reasons of staying with its wingspan within the International Aerodrome code F of 80 meters wide. The technological change toward better aspect ratios for emissions (that is an aspect ratio around 10 or 11) will then, of course, only affect the large aircraft in the total fleet.

To overview all technologies considered (see chapter 4):

The introduction of the Ultra High Capacity Aircraft will only affect part of the in this study defined segment of large aircraft (>350 seats).

Reduced flaps and thrust take-off will affect all conventionally winged aircraft. A Blended Wing Body has a totally different stability and control system and no study exists on a Blended Wing Body take-off procedure with reduced flaps and trust.

Blended Wing Body studies showed positive effects for very large aircraft of 500 and more passengers and for mid-size aircraft containing slightly over 200 seats. So, in this study, it is assumed that Blended Wing Bodies will affect only those aircraft that can be categorized in the 175-350 seats category and in the category of aircraft with more than 350 seats.

Where the technology requires hydrogen, it is assumed that hydrogen is widely available. The system boundary is drawn quit strictly around the aviation system. Therefore, this study does not take into account how hydrogen is generated. The generation of hydrogen is problematic today for reasons of capacity. An important issue for the future is that not only enough capacity to make hydrogen is available, but that also its generation is done in a sustainable way. This study does not pay attention to how such sustainable generation of hydrogen can take place.

Studies have shown the possibility for hydrogen for conventional small and mid size aircraft (see chapter 4). No studies exist on the use of hydrogen on very large aircraft or unconventional aircraft like the Blended Wing Body. As very large aircraft like the A3XL are basically the same design paradigm as the conventional small and mid-size aircraft, it can be argued that also these aircraft could be fuelled with hydrogen in the future. It is however, unlikely that the preliminary studies of Blended Wing Bodies (BWB), as it is in its current existing designs, can be easily changed to be operated on hydrogen. If such a redesign would take place, nothing can be said now about the effects running on hydrogen will have on the indicators representing Sustainable Development. Therefore, this study assumes that hydrogen can be used for conventional aircraft, not for Blended Wing Bodies.

6.5.3 Results of the analysis

Based on all the assumptions described in section 6.5.2 and based on the individual study findings as described in the different paragraphs in chapter 4, now the effects of the different technologies can be determined on the outcome indicators for Sustainable Development (as identified in chapter 3). The result of the calculations are the so-called scorecards as have been introduced in chapter 2 and in section 6.2. These scorecards are the final product of this research. Using these scorecards, decisionmakers have some appropriate information to base their decisions upon. This research presents four scorecards, one for each of the considered scenarios. Scorecards for the high air travel growth scenarios A1 and A2 (Table 6.3 and 6.4) and scorecards for the low air travel demand growth scenario B1 and B2 (Table 6.5 and 6.6).

As an example for the calculations that form the basis of the Tables 6.3 through 6.6, let's go through the calculations of the scores for the Blended Wing Body. In Figure 4.17 (in chapter 4) the scores for the Blended Wing Body on the indicators representing the contribution to Sustainable Development are mentioned. Issue is that these scores 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: in the low growth hub-and-spoke scenario B2 (see Table 5.13 in chapter 5) for 2050 the total number of aircraft that contain more than 175 seats are:

$$(444225 + 768528 + 397022) + (183683 + 638257 + 266751) = 2698466$$

As the total number of seats in that scenario is 5220388, these 2698466 seats make up:

$$\left(\frac{2698466}{5220388}\right) * 100\% = 51.7\%$$

The effect of 51.7% of the total fleet flying around and having 20% less CO_2 emission on the total fleet is then:

$$1 + (0.517 * (-0.20)) = 0.8966 \approx 0.90$$

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, due to the growth of the traffic between 2004 and 2050. Therefore the score for the Blended Wing Body on CO_2 emissions in Figure 6.4 is then:

$$0.8966 * 3.49 = 3.1292 \approx 3.13$$

In the low growth point-to-point scenario B2, the calculation is comparable, but the number of possible Blended Wing Bodies is different, since in that scenario many more mid-size 175-350 seaters fly around. For scenario B2 this total number of aircraft in the 175-350 seats category and the 350 and more seats category is:

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

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, due to the growth of the traffic between 2004 and 2050. Therefore the score for the Blended Wing Body on CO_2 emissions in Figure 6.4 is then:

$$0.8548 * 3.49 = 2.9831 \approx 2.98$$

All other calculations are performed comparably, according to the different assumptions made for each technology and according to the size a particular technology makes up of the total fleet that is flying around in the different 2050 scenarios (A1, A2, B1 and B2) as presented in chapter 5.

Policy case 2050 ***Scenario A1 High Growth Point-to-Point*** Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<10.12	10.12	<10.12	10.12	10.12	10.12	<10.12			<10.12	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		9.88	7.08	9.95	9.92	10.12	5.07	0.61			9.10	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<10.12	7.08	10.12	10.12	10.12	10.12	10.12			<10.12	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		2.12	2.12	2.12	2.12	2.12	2.12	2.12			2.12	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		2.12	2.12	2.12	2.12	<2.12	2.12	2.12			2.12	
Number of connected geographical places via operated air routes in the EU.		3.24	3.24	3.24	3.24	<3.24	3.24	3.24			3.24	

Table 6.3. Scorecard for all considered technologies in the high growth scenario A1 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 ***Scenario A2 High Growth Hub-and-Spoke*** 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	10.01	1	<10.12	1	0.97	1	1	1	>1	1	M	Su
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	M	M
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	Su	Su
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	Sm	M
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	Sm	Sm
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	L	L
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	Su	Su
Airships	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*																										
SkyCar	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*																										
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	8.47	1	<10.12	0.50	0.99	>1	1	1	1	1	Su	Su

Table 6.4. Scorecard for all considered technologies in the high growth scenario A2 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 **Scenario B1 Low Growth Point-to-Point** Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<3.49	3.49	>3.49	3.49	3.49	3.49	>3.49			>3.49	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		3.45	2.44	3.43	3.42	3.49	1.75	0.21			2.98	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<3.49	2.44	3.49	3.49	3.49	3.49	3.49			<3.49	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		1.37	1.37	1.37	1.37	1.37	1.37	1.37			1.37	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		1.37	1.37	1.37	1.37	<1.37	1.37	1.37			1.37	
Number of connected geographical places via operated air routes in the EU.		1.74	1.74	1.74	1.74	<1.74	1.74	1.74			1.74	

Table 6.5. Scorecard for all considered technologies in the low growth scenario B1 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 ***Scenario B2 Low Growth Hub-and-Spoke*** 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	3.42	1	<3.49	1	0.97	1	1	1	>1	1	M	Su
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	M	M
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	Su	Su
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	Sm	M
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	Sm	Sm
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	L	L
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	Su	Su
Airships	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*																										
SkyCar	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*																										
Blended Wing Bodies	1.74	1.37	<1	<1	1	1.37	<1	<1	<1	<3.49	0.90	0.90	0.90	0.90	>1	3.13	1	>3.49	0.50	0.90	>1	1	1	1	1	Su	Su

Table 6.6. Scorecard for all considered technologies in the low growth scenario B2 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

6.6 Does aircraft technology contribute to Sustainable Development?

The last section filled in the scorecard for all selected technologies from chapter 4. The Tables 6.3 through 6.6 show the final scores for all considered technologies on the sustainability indicators. Note that given the long time frames and thus the inevitable speculations and assumptions, the scores should not be considered finally and ultimately true to the decimal. The pattern of the scores, where they substantially increase or decrease, is of importance, not the decimal digits.

A glance over Tables 6.5 and 6.6, for scenario B, the low growth scenario, shows that the potential for the expert selected technologies to contribute to Sustainable Development is, given the expected expansion for the aviation system, limited. Most indicators are hardly influenced by the technology, though they do get influenced by the external variable of growth of the sector.

Three technologies form an exception: composite materials, high speed propellers and hydrogen powered flight. Although also for these technologies most indicators do not get influenced substantially. There are, however, two indicators that do get influenced substantially. Those are the indicators for fuel use (indicators PE3.1, PE3.2, PE3.3 and PE3.4) and gas emission (indicator PL1.1). Here, a serious contribution is made.

Still, however, the growth of the sector is so substantial (even in the low growth scenario B) that improvements of 50% (CO_2 emission indicator PL1.1 influenced by high speed propeller policy measure) get easily outweighted by sector growth. It should also be noted that these three technologies are among those that require most serious changes in design and system; this having a potential high risk for the manufacturers and users. As can be seen in the row of the hydrogen powered flight technology, this technology could reduce the CO_2 emissions even further. However, as already mentioned in paragraph 6.5.2, this study does not take the generation of hydrogen into account. At the moment it does not seem to be possible to generate hydrogen in the quantities needed for aviation within a limited amount of time in the future in such a way that no CO_2 gets emitted into the atmosphere.

Two important conclusions can be drawn from these scoring results. One is, that it is not very likely that technology related to aircraft will, in the time span till 2050, make serious contributions to the level of sustainability for the whole aviation system. Maybe not all possible technologies are considered. But, those considered are seen by experts as realistic, possible developments that can be expected to make large changes in the aviation system. They are all considered to be, in principle, feasible within the time frame until 2050. It must be made clear immediately that technology can make the situation on some indicators substantially better if the sector would not grow at all. This is not an open door, but an important finding, because technology thus gives society some extra margin (either in time or in severity of effects) to come up with other solutions. A combination of two techniques for instance (composites with high speed propellers) could, in a low growth scenario, not substantially deteriorate the level of CO_2 emissions for 2050. CO_2 emissions is currently a very important and hot topic worldwide.

A second important conclusion is that expert selected and expected aircraft related technology appears not to be able to influence all aspects of Sustainable

Development. It appears mainly LTO emissions, CO_2 emission and Direct Operating Costs are really influenced. That makes technology an instrument of limited capabilities in the full Sustainable Development discussion. Note that this is not for reasons of not keeping up with growth of the sector, but for reasons of a small number of effects on a concept of Sustainable Development that has such a wide variety of characteristics.

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7. Implementation and use of new aircraft technologies

7.1 Introduction

As shown in chapter 6, none of the analyzed aircraft related technological innovations, nor a combination of all, will seriously increase the level of sustainability compared to the situation in the year 2004. Some technologies might give an improvement on a few indicators for Sustainable Development. However, a lot of the indicators develop into the undesired direction. Even the smallest growth of air travel (the smallest air travel demand scenario for 2050) outweighs the positive contribution new expert selected aircraft technologies can make on many aspects of Sustainable Development. In order to increase the level of sustainability compared to 2004 levels, something else is also needed than only introducing these new aircraft technologies in the system.

However, chapter 6 also shows that not using these new technologies will decrease the level of sustainability even further. Technology, thus, can play a very important role. Not, as stated before, in bringing sustainability closer. But, as also remarked earlier, in creating margin (in time or in effects), so that more room is available for society to develop solutions that really can increase sustainability levels.

Another important issue is that, once a technology is implemented, the use of that technology deeply determines the contribution that technology eventually makes to Sustainable Development. For example, more silent engines can result in more silence around airports, but also give way to growth of traffic as it also increase the sound-capacity of that airport.

This research leaves other than technological issues (like demand management) to the problem owner. In chapter 6 it is determined what contributions expert selected aircraft related technologies can make to Sustainable Development. Although we found that these technologies can not improve the situation in 2050 compared to the situation in 2004, we also found that these technologies could give society margin (in time or effects) to come up with other solutions that indeed might improve the situation in 2050 compared to 2004. But, making changes in systems is in general not easy, especially not in the resistant to change aviation system.

This chapter therefore concentrates on the problems around the introduction of new aircraft technologies in the aviation system and the use of those technologies. It finds ways that implementation can be blocked, uses different ways to look at implementation to find explanations why blockades exist, and introduces tradeoffs decisionmakers have to make in their decisions on what role they want technology to play in making the aviation sector more sustainable.

The chapter is divided into four parts. Part I (section 7.2), *Roadblocks*, addresses the question what possible reasons there are to not start the development and/or implementation of the new technologies as identified in chapter 4. These so-called roadblocks for implementation were identified during interviews with people working in the aviation industry.

Part II (section 7.3) of this chapter, *Parallels to another industry resistant to change*, refers to research done about technological innovations in the heavy metal industry that should lead to a more sustainable situation. That research came to some important conclusion: prerequisites that should be met in a technological system in order to make technological innovations possible. The Part II of this chapters investigates whether these prerequisites are met in the aviation industry.

Part III (sections 7.4) of this chapter addresses the question why, given the positive outcomes for society as a whole in 2050 when new technologies are implemented in the aviation system, current reasons for not implementing or developing such technology (identified in Part I) are seen as more important. A closely related question then, is what can be done about that. The first question is answered using a psychological theory called “Discounting”, which gives explanations about people making choices that have both consequences paying off now and in the future. The second question, about what to do, is answered using the practical approach of Technology Assessment; a combination of theory and practice that explains and facilitates processes of technological change.

Part IV (section 7.5) closes chapter 7 and covers the issue of how the technology, when implemented, gets used. As explained in an earlier example, technology meant to reduce noise near airports, can also be used to increase capacity, therefore adding more flights, while keeping the noise levels unchanged.

7.2 Part I: Roadblocks to implementation

In chapter 4 a list of technologies has been identified that are as innovative as possible (i.e. most promising given certain indicators of performance that are considered especially important for Sustainable Development, like noise, or fuel use). However, the choice has been such that at the same time these technologies are ‘serious’ enough as there are preliminary designs or even small scale prototypes available. The items on this list therefore can potentially be further developed and implemented within the time frame of 2050 used in this research. The word ‘potential’ is used with a specific reason here, as the aviation system is very resistant to change and not automatically will adopt new technologies that do not perfectly fit all elements of that system and objectives of the actors within that system.

To get initial and very concrete reasons why these particular technologies listed can not easily be implemented in the aviation system, the list of technologies is put in front of people with work experience in different areas of the aviation system. The single question asked to these people, after giving them the list of technologies, has been “What reasons will prevent this technology from implementation?” Their answers are described below and summarized in Table 7.1.

It turns out that blocking implementation in general is done due to lock-in effects: implementing a certain technology could not be done without substantially changing surrounding system elements (e.g. runways, fuel provisions, historically grown distributions of responsibilities and power, etc.). This holds true for several of the aircraft related technologies considered in this study (see Table 7.1).

Policy measure	Major roadblocks for implementation
Ultra High Capacity Aircraft	Lock-in at airports (with high costs as a result) Psychological resistance to such large aircraft by passengers and crew. Investment risk aircraft manufacturer. Evacuation not in compliance with current ICAO regulation of 90 seconds. Operators risk: too low load factor. Issue of vortices from wing tips: larger separation times possible necessary; reducing an airports capacity.
Composite materials	Expensive investments. Knowledge not widely available and demonstrated (not yet proven technology) Relatively high development (and thus financial) risks. Requires regulation change in allowable crack size during operation (composites do not crack during life time of aircraft, but when they do crack, flying is not safe).
High aspect ratio wings (on ultra high capacity aircraft)	Lock-in at airports (with high costs as a result). Only useful for very large aircraft; therefore higher development and financial risk.
Free flight	Historically grown patterns of distribution of power and responsibilities must change. Requires large changes in Air Traffic Control: currently small building blocks of responsibilities with plans to bring those to the free market. Capacity issues near airport remain and might be or become bottle neck.
Reduced thrust take-off flight procedures	Concept of 'captains decision' (captain finally decides/has final responsibility what is best for safety in a given situation) can counter prescribed procedure. Requires changes in historically grown patterns of distribution of power between captains and air traffic controllers.
High speeds propellers	No economic incentive with cheap oil; oil price can increase a lot before economic incentive is present. Old fashioned look. Different fleet circulation across the world due to slightly slower flight speed, requires adaptation of accepted ideas of schedules by travelers. A possible lower flying altitude causes less comfort. Less comfort due to increased noise inside aircraft
Hydrogen fueled aircraft	Large investments, high financial risk. Increase in land use due to extra fuel storage places. Lock-in effects related to aircraft paradigm; aircraft is currently optimized for kerosene. No sufficient capacity for hydrogen generation worldwide.
Blended wing bodies	Large investments, high financial risk. Lock-in at airports. Evacuation not in compliance with current ICAO regulation of 90 seconds.

Table 7.1. Major reported roadblocks for implementation of new aircraft technology.

Interesting to note is that high capacity aircraft, such as the A3XL, have, according to the preliminary study, higher safety levels but that passing the 90s evacuation regulation (i.e. all passengers must be able to disembark the aircraft safely in an emergency situation within a time span of 90 seconds) is seen as a hurdle for implementation. This can be seen as another form of lock in effects. It might be, as the preliminary studies suggest, that due to evacuation possibilities to other decks or more space inside the total aircraft is so much safer that a 90s rule is not necessary. Could it be lengthened so the evacuation requirement is easier to pass? Here, no physical reason is present, but existing safety regulations block promising technologies from being implemented. The question to answer is what the requirement of evacuation within 90s adds to overall safety. The answer to that question will differ for different type of aircraft.

New technology might also have psychological effects that could work as a force countering implementation. The idea to be in an aircraft with 700 to 1000 passengers appears to scare off both potential passengers and experienced crew. A substantial part, up to 30%, of people (passengers and crew) we interviewed in the Ultra High Capacity Aircraft A3XL study (see chapter 4) reported resistance to fly such large aircraft (Blok, El Bouzidi et al. 2001). Whether their actual behavior will be parallel to their reported feelings in this research is not so important for questions regarding implementation; the reaction by the people that can influence the implementation trajectory is what counts. If these people see this reported resistance as a danger to the success of such an aircraft, the reported results might indeed work as a roadblock against implementation.

Another type of psychological resistance reported is that the reintroduction of the propeller gives an old fashioned look to aircraft. Manufacturers might be afraid that sales drop due to an old fashioned image of the manufacturer. Traditionally aviation is seen as high-tech.

The new, aircraft related, technologies considered in this research still have to be fully developed; nowadays they only exist on computerized drawing boards, as preliminary designs in reports and some as small scale test models. Developing these technologies into usable products requires huge amounts of money; so huge that may the technology appear to be not successful in sales, this could lead to the bankruptcy of the company. Although successful implementation might lead to serious financial gains, still large risks for investment are experienced that make actors hesitant to decide in favor of implementation. According to experts, this risk of investment is highest for the Ultra-High Capacity Aircraft like the A3XL, hydrogen fuelled flights, high speed propellers and Blended Wing Bodies (BWBs).

For large aircraft, the operators face a risk of not getting all seats sold. Smaller aircraft might also have their disadvantages, but more of them together make more flexible operation possible than with one, single, very large aircraft. If many fewer seats are sold than available, flight numbers can be combined in one aircraft (this happens between different cooperating airlines). A large single aircraft will have to fly; seats sold or not. That means that the airline must be very sure about substantial sufficient market routes within its schedule. This operation risk will reflect in the hesitance of airlines to (be willing to) buy the aircraft. Logical consequence will be resistance to the development of and implementation of such high capacity aircraft, despite their advantages.

Another reason for not developing new technology is the cheap availability of crude oil. Although a serious rise in crude oil price can be seen in the period 2002-2006 (up to 3 times the original price), still oil products are relatively cheap compared to investments needed for crude oil replacements and the savings those replacements will or can bring. Technologies that seriously reduce fuel use will be more interesting when more money can be saved with it, so when the oil price is high. Currently, experts think that the development costs of propellers for high flying speeds are too high compared to the fuel (and thus cost) savings that are possible with this technique. An even more serious rise in oil price than seen in the period 2002-2006 might be an incentive for developing this new technology; without this rise, the absence of an economic incentive works as a roadblock for implementation.

Current propeller technology that is used in for instance the Fokker 50 requires lower flying speeds and a lower flying altitude than the jet engine. New developments will increase both flying speed and ceiling, but it is still likely that maximum positive effects (in for instance fuel savings) still will be reached at a lower speed and lower ceiling than with current jet engines. A lower ceiling has less comfort for the passengers as a result. Especially on long haul flights, operators might not see this as acceptable for their passengers. If the operators don't buy the technology, there is no incentive for manufacturers to develop it (although other advantages might be there for other actors, or for society as a whole). A lower flying speed means that a lot of adaptations will have to be made to the schedule, a costly operation. In addition, and even worse, the fleet circulation across the world changes completely. Amsterdam-LA and back with jet engines can be done in 24h. The aircraft is back in Amsterdam on time for the next day flight to LA. With propeller technology, this route requires more aircraft to fulfill the need for a daily flight to LA and back. More aircraft requires more investment that has to be countered by cost savings. It will depend on the size of efficiency savings, due to the introduction of propeller aircraft, whether the choice for adopting the new propeller technology is made.

Of a completely different kind is the roadblock for implementing the reduced flaps/thrust take off. By reducing fuel use due to this new procedure, also overall safety levels are reduced, as, in case anything goes wrong, fewer reserves are left to overcome the situation. Within aviation there is the culture of 'captain's decision'. The captain is seen as the final responsible person for everything that happens during the flight within the aircraft. Therefore, captains have power to make all kind of decisions before and during the flight based on his/her judgments and experience. For instance, when on a specific route bad weather is expected or a relative long holding (circling near the airport till permission is given to land), a captain may decide to demand extra fuel on board. Even at the cost of cargo payload and even if in standard procedures this extra fuel is not required. Based on his/her judgments, prescribed reduced flaps/thrust take off could be overruled, even when statistics or research proves these procedures to be safe enough.

The use of the fuel for propulsion might give some serious implementation problems. Apart from economic reasons in terms of investment (as also applicable to any serious change in the system), hydrogen requires a different use of land by using much more space to store. When expansion possibilities of the airport are limited, this can cause serious problems, both in the area that is needed as well as in the safety issues that are involved related to citizens living near airports. Another issue related to hydrogen use is its total availability. Though not an official topic of this research, it should be mentioned that today's worldwide capacity for generating hydrogen is significantly smaller than what aviation would need. In addition, the generation of hydrogen can give serious problems with respect to Sustainable Development, as can bio-fuels. Hydrogen currently is generated using fossil fuels; it is in the generation phase that the CO_2 is emitted, not in the phase that aircraft are burning hydrogen in flight. Also the generation of bio-fuel can cause large scale deforesting when land is needed to grow crops to make bio-fuels. New technologies using waste crops (those parts of plants that can not be eaten of plants that are grown for their fruits or grains) might be a solution, but it is questionable if these contain enough energy to fuel a transport system. This study has put the system boundary tightly around the aviation system and has excluded the generation of fuel.

7.3 Part II: Technological innovation in the heavy metal industry

The aviation system is not the only system that is strongly resistant to change. A comparison with the situation about innovations in another such system might provide some valuable insights.

A study published in 2000 (Moors 2000) about (technical) innovations in the heavy metal industry shows clear parallels to this study. The heavy metal industry is, like the aviation industry resistant to change. Moors uses the word ‘inert’ for this. Both systems require large investments in technical installations and infrastructure to keep their processes running and use their investments products for long periods (30 years is common for both systems).

For the heavy metal industry the resistance to change is, among other things, due to geographical location, and chemical and physical processes. The industry should place plants near places to which bulk transport of raw materials is easily (and cheaply) possible. The location must also be such that heavy metal and large semi-products easily can find their way to where they are needed. The chemical and physical processes used to transform raw material (ore, like bauxite) into usable material (like aluminum) determine the whole set up of the plant site. Changing the chemical and physical processes with which certain metals are made from their ore would require almost complete tear down and rebuild of the plant site.

On these two issues there are strong parallels with the aviation system. Also this system, for its ground handling facilities, is bound to areas around large cities, metropoles or otherwise densely populated areas. Passengers will hardly be found in large quantities in the more remote areas. For its processes, also in aviation large investments are done in infrastructure (both physical as well as, for instance, technical information flows) that can not be changed overnight. A nice example is the Aerodrome Classification based on a combination of size and weight of an aircraft. Only the type of aircraft fitting these different categories can land and take off from an airfield that has the corresponding Aerodrome Classification certification. Aircraft designs that do not fit any category cannot be handled, despite their possible superior characteristics for other than airport handling issues.

Moors (2000) describes inert systems (systems that are resistant to change) as systems with a high level of technological complexity, physical and social interactions that will seriously hamper the adaptation and implementation of new technologies, as adaptations have to be made in existing systems. Implementation of new technology has large financial risks, as a lot of changes have to be made and it is not sure in advance whether the technology will produce the expected advantages in reality.

The aviation system, with its large complexity, is definitely inert (resistant to change) according to the description of Moors. The coexisting large financial risks that accompany an innovation in such a system are felt even stronger for the aviation system than for other systems, since the airlines cooperate with such a small margin. Therefore, hardly any money is available, especially not for risky projects. According to Moors one of the main requirements that have to be met in order to make radical innovations in inert systems possible, is the availability of sufficient money to invest.

The parallels between the heavy metal industry and the aviation system are so striking when it comes to resistance to change, that some conclusions in Moor's study related to technological change will be discussed here to see what they mean for aviation and to see if there are potential lessons to be learned from the heavy metal industry.

Moors (2000) formulates some initial requirements in her study that are necessary prerequisites in order to make innovations possible. Although meeting these requirements alone is not enough to make an innovation happen, they form necessary prerequisites.

The first prerequisite that enhances a technological radical innovation is the presence of a sense of urgency in the form of a serious event or an expected crisis. The second prerequisite enhancing innovation is an internal and external open network with a high density of different actors. The third prerequisite is that a change should change the whole system; it appears to be much easier to implement a radical technological innovation that replaces the whole system than one that only partially makes replacements. The last prerequisite is already mentioned: the availability of enough money is vital. This is, however, in the aviation system a serious problem.

Concrete for the implementation problem in the aviation sector this means that something serious should happen in the present or the near future that asks for a technical solution. It also means, in addition, that this technical solution must not be easily implementable in the current technological system. For instance, due to the safety issues that rose shortly after the turn of the century, all kind of measures have been taken like blocked cockpit doors. However, as these changes could easily be implemented in the current technological system, the safety issue did not serve as a sense of urgency for substantial or innovative technological change.

The lack of a sense of urgency can be seen from several issues. The enormous historical high growth figures show that many people do not experience enough sense of urgency that their behavior is actually influenced into a decision not to fly or to fly less often. It is true that many critics and complaints are expressed about especially noise issues around airports, but given the growth figures (that especially can be seen in the leisure travel sector) this noise concern does not reflect in free choices to fly or not (which leisure trips can be categorized as, different from business trips that have a more obligatory character).

Some major older airports are now noise constricted, which means that their physical capacity is larger than their noise capacity. They could handle more aircraft, but are not allowed to do so because of regulations based on noise concerns. However, the lack of concern can also be clearly observed here, since these regulations are not always strictly enforced in practice; the regulations appear to be very flexible when air travel demand gives airports the opportunities to grow in traffic size. An interesting finding to mention here is a study by Eurocontrol (Cook and Tanner 2005) showing that there is a strong difference between Western European countries and Eastern European countries. In the first group of countries, the concern about noise might be expressed although behavior is not influenced by it, while in an Eastern European country noise is seen as a necessary and acceptable burden to take for growth of the sector. This is an example of quite the opposite of the availability of a sense of urgency to implement new technologies that should, among other things, contribute to the solution to noise problems.

In the aviation system, the actors that buy the aircraft are, generally, the airlines. Competitiveness on shared routes, liberalizing the market and the pressure of low cost carriers for market share have seriously reduced the profit margin for airlines on their ticket prices. Effects of this can be seen when, if only for a short period, passenger levels go down; within months or even weeks many airlines will have gone bankrupt. As with the choosing and buying behavior of airlines it is determined what products get developed and implemented in the market, the lack of finance at the side of the airlines is a serious roadblock for implementation.

Of the prerequisites for the appearance of radical technological innovations in an open market, as formulated by Moors (2000), at least two are clearly not met in the aviation system. There is not yet a serious sense of urgency and there is also not sufficient money available. If a governmental agency, like the virtual client for this research, still wants to steer in the direction of more sustainable aviation by means of the implementation of more new technological innovations, these two prerequisites as formulated by Moors are a serious point of attention.

7.4 Part III: Discounting and Methodology of Technology Assessment

Discounting

In this part we address the question of why, given the possible long-term positive outcomes for society, short term roadblocks succeed in preventing development and implementation of these new technologies. This is done by looking at the problem from two perspectives. First, in section 7.4, this question is elaborated upon by using the psychological theory of discounting. Then, in section 7.5, the methodology of Technology Assessment is introduced to find out if anything can be done about it.

Discounting in combination with a positive time preference is the effect that people tend to value positive consequences of an action today as more valuable than getting these positive effects later in the future. This tendency can be mirrored; people also value negative consequences less negative in the future than they would value these negative consequences today (see section 1.5).

Interest and inflation are classic examples to explain discounting. A sum of money put on a bank account will accumulate interest and will, in number, increase in some years from now. Earning money now is effectively worth more than earning an equal sum in the future. Inflation will make the difference even larger. A sum of money in 10 years is worth less than the same amount of money today, as prices for products and services can generally be raised by their sellers over time.

Uncertainty and risk form another explanation for the occurrence of discounting. The further an outcome is away in the future, the less sure it is that it is still relevant to an actor. Risk is very much related to uncertainty, as it is defined as probability of occurrence times the effect. Both the probability of occurrence and the size of the effect can be determined with less accuracy the further one looks into the future. In other words, uncertainty about the probability and the effect(s) increase when they have to be determined further away in future time.

Economists tend to make Net Present Value calculations to incorporate both the effects of risk and the effect of interest and inflation. For precise calculations several models for discounting can be assumed: hyperbolic, quasi hyperbolic and exponential. All of these models assume that discounting between day 1 and 2 is larger than between day 100 and 101. Hyperbolic discounting is the form in which the discounting takes place at the slowest pace, while exponential discounting is the fastest. Mathematical functions can describe these assumed models for discounting. For hyperbolic discounting the function looks like:

$$\frac{1}{1+rt}$$

While for exponential discounting the function looks like:

$$\frac{1}{(1+r)^t}$$

In both equations r is the discount rate and t is the number of time steps. Hyperbolic discounting discounts faster in the first couple of time steps and then levels of towards far less large discounting rates further in the future. In exponential discounting the ratio between the discount value of two succeeding time steps is always fixed, while for hyperbolic discounting this ratio decreases in time. The effect is that in initial stages, the exponential discount function is much steeper than the hyperbolic discount function. Although the exponential function will always lie below the hyperbolic function (see Figure 7.1) the difference between both functions reduces in later time steps.

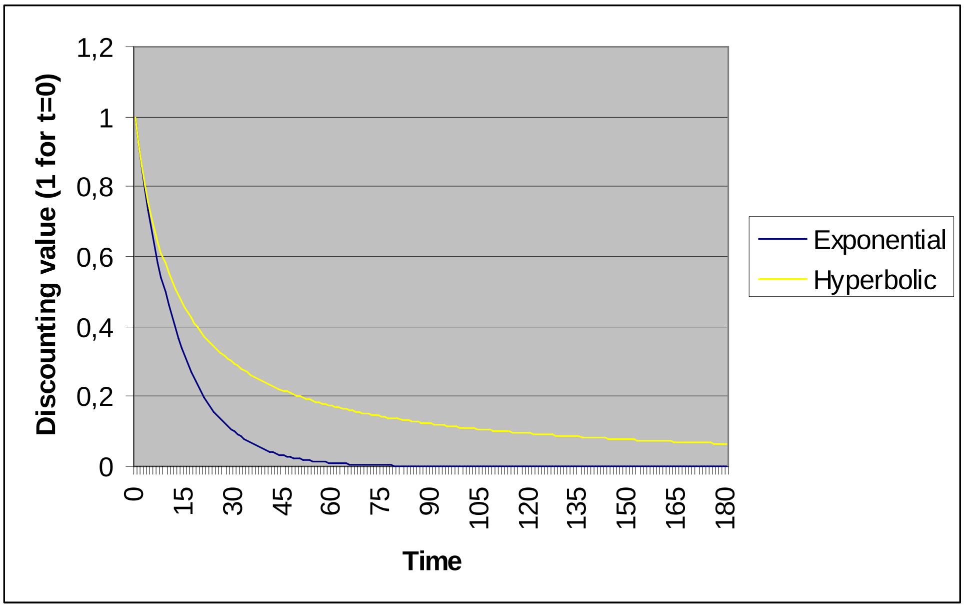

Figure 7.1. Exponential and hyperbolic discounting functions compared.

A result from the theory of discounting is the hypothesis that income is best earned as soon as possible while costs should be delayed as long as possible. More generally formulated: people want positive consequences rather sooner than later, while they also prefer to postpone negative outcomes rather than have them sooner.

Translating this hypothesis to the situation in the aviation sector would imply that very slow and small changes will occur over time. This is expected as there are long time frames between investments and pay-offs. Starting a design today might take 10 years to get a certified sellable product. It will then be logical to reduce risk as much as possible, which could be done to stick to only small changes to an already existing design.

Next to risk, there are also the discounting effects of interest, inflation and the less explicit but important psychological effects. These discount the positive consequences that in this case of aviation will appear quite some time in the future. At least 10 years before the first money is earned, but for some other sustainability indicators much later. As substantial parts of the cost (like initial research investments) have to be paid at the start of the project, these negative consequences hardly get discounted. As the total perceived pay-off of an investment decision then gets smaller, it can be expected that a decision to start the product is taken in fewer occasions.

A driving force in a market economy is growth. Firms are able to increase capital stock by investing. That these investments might not lead to radical changes in the technology is already empirically observed by Mansfield in the late 1960s (Mansfield 1968). Feichtinger et al. support this empirical finding by the theoretical contribution of modeling investment decision making taking discounting into account (Feichtinger, Hartl et al. 2006). Investing in new technology gives as advantage a longer life time, but older technology is cheaper with less discounting costs. This supports the earlier experienced and described idea that new technologies are adopted on a large scale only after a prolonged period of time.

In figure 7.2 it is shown that there can be several discounting functions to describe the observed discounting behavior. Clearly, the steeper the discounting function, the less obvious it is that more risky technological projects will be implemented. Identifying under what circumstances people tend to discount hyperbolically and under what circumstances people discount exponentially could thus give clues of how to enhance the changes of implementing new technologies (in this case technologies that have the potential to contribute to Sustainable Development).

However, investigating this issue seems to give undesired news for the problem owner of this analysis. Fernandez-Villaverde et al. (2002) point at the influence of the factor uncertainty. They claim that a lot of experiments that have been conducted in the past about discounting don't present carefully balanced choices to their experimentees. A choice between getting an amount of money now or a promise of getting a higher amount tomorrow is not balanced in terms of uncertainty as the first is clear, but the second choice is a promise, for which people have to get back to someone later and trust that person. The traditional claim that discounting tends to happen hyperbolically is weakened by this as by removing this uncertainty from the experiments Fernandez-Villaverde et al. (2002) find exponential discounting evidence. Including uncertainty in a balanced way, the observed behavior in the experiment is compatible with exponential discounting.

These findings suggest, for the purpose of this chapter, an undesirable situation, as uncertainties in the aviation industry on both short and long term are huge. If the presence of the uncertainty factor pushes people in general to more exponential discounting function behavior, there is lesser chance for investment decisions for technology contributing to Sustainable Development.

Discounting has been observed in many domains. Making a rough comparison to the three domains of Sustainable Development - social, environmental and economic - the literature suggests that people discount differently for social and economic issues compared to environmental issues. The difference is not so much in the discount function (e.g. exponential or hyperbolic) as in the choice for discounting or not discounting at all. In an overview of discounting environmental issues, Nicolaij and Hendrickx (2003) report that in studies about health (related to the social part of Sustainable Development, see chapter 3) and money decisions (related to the economic part of Sustainable Development), it is very rare to see people who do not discount. For instance, such a study by Chapman (Chapman 1996) reported zero discount rates for 0.3% and 0.5% of the experimentees. However, research on decisions related to environmental issues reported that a substantial number of the experimentees did not discount at all. For instance 30% in a nuclear waste decision experiment and 40% in a study on soil pollution (Nicolaij and Hendrickx 2003). An after experiment survey analyses showed that the most often mentioned reason for not discounting in these circumstances referred to ethics. In particular the consideration that both current and future generations have the same rights was reported and, thus, might explain the experimentally found behavior.

It is an important question if this issue is steerable, in other words, if it is possible to make people discount less when decisions are presented as ethical decisions or when it is made clear that ethical considerations play a role in decision making. This is actually a representation of a more general question about translatability of lab experimental results to reality. How well does the lab behavior of undergraduate social science students (the usual experimentees) represent the behavior of people in the position of making these decisions in reality? Lab results translating to reality is a tricky thing. Lab experiments are usually not designed to represent the real world, but more to show the existence of certain phenomena like group polarization or discounting. The above mentioned experimental results do not show more than that. The moment ethical considerations enter in a decision problem, people might not discount at all. Whether these people are the people who actually make decisions about the development and implementation of technologies contributing to a Sustainable Development remains unanswered.

In addition to the fact that people value absolute costs and incomes differently over time, which influences their decisions (described by the concept ‘discounting’), they also tend to change their decisions given the relative size of their costs or income compared to other actors in the same system at the same time. This leads to decisions that, at first sight, are not rational, but can form explanations for decisions to implement or block certain technological developments, as discussed in the remainder of this section.

In 1992 the World Development Report (International bank for reconstruction and development 1992) stated that, based on the mid 1950s ideas of Kuznet (Kuznet 1955), the relation between environmental quality and GDP had a U-shape. With increasing economic activity and as a result increasing GDP the quality of the environment would first decrease, but later improve. This idea, referred to as the Environmental Kuznet’s Curve (EKC) would imply that to improve the environmental quality, it is not wise to reduce economic growth. In essence, the EKC raises the idea that the friction, or dilemma, between environment and economy in the end does not exist.

Lawn (2006) concludes that the many studies undertaken to either prove or disprove the existence of the ECK do not bring conclusive evidence. From a strict theoretical basis, Lawn (2006) proposes a third-degree polynomial function for the relation between environmental quality and GDP. Increasing economic activity would first deteriorate the environmental quality, then leveling it off but by ever growing GDP the environmental quality would increasingly deteriorate further. This would imply that to keep environmental quality at a certain level, society should make the transition to a steady state economy with a constant stock of physical goods and a constant population size.

The author continues explaining how to reach steady state economy. Though interesting it is, it also seems to directly counteract one of the elements the problem owner considered essential - competitive market economy (EU, 2001) and growth (Transport White paper). According to Kuznet, this objective can be met without sacrificing the environmental objectives within the concept of Sustainable Development; according to Lawn, this is what is precisely impossible. Given the other publications Lawn cites, it seems so far the literature is inconclusive about this issue.

If, on the more general abstract level of markets, it is inconclusive whether just more economic growth of a steady state economy is the solution for balancing economic (‘profit’), social (‘people’) and environmental (‘planet’) objectives by innovations, let's look in more detail how certain actors in the market system may decide about implementing innovations or not.

For this, first a simplification of the current full market system is designed: a representation of that market by only two actors, A and B, instead of the many actors that are present in the real system. This is a substantial reduction of the complexity of the full market. However, when looked at the scores in chapter 6 and the practical reasons given in table 7.1 for not implementing the promising technologies, the implementation problem has characteristics of a two actor problem. One actor who sees the positive scores and would like the technology to be implemented (e.g. governmental organizations or society as a whole) and one actor that has to do the effort of developing, testing, certifying and implementing (using) the technology (e.g. aircraft manufacturer, airport, airline). It looks like one actor wants to introduce the technology and benefits from it, while the other, as part of the group, also benefits the group outcome, but has to do individual effort to introduce the technology. In personal actor terms: Actor A wants to decide on the introduction of a technology improving its pay off while decreasing the pay off of an artificial opponent.

Cason and Mui (Cason and Mui 2002) conducted experiments in which actor A can decide to innovate or not. If A decides not, there is a certain pay-off for actors A and B: S_a and S_b. Actor B however can counter the decision of A to innovate. If this happens, A and B get a pay off w. If actor B decides to continue the innovations, there is a pay-off X_a and X_b for both actors (see Figure 7.1).

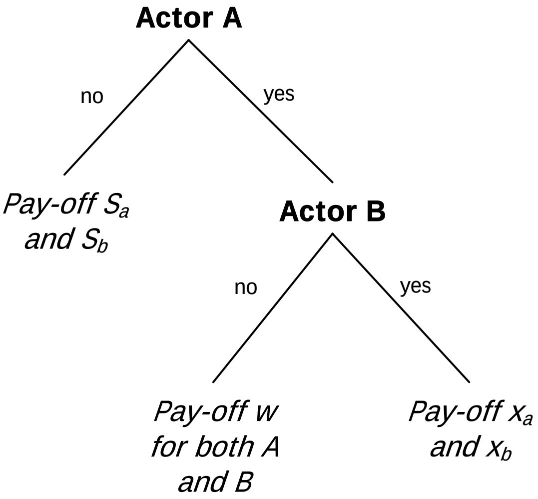

Figure 7.1. Choices for two actors A and B and their pay-offs.

In the experiment we describe here, the worst situation (in terms of innovation success) is when A wants to innovate and B rejects it. In this experiment, Pay off w is smaller than any other pay off. In all other cases the pay off for B is several times smaller than the pay off for A. However, $X_a > S_a$ and $X_b > S_b$.

As in all cases $X_a > S_a$ and $X_b > S_b$, utility maximizing functions would predict that actors A and B would always opt for innovation. This implies the widespread way of modeling individual decision making as utility maximizing. Many results of experiments like the one just described show that people do not maximize utility only. Actors pay attention to what their pay off is relative to the other actor's pay off in the experiment.

Given the list of identified factors that are potential roadblocks for implementation of the technologies considered in this research, it looks like most of them fall into the category of either risk or effort in terms of investment. The theory just presented here and the empirical evidence gives rise to the existence of some sort of reciprocity or justice that people take into account when making decisions.

The mentioned roadblocks will also face this issue. Solving them means that certain actors have to take risk (investment risk for instance) or have to put huge efforts in the system (like replacing all kind of infrastructure at airports). It will strongly depend on what actor takes what risk or effort and how this relates to the risk and effort another actor takes.

As long as there is no strong incentive for the group of actors in the aviation system to make changes, this effect of reciprocity or justice may well delay implementation of new technologies, despite their potential advantage to the whole group.

It is tempting to say that the problem owner, the European Parliament should take a leading role in this and guide the different actors towards the point where most benefit is available for the group as a whole. However, the power of the European Parliament should not be over estimated. Due to the slow democratic process and the existing lobbies, changes in decisions and regulations take a lot of time.

Methodology of Technology Assessment

In this part, the question is addressed why, given the possible long term positive outcomes for society, still the short term roadblocks are reasons for not implementing or developing these new technologies. In the previous part of this section, this question has been addressed by using the psychological theory of discounting. It was found showing experiments, that people tend to behave in such a way that long term positive group outcomes (like in the researched issue of implementation of promising technologies contributing to Sustainable Development) are not likely to happen. In the remaining part of this section, the methodology of Technology Assessment is introduced to find out if anything can be done about that.

For an individual, his or her own process of decision making looks rather rational. From the moment a problem is perceived, people can actively search for alternatives that might solve the problem. Usually, one of the alternatives is chosen to implement. When a problem is perceived in a group setting, this beautiful stepwise approach to problem solving can not so easily be recognized. While certain individuals perceive a problem and might start looking for possible solutions, others might not see a problem at all.

Cohen, March and Olsen (1972) proposed a theory that describes what happens in large groups when problems are perceived by some actors in that group and attention is being raised to find solutions. In a complex multi-actor field, these authors describe the existence of streams of problems, solutions, participants, and moments of choice. The decision making process in such multi-actor fields is very dynamic. At moments of decision in time, what actually is being decided is completely depending on what problems, solutions, and participants are at that specific moment available. This is, of course, not completely random, as the kind of solutions present and problems perceived is actively influenced by participants who have these solutions and perceive these problems.

Kingdon (1984) used the theory of Cohen, March and Olson for the specific process of public decision making. This comes close to the topic of this research as both the adverse effects of flying and the benefits are of high importance to society. Any form of decision making leading to (substantial) changes in the aviation system will influence many parties.

Kingdon (1984) distinguishes three streams: problems, policies and politics. In the problem stream, several actors (like media, pressure groups, et cetera) work actively to trigger interest in certain problems. In a sense, this stream indicates what problems are recognized as significant for society.

When actors are actively trying to push changes in the system, this will, no doubt, lead to resistance. Systems in general work in a particular way for a variety of reasons that are not always known. This resistance to change makes sense: while a system in its current state is working, changes in that system lead to a differently working system for which no proof of success in the future is in advance available.

Making successful changes in a system is therefore seen as a joint effort of a team of actors in that system (Grin, Graaf et al. 1997). It is a process in time and at its beginning it is not clear what the final outcome will be. However, at the start of a process of system change, it must be made clear what the implications of the change are for the different actors and stakeholders in the system.

A practical approach of studying and facilitating technological changes in systems as an interactive, open process between actors and stakeholders involved in that system is called Technology Assessment.

In the past, this has been different, as what at that time was called Technology Assessment was more something like an early warning system only. It tried to predict effects of a new (innovative) technology on an existing system. Such studies cost a lot of time and effort. If such studies have to be performed before the development of any new technology was allowed to take place or allowed to be widely implemtened, Technology Assessment as method was sometimes referred to as more being “Technology Arrestment” than performing the role of early warning system.

An important and relatively new stream in Technology Assessment is the Constructive Technology Assessment. It is a stream that strongly favors an active, open approach to the problem by all actors and stakeholders. This must lead to clear objectives, identify alternatives and enhance the implementation process of the chosen alternative.

Grin, Van der Graaf and Hoppe (1997) suggest answering a couple of general questions before the start of a technological change process in a system. They call it a ‘start TA’. The questions are:

1. What actors are, or should be, involved in the new technology?
2. What knowledge is available?
3. What knowledge is being used by a particular actor?
4. Are there any gaps in the available knowledge?
5. If so, can these gaps be filled?
6. Is there a discussion about values present?
7. How does the decision space look like?
8. Are any adaptations to the decision space necessary?

These questions suggest an open process, in which nothing is sure beforehand, even not the question whether there is a problem or not that the actors should pay a certain amount of attention to. On the particular topic of technological innovations, the questions reveal that also this is open for discussion and compromises among the different actors. This open, inter-actor approach has proven to be very valuable in processes where changes in systems were required (Smit and van Oost 1999).

For our research, an approach as suggested by Smit and Van Oost would be very unpractical. The research is not about a couple of actors in the aviation system that have to come to a problem statement. It is also not about negotiating about the particular technological designs that might help in solving a negotiated problem statement. This research is merely on the issue of acceptance of a technological solution for a problem stated by the client. Here, the client has the desire to raise the level of sustainability in the aviation sector. The research wants to answer the question to what extent the introduction of new expert selected technology could increase this level. If raising the level of sustainability, as is the client’s objective, would be made topic for discussion, the Technology Assessment approach would be applicable. Here, however, it is not a topic for discussion, the problem statement was fixed and the systems analysis approach chosen as the research methodology.

To the extent that more questions in the list of Grin et al. are closed for discussion, the less resemblance there is with a process of Technology Assessment. When reducing the widely open Technology Assessment methodology to a process of reducing the resistance to make changes in the aviation system by introducing new technologies, the Technology Assessment theory cannot provide more than advice about this resistance-reducing process that has to be designed.

In this research, the open Technology Assessment approach, although interesting, is not used completely. From here on, attention is paid to the resistance-reducing process that should remove some of the blockades to technology implementation.

For investigations on implementations and use of certain specific technologies in a specific system, several options exist for gathering the required amount of information or data to study implementation issues (questions 2 through 5 in the list of Grin et al.). Among others, the following can be distinguished:

1. Delphi procedure
2. Interviewing experts or actors in the field
3. Real life implementation
4. Role playing with experts
5. Simulation gaming
6. Literature study

One option, the real life implementation can automatically be removed from the list for this particular research. The reason for doing the research, is finding out in advance what the consequences of such an implementation are. Real life implementation gives the best possible answer to the question, but the risks of failure in reaching the objectives for the project are substantial.

As, in this study, the relation between actors and their complex and dynamic interaction are of specific interest, the presented list can quickly be reduced to two possible options. One is, the role-playing with experts, the other is, the simulation gaming.

When presenting radical innovations in the aviation system to experts, and asking them to give their opinions on the possibilities for implementation, a list with reasons why implementation is very unlikely, if possible at all, is easily produced (see Table 7.1). Experts working in the field have a healthy form of tunnel vision. It filters out most too radical things so their system can keep running without being disturbed too often. This might be nice when collecting data about roadblocks to implementation, however, it does not give clues to how all these roadblocks could be removed.

What is needed then, is an intervention method. Not so much the gathering of data is important, that can be done with questionnaires, interviews, literature study et cetera. However, what must be done is a change in the actors itself that all together determine in what direction the system will develop. As intervention method, from the above list, only the role playing can be chosen.

Under supervision of the author, Drost (2005) developed an initial form of this intervention method. Several people with background knowledge of the aviation system were invited to come to the experimental laboratory. First, their resistance to making changes in the aviation system was measured using a questionnaire. After that they were asked to identify all possible roadblocks for implementing a certain technology (in the experiments, the High Capacity Aircraft A3XL was chosen, this gave comparable results as can be found in Table 7.1, though on a more detailed level). These were then categorized. The experimentally found categories were safety, logistics, ground handling, aircraft characteristics and human factors.

The experimentees were given roles after this problem identification round. The different roles were the same as the actors identified in this research:

- Governments;
- Airlines;
- Aircraft Manufacturers;
- Airports;
- Air traffic control;
- Citizens living near airports, and;
- Air travelers

The group was then asked to rate (using a point system) the relative difficulty to solve the mentioned roadblocks in each of the categories. That category of problems that received most points was then further addressed in the session. The idea was that if anything could be done about the category of roadblocks that is perceived to be the hardest to solve, that other categories of roadblocks would give less problems to take out of the way.

From their particular role, the experimentees were asked to identify all possible options they could think of to solve the problems in the chosen category. After a small coffee break the group was taken out of their roles and, as a group, assigned to combine the brainstorm ideas and design an overall solution to the considered problems in the chosen problem category.

The supervisors of the experiment then introduced the idea that the experiment was over and started to hand out lunch sandwiches and drinks and started informal talks about non related issues. However, this was part of the experiment. The supervisors slowly steered the talking into the direction of the aviation system and its resistance to change. The eye-opening moment came at the end. The group, which was now busy agreeing with each other that changes in the aviation system are very hard and that the particular considered technology (A3XL) would never be implemented, was suddenly presented the solution that the group had recently designed to overcome the most important category of problems.

Main objective of this intervention method was (Drost 2005) to give the participants new insights in possible creative solutions around implementation problems of new, innovative technology in the resistant to change aviation system. The idea is that this would make participants more open for new innovations in aviation. Secondary objectives of the intervention method, some of them supporting the first main objective, are: (1) make actors learn about each others perspectives, objectives and interests, (2) creating group-atmosphere: 'we are going to solve this implementation problem', (3) Sharing information among different actors and (4) creating new possibilities for out of the box thinking.

Direct evaluation and follow up evaluation in the weeks after the experiment showed a difference in the attitude of the experimentees towards the resistance to change in the aviation system. Compared to the moment before the experiment, more possibilities for change in the system and possibilities for implementing new technologies were seen directly after the experiment, but also in the weeks following.

In the three pictures in Figure 7.2, one can see the group of experimentees with a background in aviation, in their roles, identifying roadblocks for the implementation of the A3XL to the supervisor. The second picture shows the categorization of the identified roadblocks, each on one post-it memo, in the mentioned categories safety, logistics, ground handling, aircraft characteristics and human factors. In the third picture the other supervisor shows the group the results of the voting procedure, in which the several experimentees had chosen what categories of roadblocks were seen as the hardest ones to overcome.

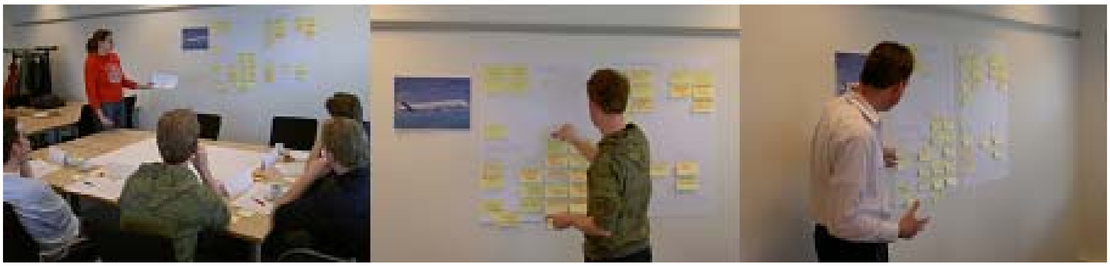

Figure 7.2. Photo impression of the initially designed intervention method.

The idea behind this experiment is that it is possible to design an intervention method that can help crack the existing tunnel vision ideas of experts why changes in the aviation system are hardly possible. In addition to more objective reasons of investments et cetera, this method tried to crack the effect of psychological reasons that strengthen the idea that change is not possible.

7.5 Part IV: Non-sustainable user options

This section covers the issue of how the technology, when implemented, gets used. Technology might be used in another way than originally intended for, which might lead to less than possible contributions to Sustainable Development.

When, in a future state of the system, new technologies have, in one or other way, been implemented the question of how these technologies will be used becomes important. In the use phase, discounting will also play a role in the choice of how the technology is actually be used. So far in the analysis, the *potential* of certain expert selected technologies is determined on several indicators representing Sustainable Development. The score cards in chapter 6 show the possible contribution of specific new aircraft related technologies to Sustainable Development. However, how a technological innovation is used will influence how much of that *potential* contribution to Sustainable Development is turned into a *real* contribution. The usage may evoke feedback loops in the system, 2nd order effects that the analysis has not taken into account, for it was (only) looking for the *potential* of these technologies.

While under serious pressure to reduce costs in the world of airlines, all ways to increase short term profit can expected to be used by the users of aviation technology. With Sustainable Development being a concept that seeks for balance between People, Planet and Profit, the incentive described here will push to non-sustainable developments as it will favor short term profit increases over improvements in the people and planet category.

When the 2050 state of aviation is reached using traditional technology, the demand for air travel reaches a certain value in relation to the amount of adverse effects caused by aviation. New technologies, developed with the purpose to reduce some of these adverse effects can be used to indeed create a system with the same amount of air travel and less adverse effects. It could, however, also be used to keep the amount of adverse effects constant and increase traffic volume - the later being ideal for boosting short term profit, but not necessarily bringing a sustainable state of the system any closer.

Worldwide, airports increasingly have noise restrictions, for instance in the form of noise contours. The total amount of noise caused by aircraft may not exceed a certain predetermined value; else the airport gets a penalty. Noise, however, is an important indicator in the planet category of Sustainable Development as well. With noise also being high on political agendas and penalty systems, there is a strong incentive to develop technology that will reduce the amount of noise caused by aircraft. If the noise contour restrictions would stay the same, more flights would be possible with the new technology, possibly leading to more competitive prices and a possible growth in air travel.

This example holds true for most improvements that, in unchanged form, would contribute to more Sustainable Development. Less fuel use may result in more payload, more passengers; higher safety levels may lead to more people per aircraft while still obeying the existing safety requirements; less land use may enhance airport capacity expansion, and so on.

A final remark on markets versus regulation

An important role for the virtual client of this research is to continuously monitor the potential technological possibilities. By making new regulations on noise levels, safety levels, emission levels, etc., new technologies can be used to enhance overall Sustainable Development, instead of being used to obtain other objectives.

A problem with this is, of course, that not all actors in the aviation system can afford these new technologies; these actors will be put at a serious disadvantage if these new regulations would be set.

This implementation situation looks like a choice between two objectives: Sustainable Development and a free open market economy. When a governmental institution decides to make stricter regulations because technology makes it possible to for instance reduce noise or gas emissions, then fewer actors in the system can still be active in the open aviation market (as not all actors can afford the new, more expensive, technology), but, noise and gas emission levels will indeed decrease. The less strict the governmental regulations on noise, the less sophisticated technology is needed, the less money has to be spent on that technology and thus the more actors in the system can continue their operations, but the noise and gas emission levels do not go down to the extent that the technology, in potential, can make possible.

Nevertheless, will technology indeed play a role (e.g. contribute to Sustainable Development) governmental institutions like the European Parliament should set standards for noise, safety, emissions, etc., thereby choosing for what is acceptable in terms of adverse aviation effects versus what standards for overall sustainability are technologically possible. Only in this way technology can be used to enhance overall sustainability instead of looking only at adverse effects per seat kilometer, and, thereby, completely ignoring total traffic volume growth.

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8. Discussion of the results

8.1 Introduction

This chapter will discuss the results of this research. Section 8.2 will answer the several research questions in order, as stated in section 1.5 of this thesis. Section 8.3 wraps up these individual answers to answer the two main research questions boxed in section 1.5. In section 8.4 some reflections on how this research has addressed the problem are made.

8.2 Detailed conclusions: answering the individual research questions

The list of research questions as introduced in section 1.5 is, one by one, repeated here and each of them answered elaborately.

System definition

- What is considered the problem and what is the system of interest?

Aviation brings many advantages to society, reflected in its huge growth figures. But, aviation is also criticized for its many undesired effects. The most widely known are noise disturbances and gas emissions, which hurt local living conditions around airports and which contribute to climate change.

Sustainable Development as a concept is brought forward by many of the actors in the aviation system as a way in which aviation can develop itself in order to reduce its undesired effects. Sustainable Development refers to a wide variety of factors, often categorized under the three labels social, environmental, and economic.

Some actors refer to technology as a potential solution for the undesired effects of aviation in all categories of Sustainable Development. Technology should then, in some or other way, contribute to Sustainable Development. This research tries to find out if there is some truth in that claim.

The virtual client is in this case the European Parliament and European Commission, large enough to have power over policymaking for a substantial large share of the world's aviation system. The Commission and Parliament are also seen as small enough to come to decisions that can make direct and detailed changes in a short enough amount of time.

Considering an aviation system influenced by the introduction of new technologies, this research included the following actors in the system to analyze:

- Governments;
- Airlines;
- Aircraft manufacturers;
- Airports;
- Air traffic control;
- Persons living near airports, and;
- Air travelers.

Outcomes of interest

- What is Sustainable Development?
- What are the associated outcomes of interest and outcome indicators?

The literature provides descriptions of the Sustainable Development concept. The Council of the EU (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 (INFRAS 2000) provides a description of sustainable aviation. All outcomes of interest mentioned in these two descriptions are identified (see chapter 3). The used category labels for the categorization of these outcomes of interest are social factors, environmental factors and economic factors (these labels resemble the axis People, Planet and Profit; the different cells are marked according to this: PE stands for People, PL, for planet and PR for profit) and are presented in Table 8.1.

Social	Environmental	Economic
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*
	PL4: Noise impact Low noise generation *Noise*	

Table 8.1. Factors representing Sustainable Development categorized in three columns: social, environmental and economic. 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).

Using publications by each of the considered actors in the aviation system, for each of the factors mentioned in Table 8.1, measurable indicators have been designed in this research. These indicators represent information about Sustainable Development that decisionmakers might need in their decisionmaking 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 (labeled ASI, which stands for Additional Stakeholder Indicator). In this research, no single indicator is considered more important than another. Based on the scoring pattern on all indicators, the decisionmaker can make his or her own judgments. The indicators designed in this research are listed in Table 8.2.

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

Table 8.2. Designed indicators representing the outcomes of interest.

Selecting technological innovations

- What current and future new aviation technologies selected by experts are likely to be promising in terms of their contribution to sustainable development?

To identify technologies that can be analyzed, first the aviation system is broken into subsystems to find in which subsystems aircraft related technology plays a role. We first distinguish the landside and airside subsystems. We then 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 (Figure 8.1).

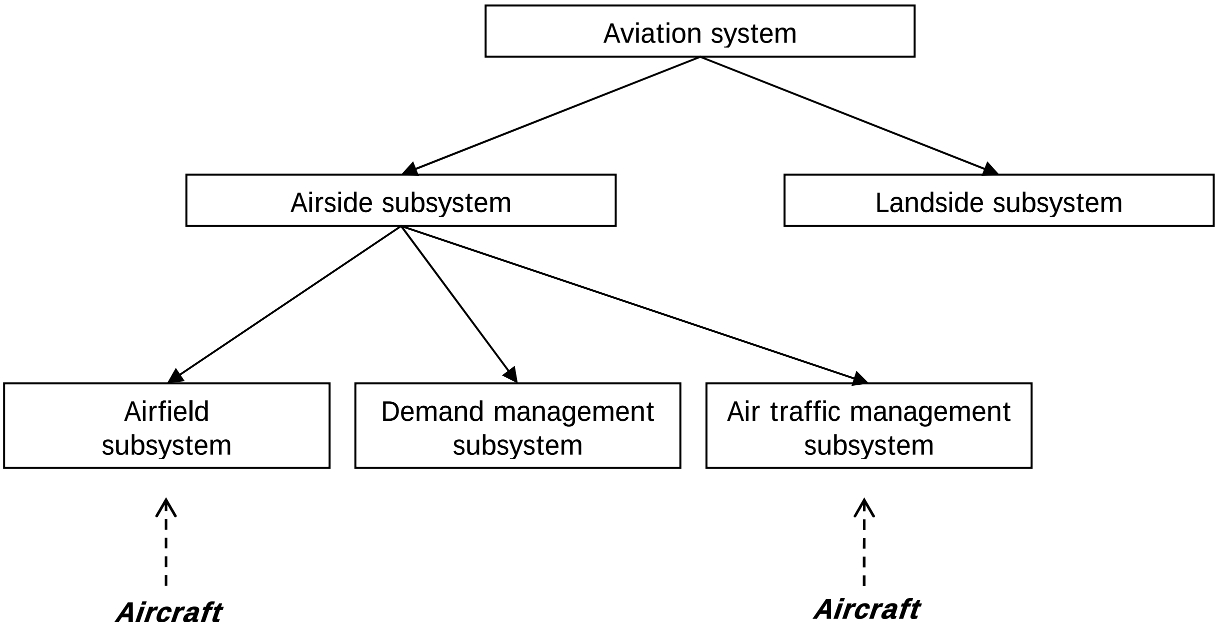

Figure 8.1. Distinguishing the subsystems within the aviation system that aircraft technology influences.

An aircraft can itself be considered a system composed of four subsystems (see Figure 8.2): structure, aerodynamics, controls, and propulsion (Anderson 1989; Moir and Seabridge 2001).

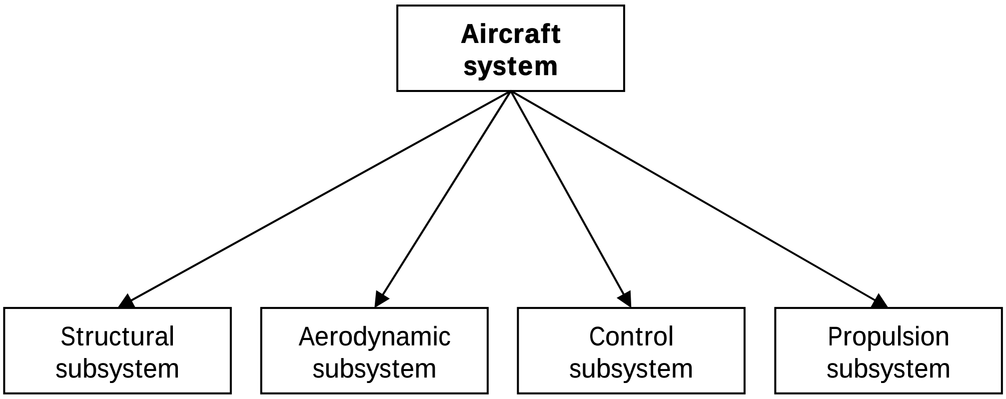

Figure 8.2. Subsystems of the aircraft system

Using expert opinion and scanning the literature, technologies have been identified in each of these four subsystems that are promising given certain indicators of performance that are considered important (such as noise, or fuel use), and 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). In addition to technologies making changes in the four identified subsystems, there are also technologies identified that change the overall aircraft system, e.g. Blended Wing Bodies and Airships. The identified technologies are summarized in Table 8.3:

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

Table 8.3. Identified technologies in the overall aircraft system and its four subsystems.

Uncertainty: scenario development

- What are the relevant future air travel demand scenarios (in terms of number of seats) within which to evaluate the innovative aviation technologies?

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. Lifetimes of aircraft are usually expressed in numbers of flights, since the number of take-offs and landings determines if the aircraft can still operate safely and economically. With the intense use of aircraft every day of the year, after 35 years most aircraft will have been replaced. Some civil passenger aircraft might fly some extra years as freighters and some will still fly in less dense markets in Africa or South America (like some old Fokker F27s and Boeing 707s and 727s do). 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 expert selected aircraft related technologies are then analyzed. Using literature and expert interviews, factors are identified that influence air travel demand. A range of plausible values for these factors between now and 2050 have been assumed, again based on interviews and literature. All possible combinations of values for these factors resulted in a set of 16 possible scenarios for air travel demand in 2050. The two scenarios eventually considered out of the 16 are the highest and lowest growth scenarios in terms of seats flying around in aircraft. The two scenarios are summarized in Table 8.4. Note that the numbers are numerical outputs of models. Their value for this research is their orders of magnitude, not their exact values to the last digit. In the analysis, within each of those two numerical scenarios, both a point-to-point system and a hub-and-spoke system is projected, giving a total of four different analysis contexts.

Possible scenarios	Number of seats	% increase compared to situation in 2004
Base case: *Situation in 2004*	*2 098 056*	-
Scenario A: *2050: High growth in traffic*	*19 131 827*	*912%*
Scenario B: *2050: Low growth in traffic*	*5 220 388*	*249%*

Table 8.4. Two numerical scenarios for air travel demand for 2050 compared to the base case (the situation in 2004).

Scoring the technological developments

- What is the relation between the promising technological developments and the outcome indicators?
- What will current technology and its incremental improvements produce on the outcome indicators in the base case (that is, business as usual or the *do-nothing* option)?
- Could ideal implementation (that is, full implementation without exceptions) of the most promising technologies lead to a sustainable solution in any of the future scenarios?

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 S.4.

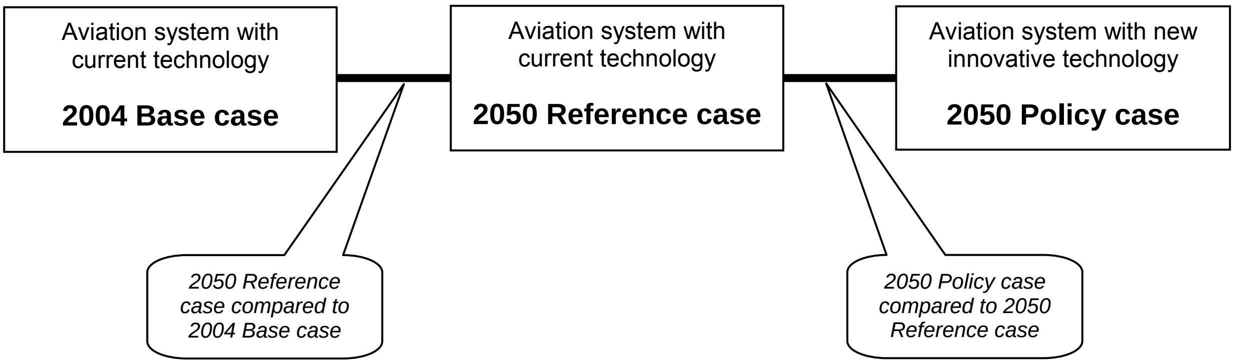

Figure 8.3. The different scoring cases compared to each other.

When, in chapter 4, a set of different technologies is identified, 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. 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 seat flown by 15%. This research uses scenarios to manage the uncertainty about the future state of the aviation system. Air travel demand is the external factor making up these scenarios (see chapter 5). This research thus has to translate the 15% direct operating cost reduction 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 first translating all the mentioned effects in the preliminary design reports or studies to an effect per flown seat. Second, the share of the particular technology in the future aviation fleet was determined. The effect of, for instance, 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. Third, 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 of all technologies on all indicators can be seen in Tables 8.5 through 8.8 for the four different scenarios. Tables 8.5 and 8.6 refer to the high growth scenario A, with A1 high growth in a point-to-point system and A2 high growth in a hub-and-spoke system. Tables 8.7 and 8.8 refer to the low growth scenario B: Table 8.7 for the low growth scenario B1 in a point-to-point system and 8.8 for a low growth scenario B2 in a hub-and-spoke system.

Policy case 2050 **Scenario A1** **High Growth** **Point-to-Point** Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<10.12	10.12	<10.12	10.12	10.12	10.12	<10.12			<10.12	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		9.88	7.08	9.95	9.92	10.12	5.07	0.61			9.10	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<10.12	7.08	10.12	10.12	10.12	10.12	10.12			<10.12	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		2.12	2.12	2.12	2.12	2.12	2.12	2.12			2.12	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		2.12	2.12	2.12	2.12	<2.12	2.12	2.12			2.12	
Number of connected geographical places via operated air routes in the EU.		3.24	3.24	3.24	3.24	<3.24	3.24	3.24			3.24	

Table 8.5. Scorecard for all considered technologies in the high growth scenario A1 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 Scenario A2 High Growth Hub-and-Spoke Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<10.12	10.12	<10.12	10.12	10.12	10.12	<10.12			<10.12	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		10.01	7.08	9.95	9.92	10.12	5.07	0.61			8.47	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<10.12	7.08	10.12	10.12	10.12	10.12	10.12			<10.12	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		2.12	2.12	2.12	2.12	2.12	2.12	2.12			2.12	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		2.12	2.12	2.12	2.12	<2.12	2.12	2.12			2.12	
Number of connected geographical places via operated air routes in the EU.		3.24	3.24	3.24	3.24	<3.24	3.24	3.24			3.24	

Table 8.6. Scorecard for all considered technologies in the high growth scenario A2 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 Scenario B1 Low Growth Point-to-Point Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.99	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<3.49	3.49	>3.49	3.49	3.49	3.49	>3.49			>3.49	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		3.45	2.44	3.43	3.42	3.49	1.75	0.21			2.98	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.99	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.99	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.99	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<3.49	2.44	3.49	3.49	3.49	3.49	3.49			<3.49	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		1.37	1.37	1.37	1.37	1.37	1.37	1.37			1.37	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		1.37	1.37	1.37	1.37	<1.37	1.37	1.37			1.37	
Number of connected geographical places via operated air routes in the EU.		1.74	1.74	1.74	1.74	<1.74	1.74	1.74			1.74	

Table 8.7. Scorecard for all considered technologies in the low growth scenario B1 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Policy case 2050 Scenario B2 Low Growth Hub-and-Spoke Indicators → ↓ Technologies		Ultra high capacity aircraft	composite materials	High aspect ratio wings	Free Flight	Reduced thrust take-off	Propellers for high flying speeds	Hydrogen powered flight	*Airships*	*SkyCar*	Blended Wing Bodies	
Design risk of innovative technology		Su	M	Su	M	Sm	L	Su	*Airships are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	*SkyCars are not considered in this research as they are not expected to take over any part of the current aviation system (see chapter 4)*	Su	
Changes in design and maintenance of aircraft		M	M	Su	Sm	Sm	L	Su			Su	
Average turn around time		1	1	1	1	1	1	1			1	
Percentage of flights leaving the airport according to schedule		>1	1	1	>1	1	1	1			1	
Number of transport modes for continental transport (including aviation)		1	1	1	1	1	1	1			1	
Number of airlines operating		1	1	1	1	1	1	1			1	
Number of innovative aviation technologies in use		1	1	1	1	1	1	>1			>1	
Direct operating cost		0.97	<1	0.99	<1	<1	0.85	1.05			0.90	
Noise production of specific innovative aviation technology		1	1	1	1	0.90	<1	0.92			0.50	
Land unavailable for other than aviation purposes		<3.49	3.49	>3.49	3.49	3.49	3.49	>3.49			>3.49	
Percentage of renewable fuel of the total amount of fuel used (1=no renewables, like in 2004; 2=all renewables)		1	1	1	1	1	1	2			1	
Total emission of CO2 during flight operations		3.42	2.44	3.43	3.42	3.49	1.75	0.21			3.13	
Different type of aircraft in service		1	1	1	1	1	1	>1			>1	
Average emission of VOCs per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.90	
Average emission of CO per LTO cycle		0.98	0.85	1	1	0.65	1	0.21			0.90	
Average emission of NOx per LTO cycle		0.98	0.85	1	1	0.65	1	<1			0.90	
Average fuel use per LTO cycle		0.98	0.85	1	1	0.65	1	0.90			0.90	
External safety weight of risk (# flight movements * risk of crash per flight * average aircraft weight.)		<3.49	2.44	3.49	3.49	3.49	3.49	3.49			<3.49	
Number of aircraft crashes per year involving aircraft >150 passengers.		0.99	1	1	1	>1	1	1			<1	
Number of internal incidents in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of internal fatalities in aviation per year.		0.99	1	1	1	>1	1	1			<1	
Number of operated larger, international airports in the remote Northern and Eastern part of the EU area.		1.37	1.37	1.37	1.37	1.37	1.37	1.37			1.37	
Number of operated larger, international airports in EU area.		1	1	1	1	1	1	1			1	
Average distance to larger, international airport.		<1	<1	<1	<1	<1	<1	<1			<1	
Average ticket price for flight.		<1	<1	<1	<1	<1	<1	>1			<1	
Average frequency of flight between two airports within the EU area.		1.37	1.37	1.37	1.37	<1.37	1.37	1.37			1.37	
Number of connected geographical places via operated air routes in the EU.		1.74	1.74	1.74	1.74	<1.74	1.74	1.74			1.74	

Table 8.8. Scorecard for all considered technologies in the low growth scenario B2 for 2050 *(Sm=Small, M=Medium and Su=Substantial; 1=equal to 2004 situation)*

Two important conclusions can be drawn from the results of the analysis. One is, that it is not very likely that technology related to aircraft will, in the time span till 2050, make serious contributions to the level of Sustainability for the whole aviation system. It is true that not all possible technologies are considered, but, the technologies listed are according to experts promising concepts and all are considered to be feasible within the time frame of 2050. It must be made clear immediately that, of course, technology can make the situation on some indicators substantially better if the sector would not grow at all. This is not an open door, but an important finding, because technology thus gives society some extra margin (either in time or in severity of effects) to come up with real sustainable solutions. A combination of two techniques for instance (composites with high speed propellers) could, in a low growth scenario, not substantially deteriorate the level of CO_2 emission for 2050. CO_2 emission is currently a very important and hot topic world wide.

The option of hydrogen fuelled flight needs some extra attention. This research has not put attention to how hydrogen can or will be generated. Today's capacity is not enough, but that can change. The problem lies in the fact that hydrogen in large quantities cannot be generated in any other way than burning or transforming fossil fuels. The CO_2 emission then takes place when generating hydrogen and not when using hydrogen.

A second important conclusion is that aircraft related technology appears not to be able to influence all aspects of Sustainable Development. It appears mainly LTO emissions, CO_2 emissions and Direct Operating Costs are really influenced. That makes technology an instrument of limited capabilities in the full Sustainable Development discussion. Note that this is not for reasons of not keeping up with growth of the sector, but for reasons of a small number of effects on a concept of Sustainable Development that has such a wide variety of characteristics.

Identifying roadblocks and non-sustainable user options

- What roadblocks can be identified that might prevent promising innovative aviation technologies from being implemented?

Should the problem owner of this research decide upon the wish to implement some (or all) of the technologies analyzed, some serious problems do arise.

First, it is not easy to implement new technology that requires changes in a system while that system has over the last 50 years been constantly improved to some performance parameters and got locked-in in itself.

Second, while the goal of the virtual client may be improvements in all three categories (social, environmental, and economic) of factors that represent Sustainable Development, individual actors in the system might opt for using these technologies slightly differently and, with that, improving indicators in only one of the three categories (profit, is the expectation).

In order to help solving the first problem, this research consulted literature and experts to come up with the following list (Table 8.7) of factors that are expected to serve as barriers for implementing particular technologies.

Policy measure	Major roadblocks for implementation
Ultra High Capacity Aircraft	Lock-in at airports (with high costs as a result) Psychological resistance to such large aircraft by passengers and crew. Investment risk aircraft manufacturer. Evacuation not in compliance with current ICAO regulation of 90 seconds. Operators risk: too low load factor. Issue of vortices from wing tips: larger separation times possible necessary; reducing an airports capacity.
Composite materials	Expensive investments. Knowledge not widely available and demonstrated (not yet proven technology) Relatively high development (and thus financial) risks. Requires regulation change in allowable crack size during operation (composites do not crack during life time of aircraft, but when they do crack, flying is not safe).
High aspect ratio wings (on ultra high capacity aircraft)	Lock-in at airports (with high costs as a result). Only useful for very large aircraft; therefore higher development and financial risk.
Free flight	Historically grown patterns of distribution of power and responsibilities must change. Requires large changes in Air Traffic Control: currently small building blocks of responsibilities with plans to bring those to the free market. Capacity issues near airport remain and might be or become bottle neck.
Reduced thrust take-off flight procedures	Concept of ‘captains decision’ (captain finally decides/has final responsibility what is best for safety in a given situation) can counter prescribed procedure. Requires changes in historically grown patterns of distribution of power between captains and air traffic controllers.
High speeds propellers	No economic incentive with cheap oil; oil price can increase a lot before economic incentive is present. Old fashioned look. Different fleet circulation across the world due to slightly slower flight speed, requires adaptation of accepted ideas of schedules by travelers. A possible lower flying altitude causes less comfort. Less comfort due to increased noise inside aircraft
Hydrogen fueled aircraft	Large investments, high financial risk. Increase in land use due to extra fuel storage places. Lock-in effects related to aircraft paradigm; aircraft is currently optimized for kerosene. No sufficient capacity for hydrogen generation worldwide.
Blended wing bodies	Large investments, high financial risk. Lock-in at airports. Evacuation not in compliance with current ICAO regulation of 90 seconds.

Table 8.7. Factors that form a barrier for implementing promising innovative aviation technology.

Of the prerequisites for the appearance of radical technological innovations in an open market, as formulated by Moors (Moors 2000), at least two are clearly not met in the aviation system. There is not yet a serious sense of urgency and there is also not sufficient money available. May a governmental agency, like the problem owner in this research, still want to steer in the direction of more sustainable aviation by means of the implementation of more new technological innovations, it should at least try to meet the above four prerequisites.

Generating explanations for these roadblocks and non-sustainable user options

- What explanations can be identified for these roadblocks and non-sustainable user options?

Discounting gives explanations for why promising (in terms of their contribution to Sustainable Development) technologies do not get implemented. In the resistant to change aviation system, a lot of investments have to be made at the start of a new technology design project. It might take at least 10 years before the first exemplars are certified and can be sold to a potential customer. Benefits for Sustainable Development will only occur after the complete old technology fleet is replaced, some 30 years later. That means that the situation is exactly the opposite as in the ideal case according to discounting theory: huge costs are in the start of the process, while the benefits ("income") are earned far in the future. This situation is generally true for new technologies (always some investments are required first and earnings come later), but in the aviation system the earnings and investments lie particularly far from each other, especially when it comes to earnings contributing to Sustainable Development.

One can represent the situation of deciding for or against the development of certain technology in its most simple form by having two actors depending on each other. It appears that actors willingly block actions from the other actors as soon as they perceive their income as being too different from others. This is strange from a utility maximizing point of view: no matter what income can be earned, as long as it is more than a net zero, not blocking any development should be preferred over blocking it. Actors look at each other and compare their relative earnings, more than they decide only upon whether they make a profit or not. This finding is important for the problem owner of this research that in one or other way will have to make sure that the earnings of implementing technologies that contribute to Sustainable Development get redistributed in such a way over the different actors in the field that they all agree on implementation. This is an extra requirement to the requirements introduced by Moors in the comparative study on introducing innovations in the heavy metal industry.

Technology Assessment originally focused on the role of Early Warning Systems; trying to predict the possible effects of the introduction of a new technology in society. Newer forms of Technology Assessment, like Constructive or Interactive Technology Assessment, focus a lot on the process of opinion forming and decisionmaking around technological innovations. In several rounds of meetings, all actors try to come to a commonly shared point about what is considered to be the problem, whether it is needed to do something about it, whether technology can be a suitable solution, what technological options there are, how they should be implemented, et cetera. This, no doubt, takes a lot of time, if in systems with many different actors and stakeholders having different and contradictory objectives, an agreement can be made at all.

Technology Assessment stresses that by a slow process of rounds of agreement on parts of the problem and the solution, more commitment is created for the chosen way among the actors and stakeholders in the system. Also, lots of attention is paid to the actual gradual change in opinion about the possibility of certain technological options. In other words, it is tried to reduce the resistance to change a bit.

This research assumes that it is not easily possible to get all major actors and stakeholders in the aviation system in an Interactive Technology Assessment procedure from beginning to end, and focused on a simple intervention method that also has as goal to reduce the resistance to change in people. Basically, what it tries to do is to change people's mindsets so that the roadblocks for implementation of promising (in their contribution to Sustainable Development) technologies (see Table 8.3) are not seen as a dead end, but as a start for which solutions have to be found.

The intervention method has been designed by Drost (Drost 2005) under the supervision of the author of this research. Direct evaluation and follow up evaluation in the weeks after participating in the intervention methodology experiment showed a difference in the attitude of the experimentees towards the resistance to change in the aviation system. More possibilities for changing it and implementing new technology were seen directly after the experiment, but also in the weeks following.

The idea behind this experiment is that it is possible to design an intervention method that can help crack the existing tunnel vision ideas of experts why changes in the aviation system are hardly possible. In addition to more objective reasons of investments, et cetera, this method tried to crack the effect of psychological reasons that strengthen the idea that change is not possible.

As the concept of Sustainable Development shows, many indicators should be addressed at the same time before a real contribution to Sustainable Development is made. However, technology can to a certain extent be used to address certain particular outcomes of interest. In a way, technology can be used to even optimize a single outcome of interest. If, for instance, a technology of high speed propellers has the effect that the current flights of the total fleet of aircraft in the world are much less noisier, there is room for growth at airports. As airports are often noise restricted (that means that their actual physical capacity is much larger than what is being used, as using to the total physical capacity would lead to unacceptable noise exposures for citizens around the airport), according to those restrictions suddenly many more flights are possible. This then can lead to much more growth of the sector, more burning up of fuels, more congestion, more delays, etc.

A final remark on markets versus regulation

An important role for the virtual client of this research is to continuously monitor the potential technological possibilities. By making new regulations on noise levels, safety levels, emission levels, etc., new technologies can be used to enhance overall Sustainable Development, instead of being used to obtain other objectives.

A problem with this is, of course, that not all actors in the aviation system can afford these new technologies; these actors will be put at a serious disadvantage if these new regulations would be set.

This implementation situation looks like a choice between two objectives: Sustainable Development and a free open market economy. When a governmental institution decides to make stricter regulations because technology makes it possible to for instance reduce noise or gas emissions, then fewer actors in the system can still be active in the open aviation market (as not all actors can afford the new, more expensive, technology), but, noise and gas emission levels will indeed decrease. The less strict the governmental regulations on noise, the less sophisticated technology is needed, the less money has to be spent on that technology and thus the more actors in the system can continue their operations, but the noise and gas emission levels do not go down to the extent that the technology, in potential, can make possible.

Nevertheless, will technology indeed play a role (e.g. contribute to Sustainable Development) governmental institutions like the European Parliament should set standards for noise, safety, emissions, etc., thereby choosing for what is acceptable in terms of adverse aviation effects versus what standards for overall sustainability are technologically possible. Only in this way technology can be used to enhance overall sustainability instead of looking only at adverse effects per seat kilometer, and, thereby, completely ignoring total traffic volume growth.

8.3 Overall conclusions

The problem formulation for this research is (repeated from chapter 1):

> *What is the potential of a set of expert-selected new aircraft technologies to contribute to Sustainable Development; i.e. what is their potential to reduce actor defined adverse effects of flying while keeping the benefits?*

As explained in chapter 1, the problem formulation can be split into two parts, leading to two main research questions:

> *1. What can expert-selected new aircraft technologies contribute to Sustainable Development?*
>
> *2. How can expert-selected new aircraft technologies with a potential to contribute to Sustainable Development be implemented and used in a way that their potential contribution turns into a real contribution?*

Research question 1: Given the results of this research, the expert-selected and assessed technology has a potential to contribute to a few characteristics of Sustainable Development, mainly the reduction of noise and gas emissions. However, on these characteristics, technology cannot keep up with the predicted growth in air travel demand, which increases the adverse effects of aviation. Not even in the smallest growth scenario can this increase in negative effects be counteracted by the introduction of new aircraft technology.

Research question 2: Some of the selected and assessed aircraft technology can influence characteristics of Sustainable Development in a desired direction. Two of these characteristics currently receive a lot of attention worldwide: noise around airports and gas emissions with negative consequences such as climate change. Also for this reason, one might decide that implementation of such new technology is worthwhile. This research shows that, especially for the aircraft related innovative technologies considered in this research, implementation of new technology and replacement of old technology takes long time frames, up to 40 years. In addition, many roadblocks (e.g. airport infrastructure adaptations) need to be taken out of the way. Psychological mechanisms like discounting and fairness appraisal play a delaying role in the implementation process. For the aviation system as a whole, two important drivers for innovation appear to be lacking: sense of urgency for change and availability of sufficient amounts of money. The use of technology can be such that second order effects (rebound effects) can be negative and larger than the promising positive effects a technology has in terms of Sustainable Development. It appears that the problem owner, in order to solve this, has to confront the conflict between the ideal of an open free market economy and the adverse effects of flying.

Since this research has shown that current ideas about new aircraft technologies do not seem able to produce big enough positive effects, it is recommended that serious investments be made and incentives created to stimulate the development of other technologies that can contribute to sustainability. In addition, one might search for other options than technology to improve the contribution of aviation to Sustainable Development.

8.4 Some additional reflections on and limitations of the research

Technological developments: autonomous or not?

This research assumes that technology in itself is not steering any changes or striving for any solutions. As can be seen in chapter 7 about implementation, it assumes that it is people who decide upon what technologies are introduced in systems. However, not all authors accept that technology indeed is neutral and could be directed onto a desired course of action. This steerability of technology is something that at first glance a lot of people do not discuss. However, more philosophical authors, such as Jacque Ellul, Martin Heidegger and Hans Jonas, do not simply see technology as a neutral thing that can be molded in any desirable way serving human needs. According to the philosopher Jacque Ellul, for instance, people do not steer developments in technology, but technology itself is actually steering people, thereby having high efficiency as the ultimate goal (Dijk et al. 1992).

Ellul might be the strongest statement maker in this case by suggesting that technology in itself has a goal and that the goal is not necessarily beneficial for society; mankind is only acting as servants to technology in order to let technology reach its goal. Ellul writes, consequently throughout his work, the word Technology with a capital T, thereby addressing the importance of technology in (or over) our society. In addition, he claims that by every introduction of a new technology, usually one problem is solved, but much more other new problems are introduced. Ellul is very skeptical about the positive role that technology is said to play in our society. He warns (actually he claims that he "diagnoses") that mankind should not trust technology to solve all occurring problems. Unfortunately Ellul does not give practical clues to overcome this.

Making the concept of Sustainable Development measurable

An important contribution of this research is the operationalisation of the broad concept of Sustainable Development for the particular case of the aviation system and new technologies that are introduced into this system. A clear goal of this research was not only to make the concept of Sustainable Development measurable, but also to score several technological innovations on their contributions to Sustainable Development. For that reason, the operationalisation of Sustainable Development resulted in a set of outcome indicators that should represent the three important fields of Sustainable Development: social (people), environmental (planet), and economic (profit).

Since not all aspects of Sustainable Development could be made measurable (as can be seen in chapter 3), the study does not claim that it measures Sustainable Development. It clearly indicates what characteristics of Sustainable Development can be measured and are expected to be influenceable by the introduction of new technology. The other (non-measurable) characteristics of Sustainable Development are not in the scorecards, which does not mean that they are not interesting or important.

Long time frame of studies for Sustainable Development

An important characteristic of studies that have Sustainable Development as their topic is, by their nature, a long time frame and their assumption that, if sustainability as a state is not reached, a catastrophe will, sooner or later, be the result.

Because catastrophes have large impacts on society, the results of these studies are very important for all members of society. However, the possible catastrophe is usually far away in time -- far away enough to be able to do some steering and try to prevent the catastrophe from happening, but also far away enough to make it receive less attention. In addition, there is the problem of uncertainty, which becomes a larger problem the further one tries to look into the future.

It is expected that a Sustainable Development in the real meaning of the word, requires organizing things dramatically different in our world society than we are doing today (WCED 1987). Big changes need big efforts in terms of time and money. The possible necessity for this effort to be spent is countered by the existing uncertainty (one does not know if such an effort is really necessary) and the attention people pay to problems in the future (people tend to value negative outcomes in the future lower than today (Chapman 1998)).

If a study like this were delayed, the level of uncertainty would definitely drop and the attention that problems around the state of sustainability would receive from society would be higher. But, at such a point in time, it might be far too late to start organizing society dramatically differently in order to prevent the catastrophe. Far in advance, one doesn’t know what to do, but there is still plenty of time to rearrange things; later in time, one knows more sure what is necessary, but there might not be the possibility anymore to make the needed changes in society.

Using scientific methods, like this research does, to investigate issues regarding Sustainable Development, requires an explorative way of studying. Clear answers about what to do and how to do it might be the objective, however, that is not possible to do. The outcomes that can be generated, like the scorecards in this thesis (chapter 6), are necessary to be able to know that precautionary action might be needed, though knowing what action to take is still highly uncertain (as can be derived from the results in chapter 7 on implementation). Without these explorative studies, there would be no early warning, and catastrophe might strike without the possibility to do something about it anymore.

Finding truth

Engineering realism accompanying positivism is the basis for the methodologies used in this research. The neutrality of the analyst and the (in theory) flawless possibilities of the scientific methodologies are hypothesized in society widely as generating superior knowledge or 'the truth'. However, since the 1960s, social construction of technology with Latour, Ellul etc., has become more and more accepted. Latour shows in his famous book *Laboratory Life* (Latour and Woolgar, 1979) that, in a group at a certain moment, interpretations of test results are accepted as the truth and are not criticized anymore.

The methodology of this research aims at rationalizing to a certain extent the problem field. With that it hopes to facilitate decisionmaking processes around the issue of aircraft technology and Sustainable Development. By no means has it wanted to claim that it contains the single truth, if such truth exists.

8.5 Suggestions for further work

It does not seem that current ideas about new aircraft technologies are able to produce big enough positive effects. In order to reach the problem owner's goal of contributing to Sustainable Development, there are two other paths to investigate: (1) work harder on the development of aircraft technologies, or (2) look for improvements somewhere else.

The first path is most in line with this research. If more serious investments are made in developing aircraft technologies and if more incentives are created for doing so, this could stimulate the development of technologies other than those considered in this dissertation that might contribute to Sustainable Development. In addition, more should be known about transitions towards these new technologies, if promising ones are found. Current studies on transitions have a very high level of abstraction; far away from the actual implementation issues and day-to-day decisionmaking. It would be very valuable, using specific case studies, to try and translate current relatively abstract theory into practical terms.

However, the success of this path of new technology and transitions is highly uncertain. Therefore, it might be wise to look for other options as well.

The non-technological path offers some interesting options. Non-technological options include changing the function of transport itself. For example, if a group of people could be transported to a holiday resort in 24 hours instead of in 1 hour and the trip as such could be experienced as part of the holiday (if there are enough opportunities to relax, party, have a good view on beautiful sights), the trip would offer less in terms of speed (compared to a traditional aircraft), but might produce less negative effects in terms of gas emissions and noise.

Even further away from aircraft technology and even from the aviation system is leaving the aviation system as it is and focusing the efforts on other systems. Aviation is not such a large system in terms of total energy use. If other, larger, systems could be changed in such a way that they contribute more to Sustainable Development (perhaps by using technology innovations from the aviation sector), that might result in an overall larger positive contribution than would be possible from changes in the aviation system. For example, technologies have been developed for light weight, highly efficient aircraft. These technologies might be able to be used in automobiles. They than might be able to play a serious role in changing another system in such a way that it contributes more to Sustainable Development.

The behavioral sciences might also be a good starting point for further research, as eventually the added choices of all consumers (i.e. their consuming behavior) determines whether society is moving towards sustainability or moving away from it. What steers people in making their choices, and can that be influenced?

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Acknowledgments

Ideas for this research project developed in the late 1990s, when the Delft University of Technology raised interest in the concept of Sustainable Development and the author's job at that time was the development and teaching of courses about this concept for the faculties of Aerospace Engineering and Mechanical Engineering. Coming from a project management job in which research about the application of a new aircraft material on a newly designed large aircraft had been the topic of the day, this was both a change and a challenge.

An inspiring colleague and professor in aircraft materials, prof.dr.ir. Ad Vlot, advised me to start PhD research in Sustainable Development. This research could: (1) provide new material for the courses I was teaching at that time, and, (2) embed the concept of Sustainable Development more in the research done at the faculty, in particular in the Structures and Materials Laboratory. He offered to be my promoter on the project and I started to "do something with aviation and Sustainable Development". Reading and interviewing a lot of people and making case studies, i.e. making designs with groups of enthusiastic students and single graduate students, were the first activities for this research. Unfortunately at that moment in time, my promoter, in his late thirties, discovered he had a lethal illness and passed away only four months later.
Since my first days at the faculty of Aerospace Engineering, Ad Vlot inspired me -- his lectures, the questions he asked us students, midway 1990s with his courses (Culture and Technology and Ethics and Technology), during my student assistentships, during my first job, and finally as promoter. Ad Vlot's ideas will most certainly have influenced my work; the people who have had the pleasure of knowing him, no doubt, will recognize traces of his ideas and visions in this dissertation. I am very grateful for his support in different stages of my student and professional life.

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I dedicate this thesis to both Ad Vlot and Jurgen Gerritsen. Both died at an age that we humans on this Earth consider far too early.

In one of our last meetings, Ad Vlot pointed to a potential problem in my research. He said that I was collecting a lot of interesting material and did a lot of interesting aircraft engineering design work with my students, but that I had no framework to analyse all this knowledge and present it in a coherent way in a book. Only a few months later, the dean of the Technology, Policy and Management faculty, the driving force behind the Delft Airport Development Center, brought me into contact with prof.dr. Warren Walker. Warren's long experiences with and enthusiasm for systems analysis quickly resolved the problem of the lack of an analytical framework. He offered to take over the supervision of my PhD thesis and became my new promotor. His ideas are throughout this thesis. They are also present in the way I supervise my graduate students and in the way I teach my courses. Warren, many thanks for your guidance.

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Delft, April 12th, 2007

Alexander

Curriculum Vitae

Alexander de Haan (1972) has Bachelor and Master degrees in both Aerospace Engineering (Delft University of Technology in The Netherlands) and Social- & Organizational Psychology (University of Leiden in The Netherlands). In 1997 and 1998 he did project management work for aircraft material development in a combined project between Fokker-Stork, Airbus and Delft University. He joined the faculty of Technology, Policy & Management at the Delft University part time in 1998 and full time in 1999, where he focused his work on Sustainable Development in Aerospace Engineering and Mechanical Engineering. From 2001 till 2003 he worked as a part time consultant at the Delft Airport Development Center, on projects related to modeling and forecasting aviation issues for airports, airlines and aircraft manufacturers. In 2002 he joined the Policy Analysis section at the faculty of Technology, Policy & Management. He is now an assistant professor in Policy Analysis. He teaches two courses, one of which is the first course all new Systems Engineering and Policy Analysis students have to take: “Introduction to Policy Analysis”. His research is now focused on the contribution experimentation can make to better decision making in multi-actor problems.