

Master of Science Thesis

Validating Airline Performance in the Future

Investigation of a Novel Holistic Validation Model for Airline Businesses

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Preface

This report is written as a Master Thesis at the Control and Operations Department of the Faculty of Aerospace Engineering of Delft University of Technology. It documents the graduation work performed between April 2013 and January 2015 on dynamic modelling of the air transport industry in the scene of the global system. Comprising socio-economics and climate systems.

It covers the conception of a novel validation framework for airline businesses to formulate and validate both short-term and long-term strategies. This report is formulated such that the reader is expected to have some fundamental knowledge about airline operations, economics and object-oriented programming. Basic modelling terminology and concepts are presented in chapter 2, after which chapter 3 introduces the model concept, followed by chapter 4 wherein all the specific structures are validated.

The framework herein was actually matured over a longer period and it would not have been possible to realise this work without the help of specific people. I would like to thank my supervisors Prof. R. Curran and Dr. W.W.A. Beelaerts van Blokland for their support and encouragement to pursue this idea. Their expertise in airline operations provide a great source of assistance when difficulties were encountered. Furthermore, I would thank Prof. D. Simons and Dr. M. Snellen for their initial help. I would also like to thank my family, friends and colleagues for their continued emotional support throughout.

Niels Antonius Aleida Jacobs

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Executive Summary

Over the last decades, air traffic facilitates the movement of people and goods all over the world, enabling economic growth and development. Despite the impact air traffic has on industries and systems all over the world, the aviation industry is influenced by the same factors as well. Energy prices, the economic situation, population growth and other aspects do impact airline businesses, as the most recent economic downturn illustrates perfectly.

The world we live in over a couple of decades may vary in many aspects and it is impossible to predict all the factors, decisions and actions that will shape it in the future. The understanding of world as one global system, its dependencies and dynamics can never be perfect, and is limited by our knowledge. Now and in the future. Despite the ability to make perfect forecasts how the world will look like in the future, scenarios can help to define how factors will act so a variety of future pathways can be explored. In order to help airline businesses and organisation, such as the IATA, formulating and validating strategies, this work focuses on the development of a framework that enables the formation and validation of scenarios that are based on dynamics, dependencies and relations of the global system.

Based on a system dynamics approach, a Integrated Assessment Model is developed based on proven concepts of socio-economic and climatological modelling. This model will form the basis for the other models that will be added to calculate the demand for passenger kilometers, irrespective of the transport mode. Based on pricing and time expenditures of a journey by a transport mode, a distribution of passenger kilometers per transport mode is calculated. An Air Transport Model is used to mimic airline operations based on three types of aircraft. In this model, the transport demand, expressed in RPKs, is used to drive the demand for flights. Depending on the utilisation capacity ratio, an airline is able to cope with the demand. Above capacity utilisation ratios, the airline has to delay flights or order new assets (aircraft or runways) in order to accommodate the transport demand. Under some situations, this might lead to higher fares or higher time expenditures per flight, which affect the balance of transport kilometers in respect to the other transport mode.

Based on the performed amount of flights and RPKs, the Air Transport Model calculated essential KPIs, which are used to express the performance of the airline businesses. A Value Operations Methodology is used to validate the performance for both economic and non-economic aspects of an airline. By this methodology, several aircraft options and airline strategies can be validated under different socio-economic scenarios. Eventually helping airlines to improve their short-term as well as long-term strategic decisions.

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Part I

System Analysis

1 Research Formulation

1.1 Introduction

Aviation has become a critical part of the global economy, providing movement of goods and services throughout the world, enabling economic growth. Over the four last decades, the mobility provided by air transportation has increased on average 5 percent per year. The sector has been expanded despite the economic downturns, aviation is strongly driven by GDP growth. New economies, such as South America, Asia and Africa, have compensated the effects of the economic downturn in the mature aviation markets, thereby the sector remained growing. As global wealth increases as well as the world population, the demand for air transport is expected to expand.

The aviation industry is not only a critical part of the economy, it impacts other parts of society too. The effects of aviation on the environment are of global interest, as the sector has an international focus. Therefore millions of people are affected by the noise effects and pollution induced by aviation. However the aircraft manufacturers and airlines have helped to reduce the number of people impacted by aircraft noise by 95%, there is space for improvement. The fuel efficiency of aircraft has been improved by 60%, resulting in less fuel consumption and a reduction of pollutants. Because the strong growth in demand, the total contribution of aviation to climate change is still increasing. The International Air Transport Association (IATA) and other organisations have formulated the goal to keep the absolute pollution induced by air transport movements constant, while the industry is growing. This stipulates the essence of continuous improvement on aircraft fuel efficiency and noise reduction.

The demand for air transportation is forecasted to grow by a 5% per annum over the next 20 years placing increasing pressure on the current airline operations. The air transport network will be operated more intensively, resulting in more complexity regarding meeting safety requirements. Aviation safety is affected by management, operations, maintenance, environment, aircraft design and traffic control decisions. The forecasted aviation growth can only be facilitated when one is taking safety into consideration, while making strategic and operational decisions towards the future.

Airline companies are by nature cash flow businesses that are sensible to local mutations in air transport demand and policy restrictions. The airline's strategy is twofold. First, airlines need to make strategic decisions regarding future challenges to accommodate growth and environmental restrictions. Secondly, the airlines need to ensure their businesses are able to survive short-term economic fluctuations. Airlines have to adapt their business strategy harmoniously in order to run their businesses profitably in current time path, while being able to cope with the challenges in the future. Airlines can only do this by focussing on the factors that form the future air traffic and challenges that lie ahead, rather than aiming at providing exact future traffic counts.

in order to help associated airlines and air transport related businesses, the International

Air Transport Association (IATA) supports airliner activity and helps formulate industry policy and standards as well as provides consultancy services on safety, security, business strategy and environmental impact of air transport. In order to facilitate airlines in formulating business strategy, the IATA can rest on detailed datasets of the air transport industry over the past years. However in order to make strategic decisions and advice towards the future, it needs to look in the future as well. However, predicting future pathways is rather difficult and subject to many aspects, both in air transport industry as well as other industries and systems.

1.2 Problem Exploration

The aviation industry is a very volatile and low margin business. In order to be able to survive short-term economic fluctuations as well as long-term trends, airlines need to have a solid strategy for short as well long-term future. Representing 84% of total air traffic, the IATA's global aim is to help the industry by simplifying processes, increase passenger satisfaction, reduce cost, improve efficiency, meet environmental targets and sustain growth and profitability. In order to achieve this goals, the IATA has to deliver best-achievable information to support the long-term planning decisions for the aviation industry.

Even if the traffic growth rates in the medium term are expected to remain well below the pre-2009 trend, there is still some potential for future growth of air traffic. One can imagine that future air traffic will be rather like the past, only with more of it. This, however, is an assumption that requires totally different approach from airlines with respect to their future strategy. The aim of a long-term forecast is to challenge the assumptions and preconceptions underlying such an imagination. Organisations and institutions are having different views about how the future might unfold. The scenarios of long-term forecast are there to provide not just a quantitative foundation for thinking about a baseline case, but also to inform a discussion of risks. The aim of a long-term forecast is above all about helping decision-makers to understand the risks: what might happen, and will our strategy work out?

The ideal flight is about moving people and goods safely, efficient, cost-effectively and with minimum impact on the environment. Aviation is a catalyst for business, tourism and manufacturing industry, now and in the future [Wegner, 2005]. Since the "why" of aviation seems immutable, the "when?", "what?", "where?", "how?" and "how much?" are up to change.

In order to be able to answer the fields of change in the aviation industry, one need to define the factors that have the potential to be different within the next 20 years. According to EuroControl, factors that do have potential to change the aviation industry are:

- *Regulation* After the recent banking crisis, in which too little regulation played its part, more regulation in markets all over the world is expected. Nowadays, the pace of environmental regulation is accelerating. Noise has also been a topic for regulation.
- *Costs* Due to the recent financial crisis, the ability of governments to invest in in-

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frastructure or subsidise transport systems. The costs of air transport will therefore be under scrutiny as never before.

- *Value Chain* However air transport management is a relatively small part of the total industry, the regulations related and similar to the Single European Sky will fundamentally change the value chain, with the sharing of cost-risk and with the business trajectories putting more power in the hands of the aircraft operator. This has the potential to change operator's profitability, but also business models [Wegner, 2005].
- *Co-modality*, collaborations between transport modes can have significant impact on the total travel demand, on the other hand progress in other transport modes can reinforce competition to aviation. Take for example the further expansion of high-speed rail infrastructure.
- *GDP* The allocation of wealth and capital over the world can have significant implications geopolitically, as it is accompanied by changes to the flows of global economy: raw materials, finished goods, and finance.
- *Climate change* anthropogenic emissions of greenhouse gases cause the climate to warm, having implications on health as well as the economy. The threats to infrastructure and daily operations are directly related to the level of climate change [Fiddaman, 1997]. The impact of climate change can be tangible and intangible.
- *Oil prices and supply* play an essential role in the future. For the last decades, global economy is strongly relying on the availability of energy sources as well as their prices. Energy prices do have giant implications on the development of economies.
- *Demographics* The economic crisis has provided an additional opportunity for governments to address what has long been identified: the sustainability, or rather unsustainability, of pension provisions. In many (European)/western countries there will be older pensioners, and poorer expected. This effect could be a higher propensity to fly on average, since those of working age fly more often [Wegner, 2005].
- *Hassle Factor* Transport remains a target for terrorists and the 'hassle factor' of security checks which has been talked about since 2001 has, if anything, become more an issue with a growing perception of the intrusiveness of the data and physical checks. This could eventually decrease, however it can also become disincentive for travel to particular destinations.

The world we live in over a couple of decades may vary in many aspects and it is impossible to predict all the factors, decisions and actions that will shape it in the future. The understanding of the world as one global system, its dependencies and dynamics can never be perfect, and is limited by our knowledge. Now and in the future. Despite the ability to make perfect forecasts how the world will look like in the future, scenarios can help to define how factors will act so a variety of future pathways can be explored. In order to help consulting organisations formulating and validating strategies, it is helpful to develop a framework that enables the formation of scenarios that are based on dynamics, dependencies and relations of the global system.

1.3 Background on the Aviation industry

The intent of this section is to approach the basics of the aviation industry from a perspective that can be used in the formulation of research questions and eventually the model development. This section will focus on the environmental effects of aviation, comprising noise effects, emissions and the aviation's impact on climate change. Also airline safety will be focused on, financial performance and air transport capacity.

1.3.1 Airline Economics

The aviation industry is on the first glance rather large, it is easy to lose sight of the fact that it is a service industry. Airlines perform a service to their customers - transporting them and their belongings from one point to another point for an agreed price [Ave, 2012]. This implicates that there is no physical product given in return for the money paid by customers.

This section focuses mainly on the airline industry within the aviation industry, which comprises other industries as well. Airlines can be characterised as capital intensive. This is the direct result of the enormous range of equipment and facilities required to run an airline business. The equipment ranges from aircrafts to flight simulators to maintenance hangars. As a result, the airline business is very capital-intensive, requiring large sums of money to operate effectively [Tyler,], [Ave, 2012]. Most of the equipment is financed through loans or obtained using lease constructions.

Airlines can also be characterised as labor intensive. Due to regulations and safety restrictions, airlines employ large amount of staff, from pilots to flight attendants, mechanics, baggage handlers, gate agents, security personnel, cooks, cleaners, managers, accountants, lawyers and other staff. Despite the fact the airline businesses can automatise processes, it remains a service business, where customers require personal attention. As result of the labor intensity, one third of the airline's revenues goes directly to it's personnel. Combined with the fact the airline industry is known for its relatively high wages, the bottom line results of all of this in thin profit margins [Tyler,]. Through the years, airlines have earned a net profit between one and two percent, compared to an average of above five percent for the global industry as a whole.

One of the other explanations for the thin profit margins can be found in the fact the airline industry is seasonal. The summer months are in general extremely busy, while the winter months on the other hand are less busy. The peaks in the airline industry in the summer months are canceled out by the winter months. As the industry is capital intensive, the airlines need to distribute their assets mainly over the summer months, resulting in very small profit margins. Due to lack of demand in the winter months, airlines cannot operate their aircrafts and other assets, resulting in unused assets, which cost money [Ave, 2012].

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Airline Revenue

About 75 percent of the global airline industry's revenue comes from passengers, about 15 percent from cargo shippers and the remaining 10 percent comes from other transport-related services.

Airline Costs

According to the IATA, airline costs and expenditures can be divided into three parts:

Table 1.1 – Model boundary chart for long-term model of Airline Value Evaluation Model Airline Value Evaluation Model interactions

Component	Description	Percentage
Flying Operations	Essentially any cost associated with the operation of aircraft, fuel and pilot salaries	27
Maintenance	Parts and labor	13
Aircraft and Traffic Service	Cost of handling of passengers, cargo and aircraft on the ground, including salaries of baggage handlers, dispatchers and airline gate agents	16
Promotion/Sales	Advertising, reservations and travel agent commissions	13
Passenger Service	In-flight service and things as food and flight attendant salaries	9
Transport Related	Delivery trucks and in-flight sales	10
Administrative	Administrative costs	6
Depreciation/Amortization	Equipment and plants	6

Looking over the total expenses of an airline, labor costs are about 35 percent of the airlines operating expenses and 75 percent of the controllable costs [Ave, 2012]. Fuel is the airlines' second largest cost and accounts for 10 to 13 percent of the total expenses. The percentage of commission to sales agents have recently been declining due to more direct sales from the airlines to the consumer through the internet. The share of airport landing fees and terminal costs have been increased over the past decades and are expected to become higher over the years [Tyler,].

Break-Even Load Factor

Every airline has a break-even load factor. That is the percentage of seats the airline has in service that must sell at a given yield, or price level, to cover its costs [Ave, 2012].

As every airlines has different costs and revenue structures the break-even load factors will differ from airline to airline, but in general escalating costs will push up the break-even load factor, will increasing prices for airline services will have the opposite effect. The over-all break-even load factor in the airline industry is estimated approximately 66 percent. The difference between one or two tickets sold on each flight can make the difference between profit and loss, indicating that airlines operate closely to their break-even load factor.

Seat Configurations

The seat configuration is very important to an airlines. As the airlines operate around their break-even load factor, the revenue generating power increases when seats are added to the aircraft. The break-even load factor does not imply the aircraft is filled with passengers for 66 percent, but the aircraft is filled for 66 with passenger equivalent that are paying for airlines services at a particular price level. Adding seats to an aircraft results in more capacity while the cost remain almost the same. In order to keep the prices for airline services as low as possible, airlines will seek to maximise the number of seats to keep prices as low as possible. On the other hand, a carrier with a strong following in the business community may opt for a large business-class section, with fewer, larger seats, because it knows that its business customers that are willing to pay premium prices for the added comfort and workspace. The key for most airlines is to strike the right balance to satisfy its mix of customers and thereby maintain profitability [Ave, 2012].

Overbooking

Airlines overbook flights historically, meaning that they book more passengers on a flight than there are seats available. This behaviour is rooted in the analysis of demand for flight, economics and human behaviour [Ave, 2012]. Changes in schedules of passengers have made it necessary for them to take different flights. Sometimes they will travel with different airlines, cancel their flight plans altogether, often without notice to the airline.

Because airlines benefit from a maximum number of seats sold, the unattended flights, cancelations or no-shows can be used to sell more seats. This will boost up the profit margin of airlines. Therefor every airline keep track of the historical flight demand to estimate the precise number of no-shows on a flight. The goal is to match the number of overbookings to the number of no-shows. In most cases this works effectively. However, in some situations the airline made a mistake and more people show up than there are seats available. In order to compensate for the inconvenience to customers, the airline offers incentives to passengers that are willing to give up their seats.

Normally, there are more volunteers than the airline need, but when there are not enough volunteers, the airline must bump passengers involuntary. In the rare cases where this occurs, federal regulations require the airlines to compensate passengers for their trouble and help them make alternative travel arrangements [Ave, 2012], [Tyler,].

Pricing

Since deregulation of the airline industry, the airlines have the same pricing freedom as companies in other industries. Nowadays they set fares in response to demand and prices of competition. This implicates that on the same flight, people can pay very different prices for the airline services.

The pricing of airline services is the response of the value for different passengers. A business traveler which has an opportunity to visit an important client is rather different than a person that is visiting a friend. The business man is more likely to pay more for

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the trip as its need is higher, while the pleasure traveler is only likely to make the trip if the fare is relatively low [Ave, 2012].

The objective for the airlines is to set the sales price for services as high as possible to maximise revenues on each flight. The pricing needs to be optimal so the aircraft is at break-even point a couple of days before departure. In this situation last-minute travellers can still attend the flight and will pay higher fares.

The process of finding the right mix of fares for each flight is called yield, inventory or revenue management [Ave, 2012].

Scheduling

Together with price, scheduling is an important factor for airlines. Airlines are free to select the destinations they want to serve and also to set the frequency. Airlines that serve a point of destination frequently are more likely to be in favour of business travellers, since they can easily rebook a flight when a meeting runs longer or shorter than they expected. A carrier that flights directly is also more in favour of the clients, since it causes less inconvenience.

Airlines schedule their flights in accordance with demand for their services and their marketing objectives. Scheduling, however, can be extraordinary complex and must take into account aircraft and crew availability, maintenance needs and airport operating restrictions [Ave, 2012].

In situations of incidents, airlines cannot arrange the required availability of labor or assets and need to cancel a flight. This happens mostly on the flight with the least amount of passengers, so it causes as less inconvenience as possible. Since aircrafts are utilised through the network of the airline, it might happen that an aircraft experiences problems that cause the cancellation of a flight later on the day elsewhere, since the demand for the aircraft cannot be satisfied. It is a myth that the cancellation of flights can be related to economic reasons, which could be the case on low payload flights.

Fleet Planning

Serving the market with the proper aircrafts is essential for airline financial success. As a result, the selection and acquisition of aircrafts is directed by top management and involves personnel from many other divisions such as maintenance, engineering, finance, marketing and flight operations [Ave, 2012].

There are multiple factors to consider when purchasing new aircrafts. Starting with the composition of the airline's existing fleet. Does existing aircrafts need to be replaced, what plans does the airline have to expand service, how much fuel do they burn per mile, how much are maintenance costs, and how many people are needed to fly them [Ave, 2012, Boeing and et al., 2013].

In general new aircraft are more efficient and cost less to operate than older aircraft. However, the efficiency gains must be weighted against the cost of acquiring a new aircraft. Can the airline afford to take on more debt? Other important factors are the willingness

of investors or banks to provide the money that is required to invest in new aircrafts and what the price of that money will be.

Another important component in the acquisition process of new aircraft is marketing strategy. An international market needs to be served using long-range, wide-body aircraft, due to the convenience of direct flight capabilities and higher service and comfort level of the aircraft. Right-sized aircraft for the markets already served may require an airline to reconfigure its fleet.

The process of acquiring an aircraft is dependent on the set of factors described above as well on the production time of an aircraft. Since the production of aircraft takes time - in most situations 2 to 3 year, airlines need to make a sound fleet planning years in advance. That makes the fleet planning one of the most difficult parts in the airline planning process, because no one knows for certain what economic conditions will be months to years in the future. A delivery of many new aircraft in an economic downturn can result in major losses for the airline, while an unanticipated boom in the air transport demand can mean lost market share for an airline that held back on aircraft purchases while competitors were moving ahead.

In some situations the requirements for an new aircraft by an airline cannot be met by existing aircraft. Therefor the airline cooperates with aircraft manufacturers about developing new models. Since the initial costs for aircraft manufacturers are very high, the manufactures need to sell substantial numbers of a new model just to break even. They usually will not proceed with a new aircraft unless they have a launching customer, meaning an airline willing to step forward with a large order for the plane, plus smaller purchase commitments from several other airlines.

1.3.2 Aviation and the environment

This section will briefly review the relationship between the aviation industry and the environment by focussing on the noise impact on communities, air quality impact, climate impact and the interdependencies between these effects and opportunities to address them, constraints on mobility, economy and the interactions between governmental and other organisational structures to address these impacts [Lee, 2009].

The presence of aviation is essential for the economy, since it facilitates the movement of people and goods throughout the world. Thereby the industry is contributing to the unwanted environmental impacts, by polluting greenhouse gases and noise. As a result of growth in air transportation, emissions of many pollutants from aviation activity are increasing against a background of reductions from many other sources. Estimates suggest that millions of people are adversely affected by the side effect of aviation [Lee, 2009]. Because of the dimensions of the industry and the rising value placed on environmental quality, there are increasing constraints on the mobility, economic vitality and safety of the world.

Regulatory actions are increasingly setting conditions for the world's airlines and manufacturers. The European Union has for example identified the climate effects of aviation as the most significant adverse impact of aviation, exceeding the importance of local air quality and noise impacts that are the current focus of attention in other regions in the

world [Lee, 2009]. As a result, there are introduced dozens of calls for regulation in the form of carbon taxes, trading, demand management and reduced reliance on aviation. Despite the research that is going on to mitigate the environmental impact of aviation, there is a significant uncertainty in assessing the climate effect of aircraft and determining appropriate means to mitigate these effects. World wide there are thousands of organisations and groups whose principal focus is aviation noise and emissions. The participants are dedicated to their charge and when focused can be very effective in bringing about change. However, in general, the activities of these organisations are not well coordinated and acting singly they are not likely to alter the global path of aviation improvements [Lee, 2009].

In the following subsections, the specific connections between aviation and the environment are discussed.

Aircraft Noise

With the international focus and orientation of aviation in mind, the number of people affected by aircraft noise is significantly. Despite the effort to reduce the number of people affected by noise is reduced over the last four decades by 90+%, millions of people are still living in areas that are subject to noise levels above the 65 dB Day-Night Noise Level. (DNL). Even more people are living in areas that are exposed to lower noise levels. The reduction of number of people exposed to aircraft noise is realised by the advances in technology, take for example high-bypass ratio aircraft. Despite the advances in technology, aircraft noise remains a problem that is anticipated to grow.

Over the last decades new aircraft engines and operational procedures have reduced the noise impact to the environment. Organisations as the FAA and the ICAO expect the future improvements on aircraft noise not to be as significant as the improvements in the past decades, since technological progress has slowed down and thereby the air travel growth outpaces the expected technological and operational advancements [Lam and Gu, 2005].

Nowadays, noise is the most important objection to airport expansion world wide. This could be considered as a significant problem, since the expansion of movements by air traffic can only be facilitated when airports can be expanded or constructed. In the current situation many airports are limited by their capacity and required expansion in order to accommodate growth. Hereby the strong role of technology and operations should be recognised. In order to be able to expand, many airports are purchasing land area around the airports to create a buffer zone for aircraft related noise.

International organisations and institutions have indicated that there is much potential for technological and operational improvements to reduce aircraft noise impact. By 2020, the European Union aims to reduce the perceived noise levels in to be one-half of the average noise levels in 2001[Lam and Gu, 2005]. NASA plans to develop technology that could enable a 50% reduction in effective perceived noise level for a new aircraft relative to the 1997 state-of-the-art by 2007 and reductions of a factor of four beyond 2007 [Lee, 2009]. The FAA states that there is a stringent need for the development of better metrics and tools to assess the aviation noise impact.

Local Air Quality

Aviation has not only impact on the environment by its sound levels, it also impacts the air quality due to the emitted pollutants. The emission of greenhouse gases as nitrogen oxides (NO_x), carbon dioxides (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC) and particular matter (PM) form a variety of sources that contribute to a local air quality deterioration, resulting in human health and welfare impacts [Lee, 2009]. Regulations and pacts concerning improvement of air quality world wide have dropped results, however, many of the technologies that are introduced for conventional industries are not applicable for the aviation industry, because of weight, volume and safety constraints. Unfortunately, although aviation is a small overall contributor to the quality of air impacts, some aircraft emissions are growing against a background of generally decreasing emissions from other sources.

Historically, the most difficult of the pollutants to control for aviation has been NO_x. Physical and chemical phenomena make it difficult to reduce the NO_x emissions from aircraft engines that employ high temperatures and pressures to reduce fuel consumption, which the NO_x production is related to. Unfortunately the available options to reduce the NO_x production by aircraft engines is at the cost of fuel consumption increase, making the advantages of reduction in NO_x vaporise. Aircraft manufactures have succeeded to improve the fuel burn per passenger-km by 60% in the last four decades, which is a significant improvement. According to the manufactures, the reduction in fuel consumption can be assigned to improvements on engines for two-third, while the resting part can be assigned to light-weight materials, better aerodynamics and operations [Lee et al., 2009, Houghton et al., 2001].

For the future years, there are plenty opportunities to reduce emissions of NO_x , CO_2 , CO, UHC and PM. As for almost everything in the aviation industry, the options for reducing the pollution introduces engineering, safety and cost challenges that must be overcome before new technologies can be implemented in the airline's fleet. In order to address the challenges, several organisations world wide have introduced research programs. One of the most important challenges to overcome is the presence of particular matter (PM). According to the IPCC, the mortality and morbidity cost of PM (per unit) are hundred times higher than other emissions. This makes the reduction of PM one of the key research areas.

This section only elaborates on the policy and regulatory aspects of aircraft emissions, a more detailed introduction to aircraft specific emissions is provided in appendix B.6.

Climate Change

The climate change debate is one of the most uncertain areas in research. Scientists believe that the chemical species emitted by aircraft affect the climate negatively. Scientific assessments also suggest that the resulting chemical and physical effects due to aviation are such that aviation may have a disproportional effect on climate per unit of fuel burned when compared to terrestrial sources [Lee, 2009]. Despite disproportional effects and believed effect on the climate, many countries still consider local air quality and noise as

the most important environmental impacts. However, this might change in the coming years due to advances in insight.

In 1999, the Intergovernmental Panel on Climate Change (IPCC) estimated that aviation was responsible for approximately 3.5% of the anthropogenic forcing of the climate in 1992 [Lee, 2009, Houghton et al., 2001]. The research has also reflected that the climate forcing of a unit fuel burned by an aircraft is double that of a unit fuel burned in land-based use, this effect could be related to the emissions at high altitudes. The IPCC study also strengthens the scientific understanding of physical effects of aviation, in particular the understanding of contrails and their effects. According to studies, the radiative forcing due to contrails is estimated to be three to four times as large as the radiative forcing due to CO_2 emitted from aircraft. A simple extrapolation of the current aviation growth, illustrates an increasing role of aviation in the contribution to anthropogenic climate change by 3% to 15% in 2050.

Because of the uncertainty in the climate impact of aviation, it is difficult to allocate technology, operational and policy options to mitigate the climate impact of aviation. For this reason current mitigation options focus mainly on the reduction of fuel burn, despite the fact that contrails for example have a believed larger climate impact. Advances in technology have resulted in spectacular reduction of fuel consumption per passenger mile, however, the rate of improvement will slow down in the next years. An expected reduction of 1% per year will not be enough to compensate the expected growth in demand for air transport movements [Lee, 2009].

Interdependencies

Noise, climate and air quality effect of aviation are the result of an interdependent set of technologies and operations, so that action to address impacts in one domain can have negative impacts in other domains [Lee, 2009]. Emission relationships make it difficult to modify aircraft engine design as a mitigation strategy since they force a trade-off among individual pollutants as well as between emissions and noise [Noel, 2005]. In order to mitigate the climate effects of aviation properly, consensus on the climate effects of individual components is essential in order to prioritize action. It is essential to develop a set of comprehensive frameworks and analytical tools and methodologies to assess the interdependencies between noise, emissions and economic performance of aviation more effectively [Noel, 2005]. This tools will not only help to inform about critical divisions on new noise and emission standards, they are also required to define appropriate research and development investments for technological and operational opportunities for reducing noise and emissions [Noel, 2005, Lee, 2009, Houghton et al., 2001].

1.3.3 Airline Safety

Although air transport has a good safety record, public perception often focuses excessively on accidents. Airline safety is affected by many aspects, such as operations, material, maintenance, environment and management. The variety of factors that affect airline safety introduce challenges while meeting safety requirements. Forecasts by the ICAO,

FAA and other organisations expect the movements by air transport to increase by 5% per year over the next 20 years, increasing the pressure on the aviation network.

Airline safety is commonly referred to as the number of accidents per 100,000 departures. However, accidents are only the top of the iceberg and do not reflect the 90% of "latent" events [Liou et al., 2007]. To provide insight in the determinants of airline safety N. Rose [Rose, 1990] state airline safety is a function of two sets of factors: safety investments and operating conditions.

Safety investments cover the actions undertaken by the airline to increase the safety of its operations, this includes scheduling of maintenance more frequently, newer equipment, more equipped personnel and implementing more intensive training programs to decrease the frequency of human error, and purchasing newer aircraft that embody more advanced safety technology [Rose, 1990].

Operating conditions describe the environment in which an airline operates. Harsh climates may raise the probability of weather-related accidents, variations in airport quality and technology may entail differential risks, systemwide traffic congestion may increase certain hazards, and advances in aircraft and air traffic control technology may improve safety over time [Rose, 1990] and [C and Clinton, 1984].

The two sets of safety factors determine the risk distribution for an airline, being the probability that a flight is involved in an accident or incident. An accident is an event that involves fatalities and serious injury, or substantial aircraft damage [Airplaness, 2012]. Incidents are referred to as being hazardous events that do not culminate in accidents [Airplaness, 2012]. Airlines make decisions based on their risk profile. The benefits of risk reduction may include lower insurance premiums, lower wagers and higher prices. This reflects on the airline passengers, employees and insurance companies that closely monitor airline safety records.

1.3.4 Conclusion

The background information on the air transport industry provided in previous sections is essential to be able to formulate the state in which the air transport industry is nowadays. In order to have airline businesses sustain in the future, one should consider a broad scope of aspect to manage closely.

The world population is increasing, parallel to the development of the economy. This requires special emphasis by the airline businesses since the available airspace will become more saturated, increasing safety risks. While on the other hand, airline businesses have to select the proper fleet size and type to accommodate the demand for transport kilometers. Unlike the previous centuries of air transport, where airlines did have less (but mostly sufficient demand) and less regulation, both on safety aspects as well as the environmental aspects, modern airline business have to balance between environment, capacity and safety, while keeping into business on short and long term. This requires perfect knowledge of the airline business itself but also feeling for the "outside world". Due to the stringent regulations and competition, airline business have to be able to deal with a broad set of scenarios. Whether they are desirable or not.

1.4 Research Question

The elemental reason people travel will roughly stay the same over time, commuting to work, visit family, going on holiday or business trip. Therefore the "why" of movements stays the same, however the way we travel, where we travel and how much we travel is subject to many aspects. The air transport passenger km demand is not only a function of the state of economy and population, it is the result of a system, demanding movements of people and goods. Being impacted by policies and resource constraints, the future for air transport might differ radically in the future. In order to help airlines formulate sound business strategies, organisations as the IATA help to explore future pathways to adept business planning and decisions appropriately to the changing environment. This work attempts to answer the main research question: *"Can a holistic model help airline businesses to formulate and assess future airline performance?"*. Before any measures can be taken to answer this research question directly, a thorough understanding of the "system" is important. Therefore this thesis is divided into three parts: Part I - System Analysis. This chapter will focus on background information on simulation modelling, the aviation industry and holistic modelling. Besides it introduces the methodology used to answer the research question. Part II - Development, describes the development of the model that will be used to simulate the system, the aviation industry is acting in. Two sub research question are used to gather information to answer the main research question. Part III - Evaluation and generalisation, will show scenario exploration to assess and evaluate business strategies and value added for airlines by aircraft types. This part also covers validation steps and sensitivity analysis. A structural overview of the thesis is provided in figure 1.1. Chapter 6 will cover the conclusions and recommendations, as well as future work.

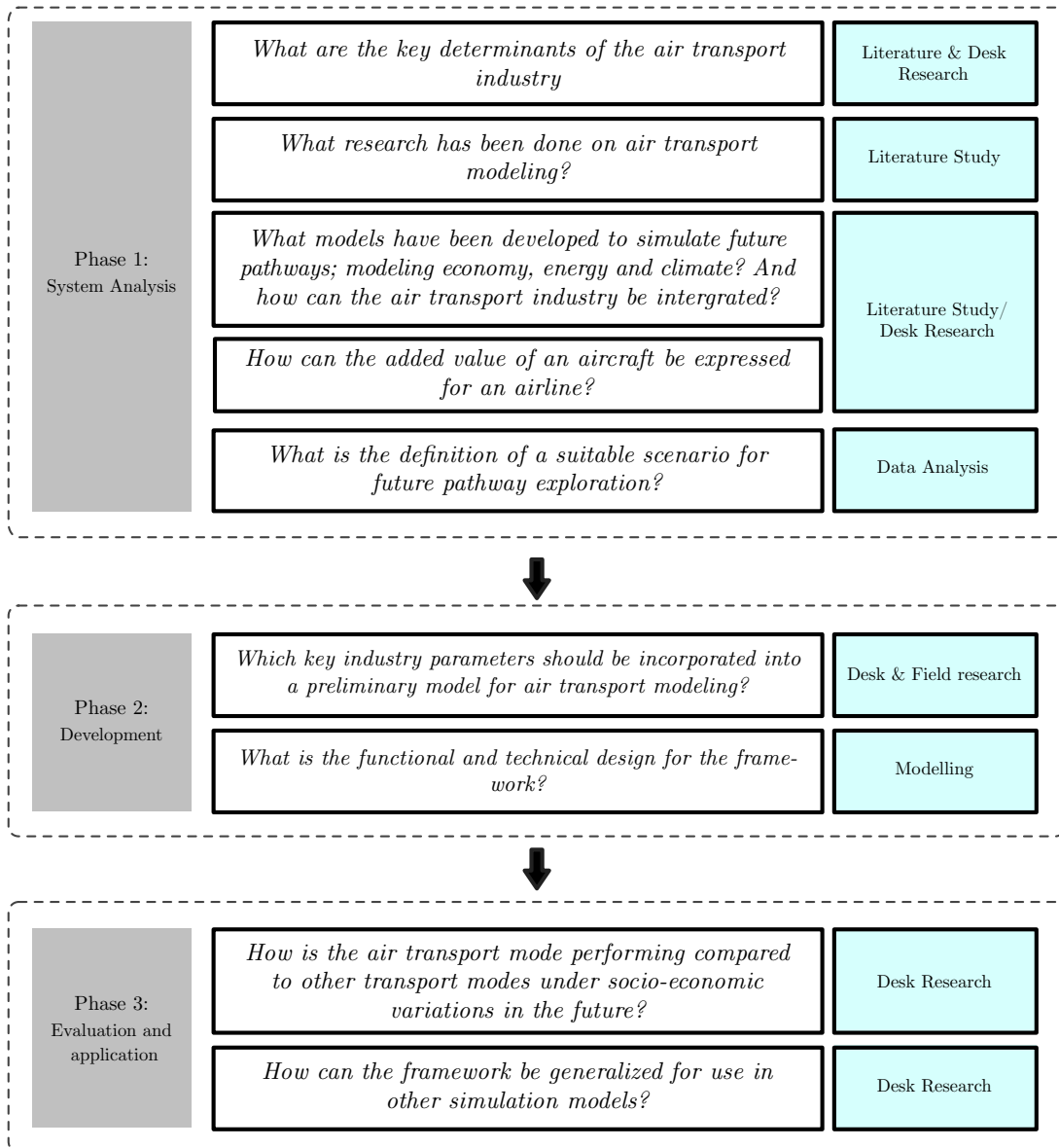


Figure 1.1 – Structure of research in phases and subquestions

2 Methodology Development

The design of a holistic model to simulate the aviation industry in relation to the global industry requires a solid research in available models, data and relations. This chapter will focus on the methodology used to design a model that is able to answer the research questions. Based on a literature review of techniques used for modelling and running simulations. This review will determine what methods are suitable for this type of research. Consecutively a study will be conducted on available models that could help formulate a hypothesis that will function as the backbone of the model to be developed. During this process the available, verified and validated models will be studied as well as the techniques that can be used to evaluate performance of airline businesses based on economic as well as non-economic KPI's.

2.1 Methods in Simulation Modeling

To date, there are three methods used for simulation modelling. By "methods" is meant a general framework for mapping a real world system to its model. The three methods are:

- System Dynamics
- Discrete Event Modeling
- Agent Based Modeling

The choice of method should be based on the system being modeled and the purpose of the modelling. Depending on the problem, the modeller can put together a process flowchart where there are entities and resources, an agent based model where there are agents affected by interaction with other agents, or feedback structures, where there are loops influencing auxiliaries and stocks in the model. Sometimes, different parts of the system are best modeled using different methods, this is known as a multi-method model.

2.1.1 System Dynamics

System Dynamics is a method created in the mid-50's by MIT professor Jay Forrester, whose original background was in science and engineering. Forrester's idea was to use the laws of physics, in particular the laws of electrical circuits, to describe and investigate the dynamics of economic and, later on, social systems. The principles and modelling language of system dynamics were formed in the 1950s and early 1960s, and remain unchanged today. The most definitions below are based on the book business dynamics by John Sterman [Forrester, 2010, Anylo, 2010, Sterman, 2000a].

System Dynamics is a method of studying dynamic systems. It suggests that you should:

- Take an endogenous point of view. Model the system as a causally closed structure that itself defines its behaviour.
- Discover the feedback loops (circular causality) in the system. Feedback loops are the heart of system dynamics.
- Identify stocks (accumulations) and the flows that affect them. Stocks are memory of the system, and resources of disequilibrium.
- See things from a certain perspective. Consider individual events and decisions as "surface phenomena that ride on an underlying tide of system structure and behaviour." Take a continuous view where events and decisions are blurred.

To feel the character of system dynamics, consider a shop with a counterperson serving the shop's clients. The more people that come to the shop per hour, the longer the queue grows. You can build a discrete event model that will give you the length of the queue as a function of the client's arrival rate and the service time. However, in a real shop, as the queue grows longer, some clients may decide not to join in the queue, and instead leave the shop. Others may decide to leave the queue after having waited longer than they expected to. In other words, the length of the queue feeds back to inhibit the rate of queue growth. The result of the "straightforward" model, will not be valid unless it addresses these circular causal dependencies. One of the key advantages of the system dynamics approach is to readily and elegantly identify such feedback loops and include them into the model.

Underlying mathematics and simulation engine

Mathematically, a system dynamics model is a system of coupled, nonlinear, first-order differential equations.

$$\frac{d(X)}{dt} = F(X, P) \quad (2.1)$$

Where X is a vector of stocks, P is a set of parameters, and F is a nonlinear vector-valued function. Simulation of system dynamics models is done with numerical methods that partition simulated time into discrete intervals of length dt and step the system through time one dt at a time.

While numerical methods may be very sophisticated in the modelling tools used by natural scientists and engineers, in particular using adaptive variable time step, the numerical methods used in system dynamics are simple, fixed-step methods: Euler and Runge-Kutta. In addition to differential equations, the simulation engine must be able to solve algebraic equations that appear in the models with algebraic loops. Unlike discrete event and agent based models, system dynamics models are deterministic, unless stochastic elements are explicitly inserted into them.

Abstraction level

System dynamics suggests a very high abstraction level, and is positioned as a strategy modelling methodology. In the models of social dynamics, epidemics, or consumer

choose, individual people never appear as well as individual product items, jobs of houses. They are all aggregated into stocks and sometimes segmented into gender, education, income level, etc. Similarly, individual events like a purchase decision, leaving a job or recovery from a disease, are not considered - they are aggregated in flows.

Although the language of system dynamics is very simple, compared to other methods, thinking in its terms and on its level of abstraction is rather difficult (Fiddaman speaks of "real art"). System dynamics models are inevitably full of notions that do not have direct material or measurable equivalent in the real world.

2.1.2 Discrete Event Modeling

Discrete event modelling is almost as old as system dynamics. These days, discrete event modelling is supported by a large number of software tools. The idea of discrete event modelling is this: the modeller considers the system being modeled as a process, i.e. a sequence of operations being performed across entities.

The operations include delays, service by various resources, choosing the process branch, splitting, combining and some others. As long as entities compete for resources and can be delayed, queues are present in virtually any discrete event model. The model is specified graphically as a process flowchart, where blocks represent operations. The flowcharts usually begins with "source" blocks that generate entities and inject them into the processes, and ends with "sink" blocks that remove entities from the model. This type of diagram is familiar to the business world as a process diagram and is ubiquitous in describing their process steps. This familiarity is one of the reasons why discrete event modelling has been the most successful method in penetrating the business community.

Abstraction Level

The level of abstraction suggested by discrete event modelling is significantly lower than that of system dynamics; the diagram mirrors sequential steps that happen in the physical system. While in system dynamics we aggregate individual objects and talk about dynamics of their quantities, in discrete event modelling each object in the system is represented by an entity or a resource unity. Discrete event modelling keeps it individual. Entities and resources may have attributes, may differ from each other, and can be treated differently by the process.

In discrete event models, time delays can be deterministic or stochastic with any probability distribution. In system dynamics, natural delays have an exponential distribution and deterministic delays are special constructs.

Underlying mathematics and simulation engine

The mathematics behind discrete event simulation are based on discrete time. The model clock is advanced only when something significantly happens in the model, namely, when an entity starts or finishes an operation. Any change in the model is associated with those events; continuous changes are approximated by instantaneous ones.

2.1.3 Agent Based Modeling

Agent based model is a more recent modelling method than system dynamics or discrete event modelling. Until the early 2000s, agent based modelling was pretty much an academic topic. The adoption of agent based modelling by simulation practitioners started in 2002 and was triggered by:

- Desire to get a deeper insight into systems that are not well-captured by traditional modelling approaches.
- Advances in modelling technology coming from computer science, namely object oriented modelling, UML, and state charts.
- Rapid growth of the availability of CPU power and memory.

Agent Based Modeling suggests to the modeler yet another way of looking at the system:

- In some situations, one does not know the system as a whole, what the key variables are and the dependencies between them, or simply don't see that there is a process flow. But some can have insight in how the objects in the system behave individually. Therefore, one can build up the model bottom-up, by identifying those objects (agents and defining their behaviour).
- Sometimes, one cannot connect the agents to each other and let them interact, other times, one can put them in the environment, which may have its own dynamics. The global behaviour of the system then emerges out of many concurrent individual behaviours.

There is no standard language for agent based modelling. The structure of an agent based model is created using graphical editors or scripts, depending on the software. The behaviour of agents is specified in many different ways. Frequently, the agent has a notion of state, and its actions and reactions depend on its state. In such cases, behaviour is best defined with state charts. Sometimes behaviour is defined in the form of rules executed upon special events. In many cases, the internal dynamics of the agent can be best captured using system dynamics or discrete event approaches. In these cases, one can put a stock and flow diagram or a process flowchart inside an agent. Similarly, outside agents and the dynamics of the environment where they live are often naturally modeled using traditional methods. Many agent based models are therefore included into multi-method models.

Abstraction level

Agent based modelling does not assume any particular abstraction level. If agents are individuals, then the agent based model is certainly more detailed than a segmented system dynamics model where individuals are aggregated based on characteristics. Agents, however, can be developed with high levels of abstraction.

Underlying Mathematics and simulation engine

Most agent based models work in discrete time (interaction, decision making and state changes are instant). In this respect, at the low level simulation engine should not be much different from the ones used for discrete event modelling. At a higher level, it is desirable that the engine supports:

- A large number of concurrent activities, including their dynamic creation and destruction.
- Correct handling of multiple instantaneous events, in particular deterministic and random execution. This is important for synchronous models.
- Networks and communication
- 2D, 3D and geographical space, and space-related functionality.

2.1.4 Best suitable simulation method

This work will focus on the development of a holistic model to mirror the behaviour and characteristics of real world systems. Therefore a very generic, accumulated approach will be used. The best method to develop a "holistic" model, is to use the system dynamics method. This method is based on differential equations, representing stocks and variables that are related to each other by feedback loops. The numerical method used by system dynamics is similar to many economic and climatological expressions. Since the other two simulation methods are rather focusing on individual behaviour of units within a system, instead of an aggregated group of units, forming a system, discrete event modelling and agent based modelling will not be used in this stage.

2.2 Modeling Methodology

In previous sections 2.1.1, the essential background on system dynamics was introduced. Chapter 2.1.1 showed also how models can become virtual worlds to help solve complex systems and gain insight in different situations. The next step is create a useful virtual world for evaluation purposes. With other worlds, what will the model look like, how will the framework be placed within the context of ambiguity, policy and regulations. The model will be developed in order to provide essential insight in the development of aviation industry within the context on the global industries, on the field of economic, energy, climate and transport demand. The development of the model is subject to a lot of iterations, learning processes and can be seen as a continuous process of formulating hypothesis, testing and revision, both in formal as mental problems [Sterman, 2000b]. This chapter describes the process of system dynamics modeling and its responsibilities.

The framework can only be successful if the problem to be solved can be identified and evaluated. However there is no recipe for successful modelling, there are several guidelines used by successful modellers to follow. Randers [Randers, 1980] listed a set of steps, that come along with some questions, to give modelers a disciplined process to follow.

The most important steps in Randers process involve the following activities: (1) Articulate the problem, (2) formulate the hypothesis, (3) formulate the simulation model to test the dynamic hypothesis, (4) testing the model until it is suitable for the purpose and (5) designing and evaluation policies for improvement[Sterman, 2000b].

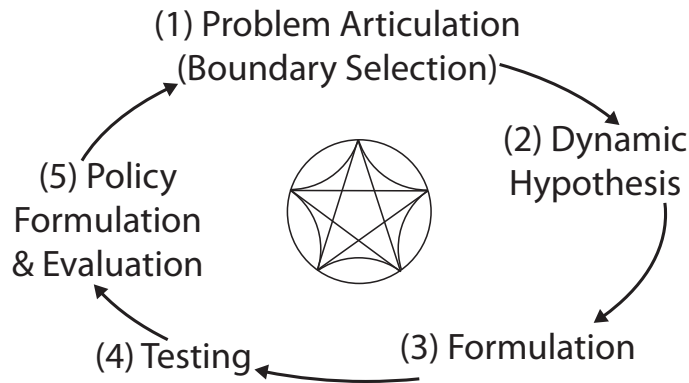


Figure 2.1 – Iterative Modeling Process

The process described by Randers is shown in table 2.1 and involves the following activities:

Table 2.1 – Steps of the modeling process [Sterman, 2000b]

Problem Articulation

- **Theme selection:** What is the problem? Why is it a problem?
- **Key variables:** What are the key variables and concepts we must consider?
- **Time horizon:** How far in the future should we consider? How far back in the past lie the roots of the problem?
- **Dynamic problem definition (reference models):** What is the historical behavior of the key concepts and variables? What might their behavior be in the future?

Formulation of Dynamic Hypothesis

- **Initial hypothesis generation:** What are current theories of the problematic behavior?
- **Endogenous focus:** Formulate a dynamic hypothesis that explains the dynamics as endogenous consequences of the feedback structure.
- **Mapping:** Develop maps of causal structure based on initial hypotheses key variables, reference modes, and other available data, using tools as:
 - Model boundary diagrams,
 - Subsystem diagrams,
 - Causal loop diagrams,
 - Stock and flow maps,
 - Policy structure diagrams,
 - Other facilitation tools.

Formulation of a Simulation Model

- **Specification** of structure, decision models.
 - **Estimation** of parameters, behavior relationships and initial conditions.
 - **Tests** for consistency with the purpose and boundary.
-

continued on next page ...

Table 2.1 – ... continued from previous page

Testing

- **Comparison to reference modes:** Does the model reproduce the problem behavior adequately for your purpose?
 - **Robustness under extreme conditions:** Does the model behave realistically when stressed by extreme conditions?
 - **Sensitivity:** How does the model behave given uncertainty in parameters, initial conditions, model boundary and aggregation?
 - ...Many other tests
-

Policy Design and Evaluation

- **Scenario specification:** What environmental conditions might arise?
 - **Policy Design:** What new decision rules, strategies and structures might be tried in the real world? How can they be represented in the model?
 - **"What if..." analysis:** What are the effects of the policies?
 - **Sensitivity Analysis:** How robust are the policy recommendations under different scenarios and given uncertainties?
 - **Interactions of policies:** Do the policies interact? Are there synergies or compensatory responses?
-

2.2.1 Problem Articulation

The most important and first step in dynamic modeling is problem articulation. In order to create a "successful" simulation model, the problem to be solved needs to be addressed. At the same time the purpose of the model needs to be clear prior to development of the framework.

In this thesis, the purpose of the simulation model is to evaluate the performance of airlines within the context of changing socio-economic situations and climate change within a timespan towards the future. Under different scenario's and boundary conditions aviation's performance can be evaluated within the framework based on the Value Operations Methodology, that is supported by socio-economic circumstances and boundary conditions simulated in the model. This enables one to gain insight in the development of important parameters in the aviation industry as well as the relative impact of aviation.

The model can become increasingly difficult if the model mirrors the entire system. Systems are represented by models as a group functionally interrelated elements that form a complex whole[Sterman, 2000a]. Every element in the system should be designed in a way it converges to a problem and can be tested properly. In other words, the elements should simplify the model so that the real world is mirrored in a responsible manner.

The problem in this approach of dynamic modeling lies in the understanding of the cycles involved in the system. To develop the Airline Value Evaluation Model, there are several elements that needs to be modeled. Each element interacts with each other in a simplified manner, since the usefulness of the model lies in a representation that it comprehensive and observable. Otherwise it would be just like the complex reality, that is not observable in respect to effect and causes, as it is in the simulation.

in fact, to create a valuable model or framework it is important to know that to cut out of the model. The essence and purpose of the model provides the criteria to cope with in

the model. The desired model is rather comprehensive and represent the entire energy consumption and emission system on global scale. For this reason, the model consist of an extensive list of variables incorporated in the model. But also in this situation, it is possible to make selections and tradeoffs whether or a variable is necessary in the model or not. Due to the scope of the model, the simulation is never finished. However, the model can provide reasonable answers to the research questions of this thesis by dealing with a select set of variables.

Reference Modes

The system dynamics model is developed to characterise the problem dynamically, analyse the pattern of behaviour over time. The model will show how the a problem arose and how it might evolve in the future[Sterman, 2000b]. The model will be more valuable if there is a reference mode available. This *reference mode* can be a set of graphs or other descriptive data, showing the development of a problem. After observing the reference mode, the time path needs to be identified as well as the variables and concepts that are considered to be important for proper understanding the problem.

Time Horizon

For extensive analysis the time horizon for the model should extend far back in history and show the problem evolution. On the other hand the time horizon should reach in the future to incorporate the delayed and indirect effects of actions. Hereby needs to be accounted for effects that do not cause an effect immediately and locally. In many situations, the effects are distant in time and location. In this descriptive model, the effects can be delayed with several months towards multiple years. The model focuses in long-term scenario development, so the time horizon for this particular simulation will reach towards 2050 and 2100.

A major risk in evaluation of problems along a particular time horizon lies in the fact the problem can change over time. As an illustrative example, the US government started an system dynamics approach to solve the desertification problem in the Sub-Saharan area. The area was experiencing rapid population growth while the desert was expanding southward, thereby reducing the grazing land for cattle. The purpose of the system dynamic study was to identify suitable policies to reduce and revolve the desertification of the grazing land. The model was used to assess the policy to place boreholes in the area to increase water supply for the cattle. Researchers had run the model to the year 2000, several decades from that moment in time the simulation was created, and concluded that the policy was successful and led to improvement. The waterholes facilitated the cattle stocks to grow and increase the agricultural output. The desertification was reversed and the carrying capacity of the area was increased rapidly. However, some decades later, the model shows that the growth in cattle stock began to outstrip the carrying capacity of the area and led to erosion and new desertification of the area. Thereby the cattle population dropped drastically and led to a food deficit in the area. This example shows the risks of selecting a too short time horizon. The model time horizon was to short to capture the feedback effects of waterholes in the area, leading to a successful

policy evaluation on short term, while the long-term result of the policy was devastating to the area.

AVEM can be considered as a long term evaluation model. Therefore the time horizon needs to be multiple times as long as the longest time delays in the model. One of these delays can be founded in the delay the development of new aircraft techniques, that normally take around 30 years before a new technology is adopted by the industry.

2.2.2 Dynamic Hypothesis

After problem articulation, the definition of the problem, within a reasonable time horizon, the *dynamic hypothesis* needs to be constructed. The dynamic hypothesis takes account for the problems in the system. The hypothesis is dynamic since it characterises the dynamics in the problem in terms of the underlying feedback and stock and flow structure of the system [Sterman, 2000b]. The hypothesis is a hypothesis since it is provisional and subject to revision and new insights along the path of development.

The dynamic hypothesis provides the working theory on how the problem arose and is fed by a dataset and experiments in the real world.

Model Interaction Explanation

System dynamics seek endogenous explanations in phenomena. Endogenous means literally "proceeding from within" in Greek ("εὐδο"=inside "- γεννηζ"=coming from). According to Sterman, endogenous theory generates the dynamics of a system through the interaction of the variables and agents represented in the model. The patterns of behaviour in the system can be explored by altering the structure and the rules of interaction within the model. System dynamic models can also be partially based on exogenous variables. These are variables that "are arising from without" the model. In other words, variables that are from outside the boundary of the model. Exogenous variables are very difficult to model and mainly beg the question, what causes the exogenous variables to change as they did. This does not mean that exogenous variables should never been included within a system dynamics system. Since exogenous variables are difficult to predict, a model contains desirable as few exogenous variables as possible, since the presence of exogenous variables diminishes the capabilities of system dynamics to stipulate the behaviour and dynamics within the endogenous variables. If there are exogenous variables to be included within a model, the boundary conditions of the model needs to be extended and preferably the exogenous variables should be modelled as endogenous variables. In some situations, exogenous variables are desirable in a model as well. Population can be modelled as an exogenous variable. The growth of the population size will be fixed and the endogenous variable will react on the increase of the exogenous variable. This enables one to investigate and make predictions on for example the demand for aviation in 2050. Based on endogenous variables, the system will simulate a particular value for the demand for aviation in 2050. Other exogenous variables can be technological change, tax rates and energy policies. Table 3.2 shows a list and summary of variables, both endogenous as well as exogenous, used in AVEM.

Table 2.2 – Model boundary chart for long-term model of Airline Value Evaluation Model interactions

Endogenous	Exogenous	Excluded
GDP		
Consumption		
Investment		
Savings		
Wages		Inventories
Inflation Rate	Population	International Trade
Labor force	Technological change	Environmental constraints
Employment	Tax Rates	Nonenergy Resources
Unemployment	Energy Policies	Interfuel Substitution
Interest Rates		Distribution Equity
Money Supply		
Energy Production		
Energy Import		

Subsystem diagram

System dynamics models are usually designed using the "bricks" of subsystems. Subsystems can be organisational subunits or in case of AVEM, higher level systems. A subsystem diagram shows the overall architecture of the model and the interaction and relations between the subsystems in the model along with the flows in goods, information, material, money and population between the subsystems. A subsystem shows the number and type of different agents represented and communicates information about the endogenous and exogenous variables in the model [Sterman, 2000b].

2.2.3 Formulating a Simulation Model

After the dynamic hypothesis is created, the conceptual model needs to be evaluated and tested. The subsystems need to be designed and all the agents involved need to be related to each other in a way the dynamic hypothesis was created. Interrelated agents can be designed using causal loop diagrams, showing their relation to one each other, being endogenous variables. The formulation of a system dynamics model generates important insight even before the model is ready to be simulated. The basic concepts of different subsystems as well as the ideas constructed in the hypothesis phase help to recognise and resolve contradictions that were unidentified in the hypothesis phase.

2.2.4 Testing

As soon as the formulation phase of a simulation model starts, the testing phase should be started. The formulation and testing phase normally run parallel. This helps the modeller to gain insight in the relations that are constructed and help to compare the simulated behaviour to the hypothesis. In many situations there is a gap between the expected simulation results and the hypothesis. Errors within the (sub)systems can be identified in a early stage, while the complexity is relatively low. Every subsystem and interrelated agent needs to be tested immediately. Since if one assigns behaviour to an

agent and models that particular agent within a system of other agents, and in the end there appears to be an error, it is very difficult to address the error in the system. Based on expected outcomes, that of course can be estimated wrong on forehand, the error is hard to detect. Normally every component or agent added to the system needs to be tested, before adding new agents to the model. This helps to behold oversight in the model and eliminate errors. In general, subsystems are tested as separated systems so their behaviour is what was expected. If all the subsystems are working properly as expected, the subsystems can be coupled to each other to the next, higher, level. Every variable in the model must correspond to a meaningful concept in the real world and every equation must be tested for dimensional consistency.

While the complete model is constructed, it must be tested for conventional as well as extreme conditions. For example, what will happen to the simulated GDP of the model if the energy supplies are reduced to zero. As one can imagine, the GDP of a modern industry will fall to nearly zero, but will not cross the zero, since GDP cannot be negative. As it is the same for the real world, simulation models cannot violate the basic laws of physics.

2.2.5 Policy Design and Evaluation

In the previous sections, the process of creating a solid and sound system dynamics is explained. The purpose of the system dynamics model however is to test and verify policy decisions and evaluate them. Since policy design is more than just changing the values of parameters, the model needs to be changed in a higher level. In fact, there are two kinds of evaluation scenarios, the first one is the parameter scenario, where the scenario is shaped by changing parameter values. The second scenario is a structure scenario, designed by changing feedback loops and decision structures.

2.3 Energy-Economy Models

Energy Economy models deal energy policies and global warming issues, multidisciplinary fields - energy, economy and the environment should be expressed as model components. Technological innovations and efficiency improvements are factors that should also be included for this model.

2.3.1 Top-down and Bottom-up models

The main concept of energy economy models is outlined in figure 2.2. There are two vectors, energy demand and supply, respectively. Each of these signals two major factors such as energy quantity and energy price.

In general two types of energy economy models can be distinguished, top-down and bottom-up models. The difference can be explained best by the definition by the IPCC [Houghton et al., 2001]. Top-down models evaluate the system from aggregate economic variables, whereas bottom-up models consider technological options or project-specific

climate change mitigation policies. The differences between their results are rooted in a complex interplay among the differences in purpose, model structure, and input assumptions. The terms "top" and "bottom" are shorthand for aggregated and disaggregated models. The top-down label comes from the way modellers apply macroeconomic theory and economic techniques to historical data on consumption, prices, incomes, and factor costs to model the final demand for goods and services, and the supply from main sectors (energy sector, transportation, agriculture and industry). Some critics complain, however, that aggregate models do not capture the needed sectoral details and complexity of demand and supply. They argue that energy sector models were used to explore the potential for a possible decoupling of economic growth and energy demand, which requires bottom-up or disaggregated analysis of energy technologies.

Macroeconomic models are also often detailed, but in a different way to bottom-up models. Top-down models account for various industrial sectors and household types, and many conduct demand functions for house hold expenditures by summing "individual demand functions".

Another distinction between the top-down and bottom-up approaches is how behaviour is endogenized and extrapolated over the long run. Econometric relationships among aggregated variables are generally more reliable than those among disaggregated variables, and the behaviour of the models is more stable with such variables. It is therefore common to adopt high levels of aggregation for top-down models when they are applied to long time frames.

Top-down models examine a broad equilibrium framework. This framework addresses the feedback between the energy sector and other economic sectors, and between the macroeconomic impacts of climate policies on global scale. As such, top-down models usually had minimal detail on the energy-consuming side of the economy. Specific technologies were not directly captured. In contrast, bottom-up models mimicked the specific technological options, especially for energy demand. Attention to the detailed workings of technologies required early modellers to pass over the feedbacks between the energy sector and the rest of the economy.

Top-down and bottom-up models have also different assumptions and expectations on the efficiency improvements from current and future technologies. Bottom-up models often focus on the engineering energy-gains evident at the microeconomic level and detailed analysis of the technical and economy dimensions of specific policy options.

The basic difference is that each approach represents technology in a fundamentally different way. The bottom-up model capture technology in the engineering sense: a given technique related to energy consumption or supply, with a given technical performance and cost. In contrast, the technology term in the top-down models, whatever the disaggregation, is represented by the shares of the purchase of a given input in intermediary consumption, in the production function, and in labor, capital and other inputs. These shares contribute the basic ingredients of the economic description of a technology in which, depending on the choice of production function, the share elasticities represent the degree of substitutability among models.

This thesis work addresses the feedback between the energy sector and other economic sectors, and between the macroeconomic impacts of climate policies on the national and

global scale.

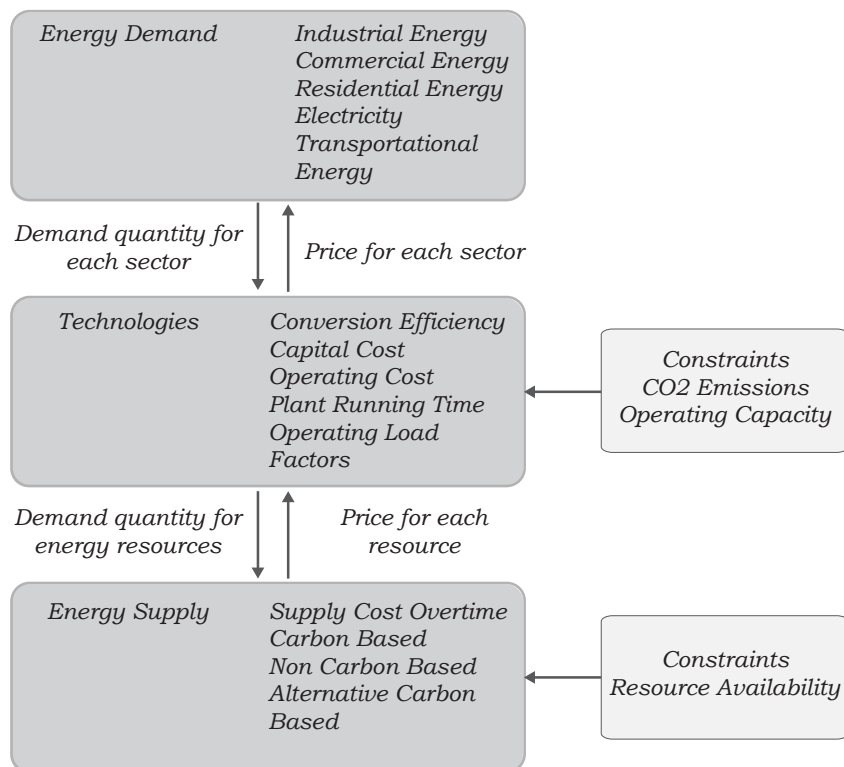


Figure 2.2 – Component of energy-economy model

2.3.2 Typical Energy Economy Models

Most of the existing IAMs are based on the same economic and social principles. For this reason many IAMs are similar in multiple aspects. However most of the IAMs are modelled to a particular problem, they are based on common social and macroeconomic principles. However the social and economic systems are structurally more uncertain than the physical systems of climate and greenhouse cycles, most of the similarities can be attributed in the root of integrated assessment models in the economic tradition of energy modelling. Fiddaman has listed a set of attributes that are shared by most integrated assessment models in their central scenario's:

- exogenous population,
- exogenous rates of economic growth or factor productivity,
- discount rates on utility or cost and benefits flows that give higher weight to welfare of current generations,
- rapid equilibration of factor inputs to production,

- general exclusion of positive feedback mechanisms in the economy (other than capital stock),

2.3.3 Technological Change

The economic and social models used in IAMs are based on proven structures and formulas, however one essential part is mostly taken out of the equation, technological change. In this perspective described as the endogenous evolution of energy technology through deliberate research and development and the accumulation of production experience. Technological change is essential for improvement of prices and the production capacity, aspects that are used in all the IAMs.

There are multiple reasons for not including technological change in models, all of them are technical. Growth theory and energy system modelling have a strong orientation toward optimisation, endogenous technology introduces the possibility of multiple optima, making models analytically intractable and making identification of optimal decisions more difficult [Sterman, 2000a, Fiddaman, 1997]. Models with endogenous technological change appeal to an additional, unobservable state variable and thus obtain greater realism at the expense of statistical tractability as well. However, according to Fiddaman, it is misleading to describe technology as unobservable. He prefers to term it as an "unobserved" variable. Because the evolution of technology is not well integrated into economic theory, existing models instead treat technology as an autonomous trend influencing efficiency of energy, production cost and omitting the positive feedback loop from learning. Therefore most models implement and test alternative causal theories of the evolution of technology, using learning curves.

2.4 Study on Existing Conceptual Integrated Assessment Models

System Dynamics is all about modelling towards the problem, by keeping the problem in mind, the modeller need to select the proper feedback structures that lead to a reliable and realistic model. The focus of this section lies in the structural differences in existing economy-energy models instead of parametric differences, since feedback structures determine the sensitivity to a model to particular parameters.

In this section a selection is made of IAMs that represent economics, climate and emissions and energy demand. Table 2.3 show the selected models and their purposes.

However the models listed above are all system dynamics models, there are differences in the simulation characteristics. Several software tools can be used for simulating, Connecticut/YOHE, DICE and TIME, Hatlebakk/Moxnes were created using the STELLA/i-Think format while the others are developed in VENSIM. Despite some models are developed using other software tools, there is no major difference between the tools. More significant differences can be found in the simulation characteristics of the models. Stochastic type model will have different characteristics than a deterministic simulation. The time interval can differ from discrete to continuous. Time horizons will differ; 1900 -

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Table 2.3 – Model boundary chart for long-term model of Airline Value Evaluation Model interactions

Model	Purpose	References
Connecticut/YOHE	Investigate the relative merits of hedging over the near term against the change that the atmospheric concentrations of carbon dioxide will be limited as a matter of global policy	Yohe and Wallace, 1996
DICE	Identification of optimal emissions reduction trajectories, valuation of information, and new policy evaluation under uncertainty	Nordhaus, 1994
TIME	Generation and evaluation of energy sector scenarios	De Vries et al., 1996
NICE	Critique and extension of DICE	Fiddaman, 1995
ICAM 2.1R	Assessment of Uncertainty, including implications for different regions and interest groups	Dowlatabadi, 1993
FREE	Investigation of implications of bounded rationality, embodied energy requirements, depletion, and endogenous energy technology	Fiddaman, 1996
Hatlebak/Moxnes	Basis for a simulation game investigating misperceptions of feedback in climate change policy	Hatlebak and Moxnes, 1992

1975 to 2100-2300. The interval, 5-10 years using Euler integration. Table 2.4 show the simulation characteristics for seven SD models.

Table 2.4 – Simulation characteristics for similar System Dynamics Economy-Energy or Economy-Climate Models. (EI is an acronym for Euler Integration)

Model	Type	Time	Horizon	Interval	Original Language
Connecticut/YOHE	myopic optimisation	Discrete	1975-2100	5-10 years	SuperCalc
DICE	intertemporal optimization	Discrete	1965-2100	10 years	GAMS
TIME	deterministic simulation	Continuous	1900-2100	<1 year (EI)	STELLA/iThink
NICE	stochastic simulation	Continuous	1965-2011	<5 years (EI)	Vensim
ICAM 2.1R	stochastic simulation	Discrete	1975-2100	5 years	DEMOS
FREE	deterministic simulation	Continuous	1960-2100	.125 year (EI)	Vensim
Hatlebak/Moxnes	stochastic simulation	Continuous	>100 years	<1 year (EI)	STELLA/iThink

The level of aggregation is also an important characteristic for a model. Every model is developed to answer a particular question or problem, yet it results in a different level of aggregation. Table 2.5 illustrate the aggregation of the models based on different aspects.

Table 2.5 – Aggregation of aspects in SD models

Model	Regions	Economic Sectors	Energy Sources	Energy Carriers	Greenhouse Gases
Connecticut/YOHE	1	1	2	1	1
DICE	1	1	-	-	1
TIME	1	4	6	5	-
NICE	1	1	3	1	1
ICAM 2.1R	7	1	4	1	4
FREE	1	1	4	4	1
Hatlebakk/Moxnes	1	1	-	-	1

2.4.1 Discrete Time Models versus Continuous Time Models

The selection of a simulation time is dependent on the available software. Continuous simulations are known for their precision, while discrete time models can have problems with some time constants in the model. In many situations the model compensates for discrepancies in time constants.

For example DICE, this model has a set of time constants incorporated in the model that span 50 years (population growth), 120 years (CO_2 storage) and 50 years (ocean and atmosphere heat transfer), but also 10 years for capital stock. Since the simulation time in the model is discrete and the interval is 10 years, the accuracy for the model is not significant. Therefor DICE uses a correction factor for capital life to account for compounding, using instead a fractional depreciation rate of 65% per decade. In equation 2.4 and 2.2 one can see the differences in formulation of the capital stock.

$$K(t + 1) = K(t) - \delta * K(t) = (1 - \delta) * K(t) \quad (2.2)$$

$$K(t + n) = (1 - \delta)^n * K(t) \quad (2.3)$$

$$dK/dt = I(t) - \delta * K(t) \quad (2.4)$$

$$K(t) = \int (I(t) - \delta * K(t))dt \quad (2.5)$$

$$I(t) = K(t) - K(t - 1) + \delta K(t - 1) \quad (2.6)$$

One of the downsides of discrete simulations is the current output of the model is based on the previous value of the output. This implicates that the previous value of capital is used as input to the investment function, as expressed in equation 2.6. Hereby the output term is always suboptimal, since the next iteration the current value will be found. There are multiple ways to resolve this problem, one is to shorten the time interval. This will

make the error rather small or even negligible.

Another option is to rewrite the equation for discrete time in an adjusted equation for the time interval. A function as illustrated in equation 2.7 is adjusted for a time interval of 5 years and is expressed as in equation 2.8

$$T(t) = \alpha T(t - 1) + \beta R(t) \quad (2.7)$$

$$T(t) = \alpha^5 T(t - 5) + \beta R(t) \left(\frac{1 - \alpha^5}{1 - \alpha} - \frac{1}{5} \frac{\alpha(1 - 6\alpha^5 + 5\alpha^6)}{1 - \alpha^2} \right) + \frac{1}{5} \frac{\beta R(t - 5) \alpha(1 - 6\alpha^5 + 5\alpha^6)}{1 - \alpha^2} \quad (2.8)$$

However equation 2.8 is correct, it is not at all transparent to model consumers. Therefore it is much better to express the equation in continuous time and compensate for the compounding.

Not only discrete time models do have disadvantages towards simulating real world scenarios. Continuous time models are also subject to common problems and limitations. The behaviour of a continuous model should be independent of the time interval and integration method used to simulate it [Fiddaman, 1997]. According to Fiddaman, for accurate integration, the time interval of the simulation must be significantly shorter than the shortest time constant in the model. High-order integration methods and models with oscillatory behaviour are subject to integration errors from amplifying oscillation. This behaviour can be eliminated by using discontinuous relationships in the model, for example an IF .. THEN, ELSE logic.

Another difficulty with continuous models involves the representation of feedback loops with short time constants. One may include the feedback loop, and accept the degradation of speed that occurs because of the short simulation time step required. Alternately, one may solve for equilibrium in the subsystem with short time constants, and use only the equilibrium relationship in the model [Fiddaman, 1997]. In the reviewed models, there are no such situations and all time constraints to market adjustment are short with respect to the simulation interval.

2.4.2 Model Complexity

The complexity of the models reviewed, varies significantly. The complexity of a model is based on multiple determinants, the richness of the endogenous feedback structure, the system order and the nonlinearity of the model relationships.

Fiddaman has converted all of the reviewed models into a continuous model and compared the feedback structures and complexities. The DICE and Connecticut/YOHE model were relatively easy to convert, while the ICAM model was extremely difficult. Table 2.6 illustrates the metrics in the models and their characteristics with respect to their complexity.

One of the first remarks to be made is concerning the amount of feedback loops in the NICE, TIME, FREE and ICAM 2.1R models. Each ranging from a couple of hundred to

Table 2.6 – Aggregation of aspects in SD models

Model	Equations	State Variables	Search Space
Connecticut/YOHE	180	6	2
DICE	170	4	80
TIME	1420	100	-
NICE	100	9	-
ICAM 2.1R	700	high	22
FREE	300	21	4
Hatlebakk/Moxnes	650	94	-

thousand feedback loops and key variables. Table ?? illustrates the number of equations, state variable and search space for optimisation, while table 2.7 show the aggregation of the models with respect to economy, energy, Greenhouse Gases and Climate.

2.4.3 Nonlinearity

The real world is fundamentally nonlinear. Linear models are not sufficient to model real world system such as the carbon dioxide uptake by the atmosphere, the increase of utility or the Cobb-Douglas and Constant Elasticity of Substitution (CES) production functions. All of the models reviewed consist out of nonlinear relationships expressed in feedback loops.

The carbon cycle in the DICE, Connecticut/YOHE and ICAM model are linear, in which the uptake of carbon is strictly proportional to the atmospheric concentrations, regardless of how high it becomes. This is radically different for the NICE, FREE and Hatlebakk/-Moxnes models, where the uptake of carbon dioxide has a logarithmic effect on the radiative forcing [Nordhaus and Boyer, 1999, Yohe et al., 1995, Yohe, 1990, Dowlatabadi, 1995].

According to Fiddaman and Sterman, the problematic nonlinearity can arise from discrete changes or discontinuities in the model relationships. These discontinuities arise in several ways, logical statements (i.e. IF..THEN...ELSE) can generate output that is a discontinuous function of the output. MIN and MAX statements produce discontinuities in the slope of a relationship, as can lookup tables [Fiddaman, 1997].

2.5 Value Operations Methodology

This section provides insight in the development of a Value Operations Methodology (VOM) that can be used to support the evaluation of aircraft performance in a system dynamics framework. According to Curran et al. VOM establishes expressions for operational value levers that are incorporated into a weighted value function. This function

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Table 2.7 – Aggregation of aspects in SD models

Model	Economy	Energy	GHG Cycles	Climate
Connecticut/YOHE	capital output	cumulative carbon fuel production	atmospheric carbon	(surface ocean temperature, deep ocean temperature
DICE	capital	-	atmospheric carbon	surface ocean temperature, deep ocean temperature
TIME	capital (4 sectors) embodied energy requirements irreversible price induced energy efficiency adjustments	energy resources, energy reserves, energy producing capital, capital under construction, transmission and distribution capital, energy technology adapted tax level, reversible emissions, irreversible emissions	-	-
Hatlebakk/Moxnes	capital natural resources	adapted tax level, reversible emissions, irreversible emissions	atmospheric carbon	temperature, adapted temperature
ICAM 2.1R	-	cumulative energy production, partial price adjustment	atmospheric carbon, methane, NO _x , sulphate aerosols	multiple temperature models
NICE	capital	cumulative energy production, energy intensity of capital	atmospheric carbon, surface ocean carbon deep ocean carbon, biomass carbon	surface ocean temperature, deep ocean adapted temperature
FREE	capital embodied energy requirements embodied AEEI energy price perceptions relative return perception	energy producing capital, capital under construction, relative rerun perceptions, cumulative energy production, energy technology, energy prices	atmospheric carbon, surface carbon, deep ocean carbon, biomass carbon	surface temperature, deep ocean temperature, adapted temperature

is then used to evaluate the performance of aircraft based on the aircraft variables that resulted from airliner operations, as described in chapter 1. VOM can be used to drive a design process based on the optimisation of design variable that are valued by the methodology. This work will employ VOM in a way it is able to value the operational performance of an aircraft type under different scenarios. By adjusting the weighing factors for the levers used in the VOM expression, one can put emphasise on fields of interest, for example the impact of air transport on climate change.

In 1992 Ralph L. Keeney (1992) raised the similarity between the general structure of a value model and the models relating unit selling price and a fixed variable cost of

producing the product [Curran et al., 2010, Keeney, 1992a]. The hedonic model is based on the idea that a cost differential between two systems consisting of a set of similar characteristics can be used to value the characteristics. The hedonic model is explicitly based on a price constant, α . A typical hedonic function that connects the variation in cost to the variation in characteristics is shown in equation 2.9

$$\ln(P_1) = \alpha_1 + \sum \beta_j x_{ij} + \epsilon_i \quad (2.9)$$

In equation 2.9 $j = 1, \dots, m$ is a set of value levers of the system that is analysed, P is the price, β is the weight factor. The equation above is used to define the percentage change in price the stakeholder is willing to pay for an adjustment in the value lever x . The value model is based on Keeney's representation of theorems for quantifying values using utility functions. Research conducted by Curran et al. states that the theorem of Fishburn suits the VOM approach best: Keeney defines Fishburn's function as the additive utility function, expressed in equation 2.10.

$$u(x_1, \dots, x_n) = \sum k_i u_i(x_i) \quad (2.10)$$

Where u_i is a single attribute utility function over attributes x_i and k_i are the scaling constants needed for value tradeoffs.

The basis for a value model is a set of goals G_i , where i ranges from 1, ..., N . The consequences x are part of the attribute X measuring goal G . According to Fishburn, the additive utility function exists only in situations where the additive attributes are independent to each consequence x , so there is a corresponding number u that indicates the value. The proof for this function is given in Fishburn 1965 [Fishburn, 1964].

Based on the publications by Fishburn and Curran, the hedonic model establishes:

- differential principle: which is more reasonable to relate the value of one instance with another.
- additive principle: the value relating to an instance should be simply accumulated.

One of the advantages of the additive principle is that value relating to an instance should not be modelled individually. Instead it can accumulate, which can result in a set of value levers that are equated using the differential-additive principles described above, see equation 2.11

$$\Delta V = \alpha_a(A_a/A_b) + \alpha_b(B_a/B_b) + \alpha_c(C_a/C_b) + \alpha_d(D_a/D_b) + \epsilon \quad (2.11)$$

The value levers in equation 2.11 consist of the sum of the specific system characteristics Δ multiplied by the corresponding weighing factors, α_i , i ranging from 1, ... N . The value model is based on a reference input (subscript 0) and an object that is put under consideration (subscript 1).

A value lever in equation 2.11 can be modelled in detail as shown in equation 2.12

$$A = \omega_1 \cdot d[\textit{ValuePoint}_1] + \omega_2 \cdot d[\textit{ValuePoint}_2] + \dots + \omega_3 \cdot d[\textit{ValuePoint}_3] \quad (2.12)$$

Where A is a value lever variable and represents the number of value point corresponding to the value components of the value lever. ω_i are the weight factors corresponding to the individual deltas.

The ω 's in equation 2.12 indicate how much value can be obtained by an improvement of the design.

2.6 Using the Analytic Hierarchy Process to Identify the Value Components

In order to identify the components that are valuable for the mode, the methodology uses a trade-off process developed by the NASA and is published in the Analytic Hierarchy Process (AHP) in the NASA Systems Engineering Handbook and is developed by Thomas L. Saaty. The AHP process produces a figure of merit for every design option. According to the NASA handbook, the process is as follows:

1. Describe in summary form the alternatives under consideration.
2. Develop a set of high-level evaluation objectives; for example, science data return national prestige, technology advancement, etc.
3. Decompose each hi-level evaluation objective into a hierarchy of evaluation attributes that clarify the meaning of the objective.
4. Determine, generally by conducting structured interview with selected individuals or by having them fill out structured questionnaire, the relative importance of the evaluation objectives and attributes though pair-wise comparisons.
5. Have each evaluator make separate pair-wise comparisons of the alternatives with respect to each evaluation attribute. These subjective evaluations are the raw data inputs to a separately developed AHP program, which produces a single figure of merit for each alternative. This figure of merit is based on relative weight determined by the evaluators themselves.
6. Iterate the questionnaire and AHP evaluation process until a consensus ranking of the alternative is achieved.

After selecting the valuable components for the value model, the components should be weighed. The AHP leads to criteria of unequal weight and also to non-quantifiable criteria. In order to be able to construct a sound value model, the importance of each criterion needs to be established relative to other criteria. This is done by making pair-wise comparisons between the different criteria. In each comparison it is determined how much more (or less) important one criterion is over the other in relation to the design that is to be traded off. This methodology uses the same scale as is Curran et al. [Curran et al., 2010] and ranges from 1 to 9 and the reciprocal values (1/9 to 1). When all

2.6. USING THE ANALYTIC HIERARCHY PROCESS TO IDENTIFY THE VALUE COMPONENTS

n criteria are compared to each other the results are put in a matrix, resulting in an $n \times n$ matrix, where two items are of particular importance, the eigenvalue and eigenvector.

The eigenvalue is calculated using equation 2.13

$$\det(A - I\lambda) = 0 \tag{2.13}$$

The eigenvector of the matrix is calculated using equation 2.14.

$$Ax = \lambda x \rightarrow^\Delta (A - \lambda I)x = 0 \tag{2.14}$$

The normalised eigenvector is obtained by dividing every value in the eigenvector by the sum of all items [Saaty, 1987]. It states that the comparison matrix will result in a matrix where each row is a constant multiple of the first row, where the matrix has a rank of one and thus only one eigenvalue that is nonzero, see table 2.8. When the normalised eigenvector belonging to that nonzero eigenvalue is obtained, the values in the eigenvector ($\vec{v} = [v_1, v_2, \dots, v_n]^T$) [Saaty, 1987, Curran et al., 2010].

	Criterion 1	Criterion 2	...	Criterion n	Eigenvector	Consistency Ratio
Criterion 1	w_1/w_1	w_1/w_2	...	w_1/w_n	v_1	CR
Criterion 2	w_2/w_1	w_2/w_2	...	w_2/w_n	v_2	
...	
Criterion n	w_n/w_1	w_n/w_2	...	w_n/w_n	v_n	

Table 2.8 – Weighing Matrix

Since the comparisons are performed by naturally subjective actors who compare items that are not necessarily easy to quantify, there will almost certainly be inconsistencies in the comparisons. Saaty has shown that the eigenvalue method is not only still valid for inconsistent matrices, but contents contends that it is also the only valid method for deriving the priority vector from a pair-wise comparison matrix. Any inconsistency in the matrix will show in the Consistency Ratio (CR), where CI is the consistency Index and RI the Random Consistency Index. The value of the CI is obtained using equation 2.16, in which λ_{max} is the largest eigenvalue on the $n \times n$ matrix. The value for RI is obtained from table 2.9, which shows the result for the CI value of a matrix of size $n \times n$ when the average value is taken from 500 computations on reciprocal matrices with randomly chosen inputs; as explained by Saaty and Curran [Saaty, 1987, Curran et al., 2010].

$$CR = \frac{CI}{RI} \tag{2.15}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2.16}$$

In the situation that the comparisons relate perfectly to each other, the value of CI will be zero. This is the result of the fact that for a perfect comparison there is only one

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 2.9 – *Random Consistency Index (RI) values for reciprocal (comparison) matrices of size $n \times n$ [Saaty, 1987]*

eigenvalue, which will be equal to the trace of the matrix and thus λ_{max} is equal to n . In situations where the comparison is not perfect, the comparison matrix is not perfect and λ_{max} will differ from n . Saaty states that the value of CR should not exceed 0.10. In situations where the CR is higher than 0.10, the comparison matrix should be reviewed and updated.

2.7 Chapter Summary

The previous chapter has served as an introduction to the basics of the airline industry and problems that airlines have to cope with on both short and long term. These topics were covered for a better understanding of the given problem and the related literature. All of the airline companies encounter variations in socio-economic and technological situations that endanger the stability of an airline.

In order to extract the key variables that impact the world as we live in today, this chapter focuses on existing models that mimic real-life global systems. Based on a literature study, there are three simulation methods that could be used to simulate complex dynamic systems. Since the aim of this work is to develop a holistic model to mirror the behaviour and characteristics of real world systems, a very generic and accumulated approach will be used. Based on the literature study, system dynamics turned out to be the best suitable method for this work’s purpose. Based on differential equations, representing stocks and variables that are related to each other by feedback loops, real world systems can be mimiced.

Since system dynamics is based on differential equations, proven and relevant definitions originating from socio-economics, finance, mathematics and geophysical studies can be modelled, each forming sub-models or sub-systems in the holistic framework that will be designed in this work. This method allows one to convert existing climate-economy (sub)models into a new holistic Integrated Assessment Model which will form the basis of this work’s model.

The concept of holistic modelling requires balanced conditions among energy, the economy, and the environment and social aspects as well. Typical models that meet the essential conditions for this work are Integrated Assessment Models, based on a system dynamics approach. The model components can interact with a transport model, which incorporates an air transport model as well. By having the air transport model interact with the IAM, the relative impact of air transport can be assessed. By enhancing the model, which is object oriented, with a Value Operations Methodology (VOM), the air transport model can be ran for different types of aircraft. VOM can be used to support the evaluation of aircraft performance in a system dynamics model. According to Curran et al. VOM establishes expressions for operational value levers that are incorporated

into a weighted value function. This function is then used to evaluate the performance of aircraft based on the aircraft variables that are incorporated into it. VOM can be used to drive a design process based on the optimisation of design variable that are valued by the methodology. The structure of this work is illustrated in figure 2.3.

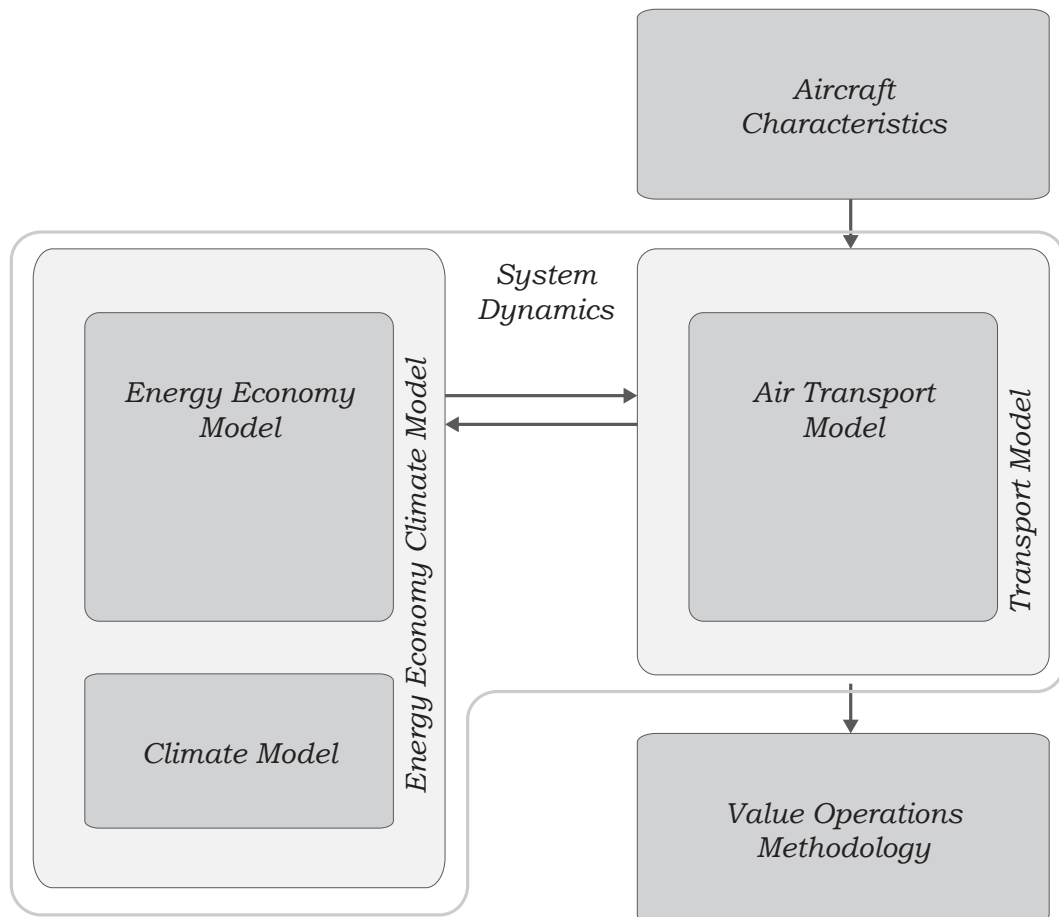


Figure 2.3 – Schematic of thesis work

Part II

Development

3 Method and Development of the Air-line Value Evaluation Model

Chapter 2 provides useful information about the development of methodology. Previous chapter has also shown that system dynamics can be used to develop a model that is able to support the research questions of this work. Based on the modelling methodology defined in chapter 2 this chapter will focus on dynamic hypothesis and formulation of the model. Validation of the formulated model will take place in chapter 4.

Since system dynamics can easily become tremendously complex, this chapter is structured based on the methodology for system dynamics, see 2.1. This methodology describes one should first select critical aspects of the model before the time horizon is determined. Since the longest time constant in the model cannot exceed the time horizon of the model itself. Based on both the critical aspects and time horizon, the boundaries of the model can be defined in a dynamic hypothesis. This can be placed into an abstract model structure. Each of the systems within the model will be treated separately.

3.1 Selection of Critical Aspects of the Model

Based on the model structure as illustrated in previous chapter, see 2.3, it is important to identify important aspects the model should incorporate. Since the model can be divided into three components:

- IAM
- Transport Model
- Value Operations Methodology

It is important to select the proper "receptors" in order to provide feedback and mimic realistic behaviour of all models involved. Based on literature study performed in previous chapters, a set of must-have aspects are listed.

- have a realistic population count
- match macro-economic consumption behaviour
- represent the carbon cycle realistically
- represent the emissions
- represent the climate system
- expresses utility
- express effects of innovation on energy consumption

- incorporate the effects of (carbon)taxes

Since the aim of the model is to evaluate the performance of airline businesses under changing socio-economic scenarios, it is important that the airline component is related to the simulated systems. As the aspects listed above illustrate, they are high-level abstract aspects. This aspects can be used to determine the mid-level implementation of subsystems for the model. Think for example the effects of population on the economy, or the effect of carbon taxes on energy consumption.

3.2 Time Horizon

After having selected a set of essential receptors and characteristics, it is essential to determine the time-frame of the model. In other words the time horizon. The IAM used as basis in this work is designed and validated for a time horizon ranging from 1965 to 2150. In order let the basic principles and theories behind the model undisturbed, this work will use the same time horizon.

Since this work needs to be verified and validated as well, it is extremely useful to have some data available to do so. In system dynamics it is essential to design a model in a way the longest time constant in the model cannot exceed the time horizon of the model. This allows one to review the impact of a change in a system within the model runtime. The World Data Bank provides datasets on many aspects that could be related to this work, offering great opportunities to verify and validate the models outcome.

3.3 Boundary

While designing a system dynamics model, it is important to keep track at the boundaries. In this work the boundaries of the (air)transport model are partially formed by the Climate-Economy-Energy model or named Integrated Assessment Model (IAM). Table 3.1 illustrates the boundaries of the used IAM.

Table 3.1 – Model boundary chart for long-term model of Airline Value Evaluation Model interactions

Endogenous	Exogenous	Excluded
GDP		
Consumption		
Investment		
Savings		
Wages		
Inflation Rate		
Labor force	Population	Labor mobility and participation
Employment	Technological change	Money stocks and monetary effects
Investment	Nonenergy CO_2 emissions	Non-energy resources
Interest Rates	Greenhouse gases other than CO_2	Regional disaggregation
Money Supply	Level of international focus	Sectorial disaggregation
Energy Production	Autonomous energy efficiency improvements	Inventories and backlogs
Depletion		Transport sector disaggregation in non-air transport modes
Carbon Cycle		
CO_2 emissions	Energy Policies	
Atmosphere and Ocean temperature		
Climate damages		
Energy Prices		
Transport Demand		
Transport Infrastructure		

The air transport model, within the transport model, is constructed based on a system analysis and literature study, as provided in chapter 1. The boundaries of this work are formed by the information provided in that chapter. Figure 3.1 illustrates the boundaries within each model, as well as how each model sets boundaries for related models.

METHOD AND DEVELOPMENT OF THE AIRLINE VALUE EVALUATION MODEL

Model Boundaries →	IAM	Transport Model	Air Transport Model
IAM	GDP Consumption Investment Savings Wages Inflation Rate Labor force Employment Investment Interest Rates Money Supply Energy Production Depletion Carbon Cycle CO2 emissions Atmosphere and Ocean temperature Climate damages Energy Prices Transport Demand Transport Infra-structure	Utility	
Transport Model		Initial time required "alternative" transport mode Variable time per passenger km for "alternative" transport mode Initial costs for "alternative" transport mode Variable costs per passenger km for "alternative" transport mode	
Air Transport Model		Initial time required air transport mode Variable time per passenger km for air transport mode Initial costs for air transport mode Variable costs per passenger km for air transport mode Stage length	Initial aircraft fleet size Initial capacity runways Aircraft capacity (passengers) [A/C] Aircraft Fuel consumption (GJ/PKM) [A/C] Aircraft Crew [A/C] Aircraft Maintenance Cost [A/C] Aircraft Emissions [A/C] Airframe Cost [A/C] Aircraft production time [A/C] Aircraft Cruise Speed [A/C] Aircraft Turnaround Time [A/C] Aircraft optimal capacity rate Aircraft Lifetime [A/C] A/C comfort (seat pitch, attendants, etc)[A/C] Runway optimal capacity rate Runway construction cost & time Airport operational time frame

Figure 3.1 – Schematic overview of the inter-model boundaries

3.4 Model Structure

Based on the problem articulation and the boundaries given in previous section, the basis Integrated Assessment Model needs to be designed. This work used a variety of IAMs to form the basis of this thesis. A high-level overview of the final IAM is provided in figure 3.2.

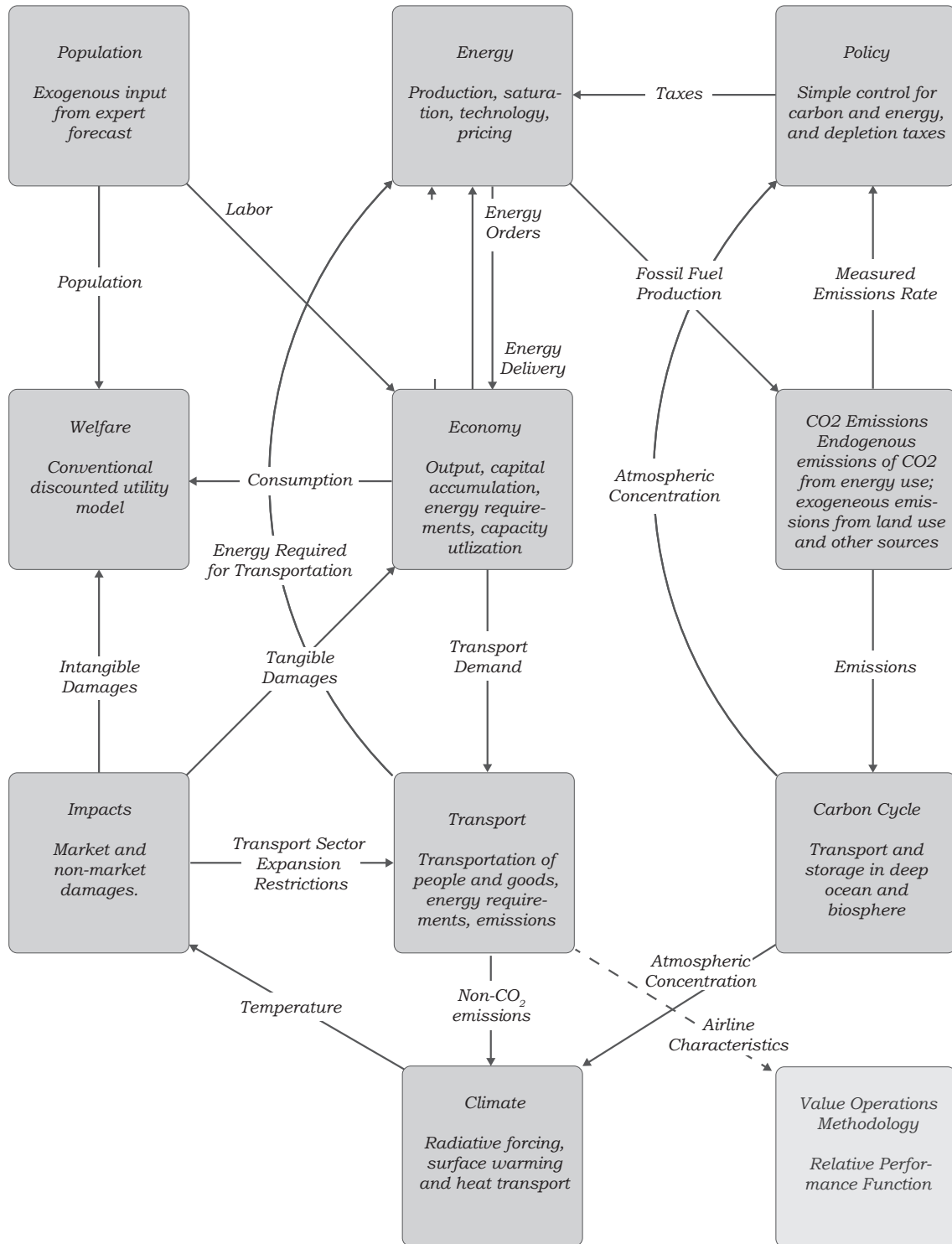


Figure 3.2 – Schematic overview of the Airline Value Evaluation Model system components

Figure 3.2 illustrates the systems within the IAM and is used for scenario creation. Based on economic, demographic, energy and policy decisions, the model simulates the development of relevant aspects of the real world in the future. Some subsystems interact with other subsystems in the model, whether it is the transport model or the air transport model.

METHOD AND DEVELOPMENT OF THE AIRLINE VALUE EVALUATION MODEL

The transport model simulates the demand for passenger kilometers for two transport modes. The air transport industry is modeled in as one airline which provides all the global air transport services. The airline operations are structured and provided in the model. Based on these operations, the airline has to provide air transport services. The cost for providing these services are normalised to one passenger kilometer price, which is, together with the time restrictions, the feedback mechanism for the transport model. Figure 3.3 illustrates the relations of the transport model to the IAM and the air transport model.

Inter-model Feedback →	IAM	Transport Model	Air Transport Part of Transport Model
IAM		Population GDP Utility Factor Productivity	Energy Cost (\$/GJ) Energy Taxes (\$/TonC) Income per Capita(\$) Interest Rate
Transport Model	Price of Transport Maginal Utility Transport Transport Energy Consumption [T] Transport Emissions [T]		Air Transport Demand (km)
Air Transport Part of Transport Model		Air Transport Energy Consumption (GJ) Air Transport Emissions Air Tranport Cost (\$/km) Air Transport Time (h/km)	

Figure 3.3 – Schematic overview of the inter-model feedback structure

3.5 Development and Verification of the Integrated Assessment Model

Based on a literature study performed by Thomas Fiddaman, this section provides an overview of the feedback structures used in the system dynamics models as reviewed in previous sections. Section 3.4 explains the high-level feedback structures in the model that forms the basis for this thesis. In the next sections, more insight is given into aggregated aspects of the model.

As described in previous chapter, AVEM is constructed using a set of systems which together form a set of key indicators over time that represent the world for the next 150 years. However, most of the data is theoretical, and a lot of "real life" systems are not incorporated in the model, it should be able to provide enough information to construct an emission scenario scene, which can be used for multiple purposes.

3.5.1 Population

One of the exogenous variables in the model is population. Population is important to the economy, since it delivers labor to the economy. Which on its turn can convert labor into capital, which will deliver consuming power to the population, which is expressed in GDP per capita and welfare (utilisation).

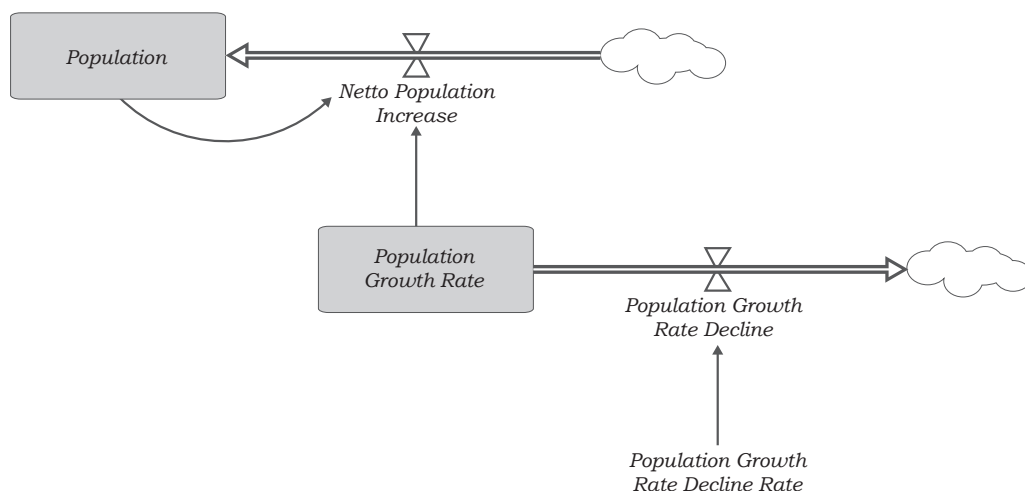


Figure 3.4 – System dynamic approach of the population component

The population in the model is modelled using stock variables. Using a growth rate, which is modelled as a stock variable as well, the increase in population is defined as the current population size multiplied by the population growth rate (dmnl). The population growth rate will be corrected by the population growth rate decline rate, which regulates the outflow of the population growth rate stock variable, as illustrated in figure 3.4.

METHOD AND DEVELOPMENT OF THE AIRLINE VALUE EVALUATION MODEL

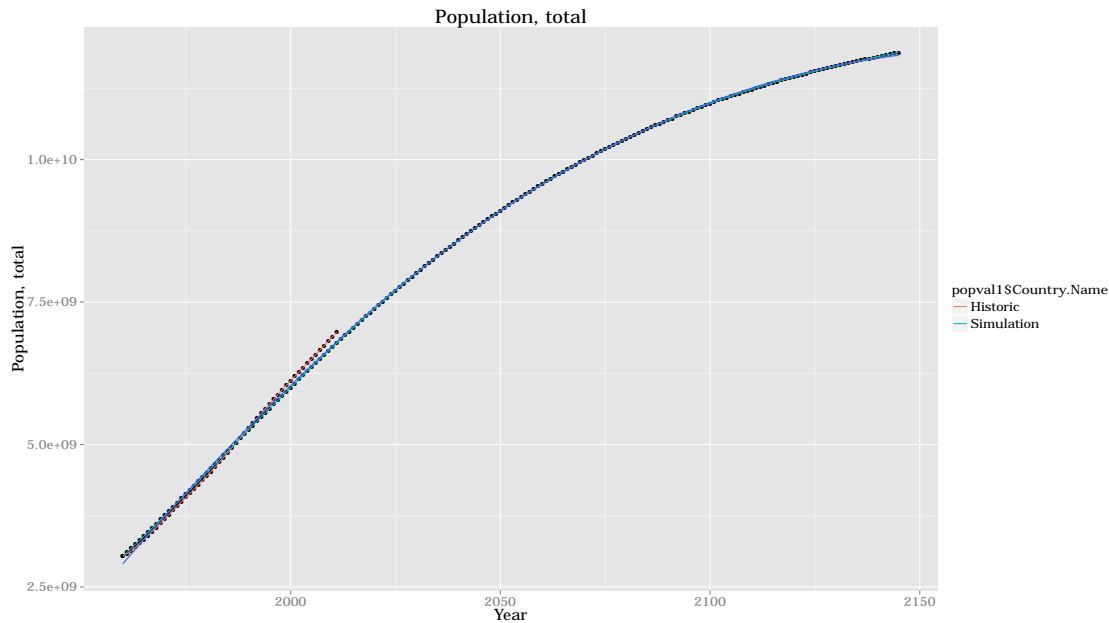


Figure 3.5 – Population according historic data and simulation results (population growth rate (0.0225) and population growth decline rate (0.011))

Based on historic data, the population growth rate and population growth decrease rate, the values for both rates are 0.0224 and 0.01 respectively. Based on an initial population size of 3.04e9 people in 1960, this will result in a population size of 9.29e9 people in 2150.

Table 3.2 – Model boundary chart for long-term model of Airline Value Evaluation Model interactions

Parameter	Value	Units	Notes
Initial Population	3.04e9	people	World Data Bank
initial Population Growth Rate	0.0225	1/year	World Data Bank
Historic Population Growth Rate Decline Rate	0.011	1/year	World Data Bank
Forecast Population Growth Rate Decline Rate		1/year	World Data Bank

The population system is modelled as a single variable, whereas some other IAM uses disaggregated age-groups, AVEM uses a single group. The effects of labor and investment on the capital system will become much more difficult in case a disaggregated population model is used [Dowlatabadi, 1995]. Therefore AVEM uses the simplified model.

3.5.2 Welfare

Welfare, or economic welfare, refers to the level of prosperity and living standards of the population in AVEM. In order to quantify and measure the level of welfare, the indicator utility is introduced. Utility refers to the part of welfare that can be fulfilled through economic activity. The higher the utility of a group, the better the welfare will be. This principle was introduced in system dynamics by William D. Nordhaus and is used as an indicator for AVEM.

The welfare, expressed in cumulative discounted utility, is the utility is weighted by the

population and a discount factor for pure time preference, and is expressed by formula 3.1

$$CDU = \int e^{(-\rho t)} L(t) U(t) dt \quad (3.1)$$

$CDU =$ cumulative discounted utility
 $\rho =$ rate of time preference

$L =$ population
 $U =$ utility of representative individual

Rate of time preference can be seen as the weighing factor in calculation of welfare. If the rate of time preference is positive, the utility of future generations receives a diminishing weight in the calculation of cumulative welfare as time progresses.

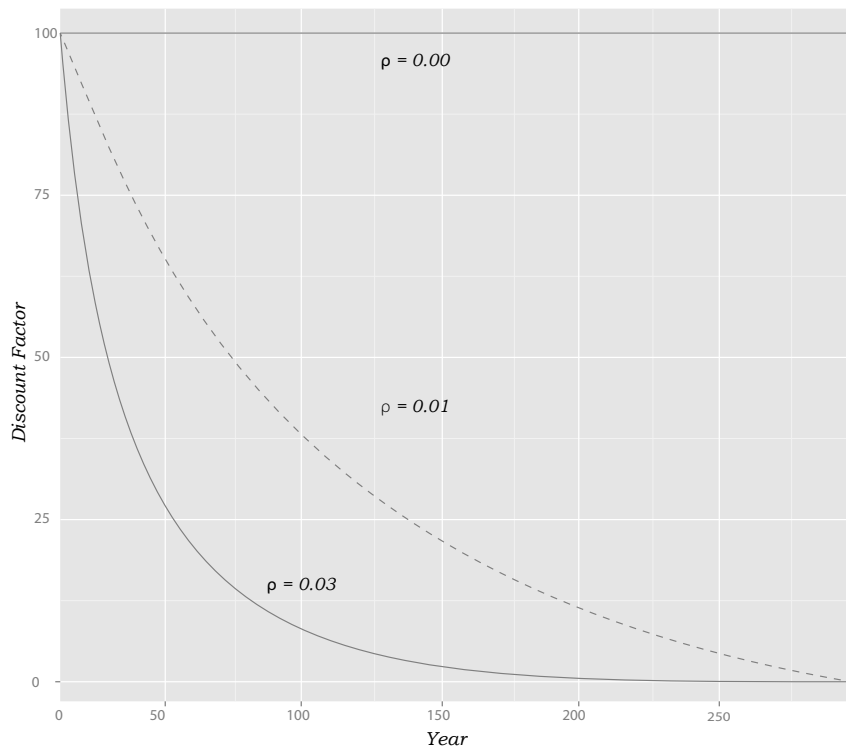


Figure 3.6 – Rate of time preference

The utility of a representative individual depends on the consumption of good and intangible environmental services, equation 3.2. Goods and environmental services are aggregated by a Cobb-Douglas production function as used by Thomas Fiddaman, equation 3.3.

$$U = \frac{ECI^{(1-\theta)} - 1}{1 - \theta} \quad (3.2)$$

$ECI =$ equivalent consumption index

$\theta =$ rate of inequal aversion

METHOD AND DEVELOPMENT OF THE AIRLINE VALUE EVALUATION MODEL

$$ECI = \left(\frac{c}{c_0}\right)^\Omega \left(\frac{S}{S_0}\right)^{(1-\Omega)} \quad (3.3)$$

c = consumption per capita

S = environmental services

c_0 = reference consumption per capita

S_0 = reference environmental services

Ω = share of consumption in utility

$S = S_0 D_n$

As the Cobb-Douglas based function 3.3 indicates, the utility of an individual is assumed to be purely a function of consumption in situations where $\Omega = 1$. But in situations where $\Omega < 1$, the importance of environmental services becomes more important. Since the environmental services are limitedly available, their importance increases when the wealth is increasing, implicating that the willingness to pay to avoid climate effects will increase.

The formulation of utility implicates directly that the marginal utility decreases when the wealth increases. Poor individuals gain more utility with an increase in consumption compared to a rich individual. This effect is trapped in the rate of inequality aversion, expressed by θ .

In order to set a base case scenario for future welfare, the parameters used in AVEM are based on research of Rothenburg and Becker. Their research state that if the utility of individuals in the future will not decrease. In order to implement this statement in the simulation, the parameters used in the model should be matching the ones indicated in table 3.4. The described parameters to provide interesting "tweak" parameters to change future welfare.

Table 3.3 – Welfare parameters for sustainable welfare over multiple generations

Parameter	Alias	Value	Units
Rate of Time Preference	ρ	0	1 / year
Rate of Inequality Aversion	θ	2.5	dmml
Share of Consumption in Utility	Ω	1	dmml

3.5.3 (Macro)economy

Emissions in AVEM are the result of consumption of a combination of emissions due to the consumption (and burning) of energy sources and non-energy related emissions, such as vulcano eruptions, and other forcings. In order to obtain the energy related emissions, the relation between economic performance, population size, consumption and other indicators need to be determined.

AVEM is based on the macroeconomic principles, which is the branch of economics that deals with the performance structure, behaviour and decision-making of an economy as a whole, rather than individual markets [Blaug, 1962]. Using the macroeconomic approach, the model is constructed to establish relationship between national (regional) income, output, consumption, unemployment, inflation, savings, investment and finance.

Macroeconomic theories usually relate the phenomena of output, employment and inflation. These three topics are essential for the determination of the energy consumption in the model, that result in the emissions.

Output and Income

The output of the system is described as the total value of the production of a region in a given period of time. According to Blaug, everything that is produced and sold generates income. Therefore, output and income are usually considered equivalent and the two terms are often used interchangeably.

The macroeconomic output is often measured by the Gross Domestic Product (GDP) or other (national) accounts. AVEM is a global model, which assumes the total output to be equal to the sum of all regions or nations together. Advances in technology, accumulation of machinery and other capital, better education and human capital all lead to increased economic output.

Unemployment

Unemployment is an important aspect in economic prosperity. Since the labor force has a significant impact on the economic output, unemployment has a negative impact on the output [Blaug, 1962]. In macroeconomic approaches, one can distinguish several types of unemployment. Since AVEM lacks the presence of a disaggregated population model, which divides the population in multiple age-groups, the model cannot be enhanced with an (un)employment indicator. Instead of simulating the precise rate of unemployment to indicate the output, the model is based on a labor factor productivity parameter.

The labor factor productivity parameter per capita indicates the relation between the economic output and the amount of labor hours per capita. The higher the unemployment rate, the lower the factor productivity parameter, which results in lower economic output.

Inflation and deflation

Inflation, the general price increase in the entire economy, is an important indicator of economic performance. Simplified, inflation leads to higher prices, which will result in lower purchasing power of consumers, which result in less economic output.

Deflation on its turn, results in the decrease in prices. This sounds positive, however, the decreased prices result in lower output, which is negative as well. Monetary policies focus to avoid changes in price level and ensure stable economic output.

Interest Rate

According to macroeconomics, the investment decisions in goods and energy production are the result of the prevailing rate of interest against the marginal product of capital, net of depreciation. Low interest rates result in an increase in demand for the production of goods and energy, since that will fulfil the objective to obtain higher marginal effect of capital. In other words, the interest rate is an important determinant of the balance between investment and consumption. High interest rates lead to more investment, while lower interest rates make it more profitable to consume.

METHOD AND DEVELOPMENT OF THE AIRLINE VALUE EVALUATION MODEL

Since investment decisions are not the topic of this thesis, a simplified, but convenient, alternative for the interest rate is used. The interest rate is based on the model developed by Yohe [Yohe et al., 1995], which describes the determination of interest rates for disaggregated population models, which the AVEM is.

The Yohe interest rate determination is based on the optimal consumption path, developed by Ramsey [?]. Which describes the amount of consumption based on key economic indicators. The Interest rate is equal to the sum of the rate of pure time preference and the product of the rate of inequality aversion and the fractional rate of growth of per capita consumption:

$$r = \frac{(\frac{\delta}{\delta t}c(t))\theta_c}{c(t)} + \rho_c \quad (3.4)$$

c = per capita consumption

θ_c = rate of inequality aversion

r = interest rate

ρ_c = rate of time preference

According to Ramsey, a economy should remain stable by adjusting the interest rates so that the input and output remain equal. Since the consumption is a function of both output and interest rate, the rate of change of consumption depends on the growth rate of output and on the rate of change of the interest rate. In case of an external reduction of output, the consumption falls, and thereby the interest rate will fall as well. In order to keep AVEM stable, an equilibrium is established that balances input and output. In real situations, this equilibrium will not exist. More precisely, the system will be balanced by balancing and reinforcing feedback loops, Since this results in a complex multiple order feedback system, for the sake of simplicity this loops are discarded from the Ramsey model.

Output

The economic output of the system is determined using a Cobb-Douglas function. Based on the factor productivity of labor, population and capital intensity, the amount of value added is calculated, according the following function:

$$Y = Y_0 T \left(\frac{P}{P_0}\right)^\alpha \left(\frac{KO}{KO_0}\right)^{(1-\alpha)} \quad (3.5)$$

Y = gross output

P = population

Y_0 = reference gross output

P_0 = initial population

T = factor productivity

KO = capital

α = capital elasticity of output

KO_0 = reference capital

The energy intensity of the output is decoupled from the capital intensity. Some models, like for example the Feedback Rich Energy Economy (FREE) model, combine energy and capital to account for the fact that produced goods cannot be separated from their specific energy use. This model assumes there is a possibility to separate energy use from

3.5. DEVELOPMENT AND VERIFICATION OF THE INTEGRATED ASSESSMENT MODEL

the produced goods by more efficient fuels, conversion to more energy efficient measures. For example, this model assumes that a produced aircraft can be made more fuel efficient after being produced, by installing new engines only or more energy efficient fuels. FREE assumes that an aircraft cannot be made more fuel efficient over time. Which is in contradiction with the technology developments for example the Boeing 747, new flight patterns and behaviour. Buildings for example can be made more energy efficient, even without being totally rebuilt.

The parameters required to simulate the gross output need to be set at realistic values, the values can be obtained from the table below, see table 3.4. The parameter values are obtained from literature study and do match the historic values for gross output, as can be seen in figure 3.7. The historic data in the figure is obtained from the world data bank and represents the gross output of the world, which is the aggregate of the yearly gross output of all countries.

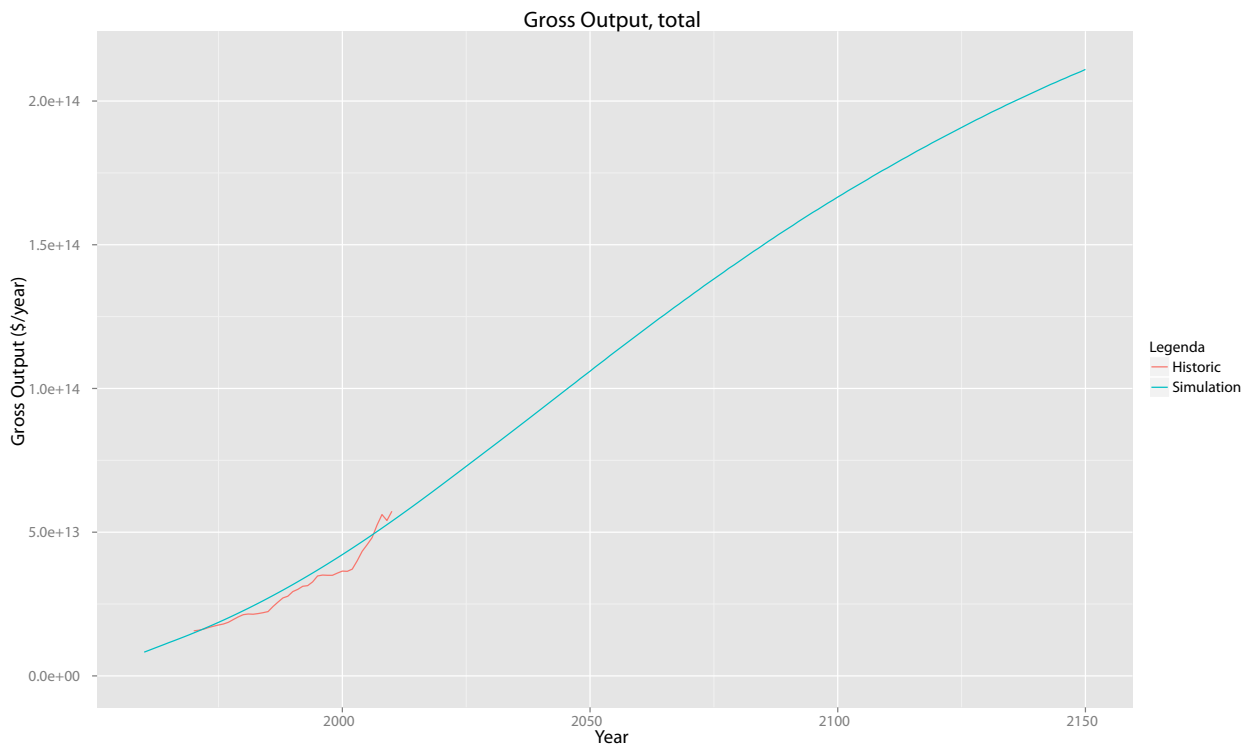


Figure 3.7 – Gross output for total world population

Table 3.4 – Welfare parameters for sustainable welfare over multiple generations

Parameter	Alias	Value	Units
Capital Elasticity of Output	α	0.25	dmml
Reference Gross Output	Y_0	8.261E+12	\$ / year
Initial Population	P_0	3.04E9	people

Factor Productivity

Economic output is strongly impacted by the factor productivity as could be seen in formula 3.5. Thereby the factor productivity is a direct and important driver of economic growth. Based on literature study and other integrated assessment models, the factor productivity is assumed to grow exogenously and grows towards a constant asymptotical value. Therefor the factor productivity in AVEM is modeled as illustrated in figure 3.8. The two stock variables are for the factor productivity at a particular time in the simulation and the corresponding factor productivity growth rate, which will diminish over time to simulate the asymptotic behaviour of the factor productivity as the time evolves.

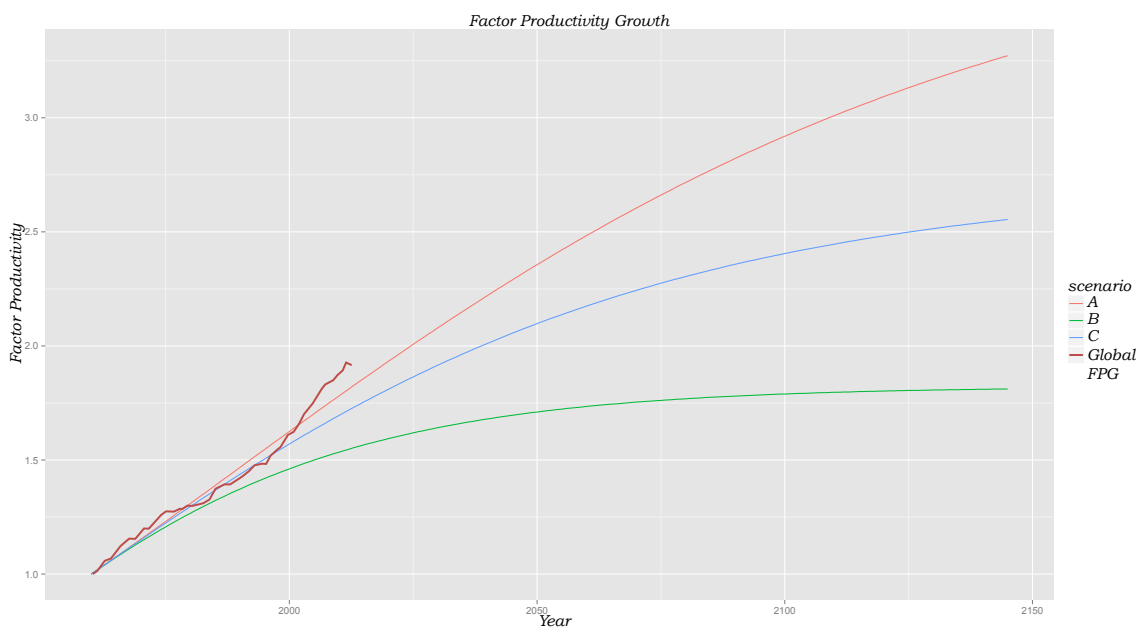


Figure 3.8 – Schematic overview of the factor productivity approach in AVEM

As could be expected from this type of structure, the factor productivity can either increase exponentially, or can stop at a particular level, which could be considered as the asymptotic value. Based on the initial factor productivity growth rate and the factor productivity growth rate decline rate (which drives the diminishing growth rate), multiple scenarios for factor productivity and thus economic output can be simulated.

Due to the sensitivity of this structure, factor productivity parameters should be selected carefully, otherwise the economic output can become a rather random number. Since the determination of factor productivity growth rates and growth decline rates is investigated by Nordhaus in 1997 [Nordhaus, 1997], the value for the factor productivity parameters is based on the assumptions and values proposed by Nordhaus. These values can be obtained from table 3.5.

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Table 3.5 – Factor productivity parameters, proposed by Nordhaus [Nordhaus, 1993]

Parameter	Value	Units	Reference
Initial Factor Productivity Growth Rate	0.015	1 /year	Nordhaus 1993
Factor Productivity Growth Rate Decline Rate	0.01	1 /year	Nordhaus 1993

Capital

The formation of capital is depending on the investments made in the economy and the depreciation of capital. Capital in the model is simulated according equation 3.7:

$$K(t) = \int I(t) - \delta K(t) dt \quad (3.6)$$

$K = \text{Capital}$

$\delta = \text{fractional depreciation rate}$

$I = \text{investment rate}$

Capital is discarded after a fixed amount of time. Therefore depreciation is introduced in the model. Capital is modelled as a stock variable with inflow investment and outflow due to depreciation. Every economy is dependent on an amount of capital available to produce goods and deliver services, therefore a desired capital stock is required. On the other hand there is the actual capital stock. Based on the marginal productivity efficiency of capital and depreciation rates, the capital system balances the capital stock by adjusting the investment fraction in investment in capital. The relations in the capital system are expressed using equation 3.7:

$$\Delta IF = \frac{(DIF - AIF)}{\tau_i} \quad (3.7)$$

$\Delta IF = \text{change in investment fraction}$

$DIF = \text{desired investment fraction}$

$AIF = \text{actual investment fraction}$

$\tau_i = \text{investment correction time}$

Whereby DIF can be expressed as in equation 3.8:

$$DIF = AIF * \left(\frac{DK}{MK} \right)^{c_i} \quad (3.8)$$

$DK = \text{desired return of capital}$

$MK = \text{Marginal product of capital}$

$c_i = \text{investment coefficient}$

Whereby MK is depending on the marginal product efficiency of capital minus the depreciation rate on capital. DK is dependent on the expected growth of the capital sector, based on the historic numbers for economic output, time preference and growth trend.

The capital system is illustrated in figure 3.9

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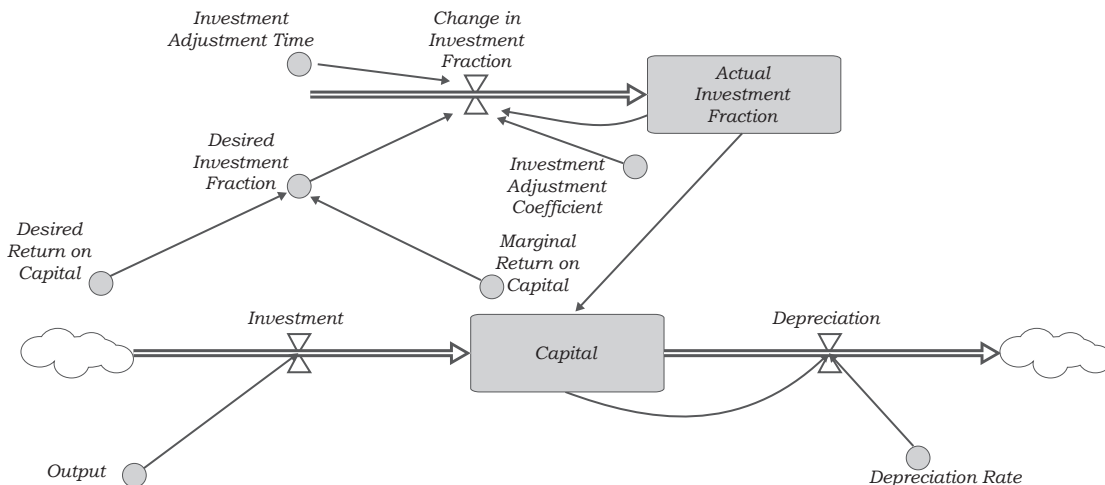


Figure 3.9 – Schematic overview of the capital system in AVEM

Energy Production

Energy production is strongly dependent on the capital stock, which is responsible for the production of goods and services. The energy intensity of capital, which expresses the amount of GJ per \$ expended, is combined with the "used" capital. This results in an energy demand for the total economy. This energy demand should be met in order to produce all the goods and services required.

The energy demand will be met using three kinds of energy sources:

- Carbon based fuels
- Non carbon based fuels
- Alternative carbon based fuels

AVEM provides three sorts of energy sources, which all have their own specific carbon content, price, availability and technology path. Based on these criteria, the model calculates the most appropriate energy source.

The production of energy is modelled as a stock variable, which means that the annual energy production is accumulated and having a negative effect on the available resources per energy source. The annual production of fuel is illustrated in figure 3.10.

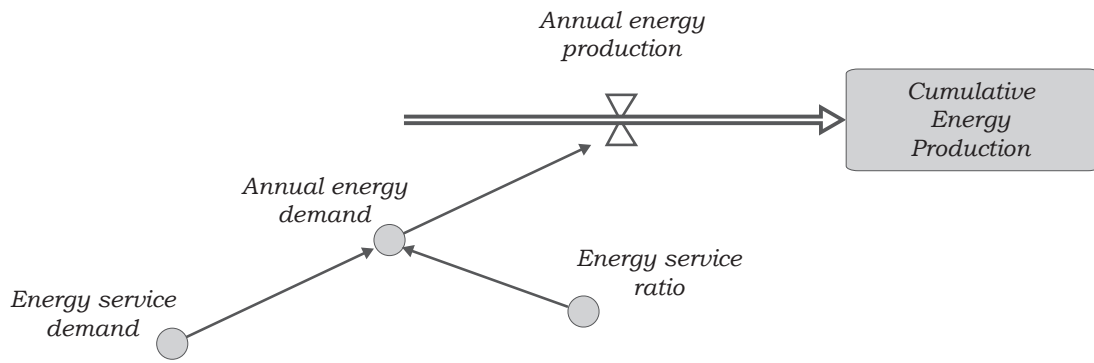


Figure 3.10 – Schematic overview of the energy production

The energy service demand is the resultant of the product of the energy intensity of capital and the required amount of capital, while the energy service ratio is the ratio per energy source for the energy demand. The energy service ratio is normalised to match the energy demand exactly. The mechanism behind the energy service ratio is expressed in figure 3.11

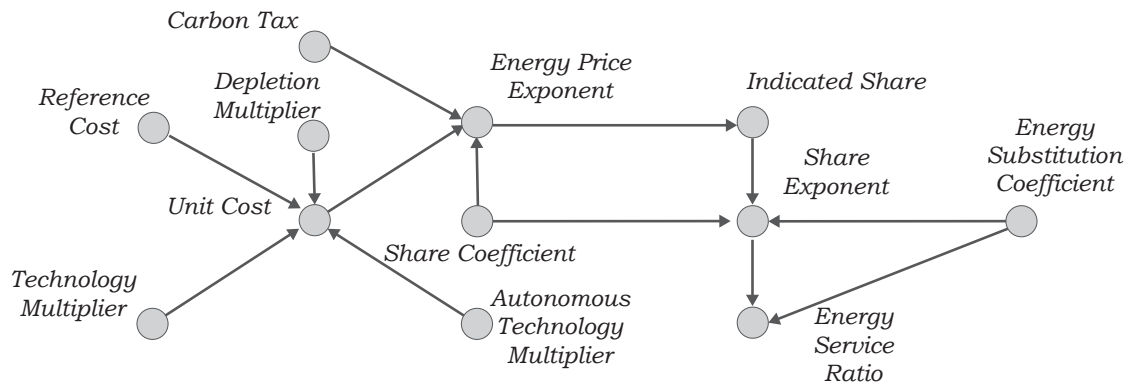


Figure 3.11 – Schematic overview of the energy service ratio

The idea of this system is that the unit cost are based on the product of the reference cost, technology multiplier and autonomous technology multiplier are divided by the depletion multiplier to obtain the basic cost of energy per energy source, see equation 3.9. This principle is based on the method used by Thomas Fiddaman in his IAM DICE.

$$P_i = \frac{P_{i_{ref}}}{Depl_i} * T_i * AT_i \quad (3.9)$$

P_i = Unit price

T_i = Technology multiplier

i = energy source

$P_{i_{ref}}$ = Reference unit price

AT_i = Autonomous technology multiplier

In order to obtain the energy prices exponent, the unit cost are enhanced with the optional

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carbon taxes, which result in the basic energy price, which result in the aggregated energy price per energy source, calculated by equation 3.10. Where by the energy substitution elasticity is indicating the price elasticity among other energy sources.

$$P_{exp_i} = \left(\frac{P_i}{c_{s_i}}\right)^{-\epsilon_i} \quad (3.10)$$

$\epsilon = \text{Energy substitution elasticity}$ $c_{s_i} = \text{Energy share coefficient}$

The share exponent per energy source relative tot the normalised total amount of energy required, is expressed by equation 3.11. The result of this equation is the market share for an energy source.

$$Share_i = \frac{P_{exp_i}}{\sum P_{exp_i}} \quad (3.11)$$

$Share_i = \text{normalised share per energy source}$

In order to obtain a weighted contribution of energy sources to energy services, which is required for the calculation of the ratio of physical energy input to the energy services output, the share expectation is calculated according equation 3.12

$$Share_{exp} = c_{s_i} (Share_i)^{c_\epsilon} \quad (3.12)$$

$c_\epsilon = \text{Energy substitution coefficient}$

The bottom line of the energy problem is the ratio between the energy output by the system and the energy input. This can be calculated by the Energy service ratio, and is defined as in equation 3.13. The the ratio

$$R_{energy} = \sum P_{exp_i} \left(\frac{1}{c_\epsilon}\right) \quad (3.13)$$

Production of Energy

The energy sector is one of the most important sectors in the system. The energy sector produces energy that is used by other sectors. As the other sectors use energy to produce their goods and services, the energy sector itself consumes energy too. AVEM compensates for the additional energy consumption that is required to produce the required amount of energy by other sectors.

The product of energy intensity of capital and the capital in the market available for production, result in the total energy service demand, this energy service demand is corrected to the amount of energy required to meet the energy service demand and finally results in the total energy demand.

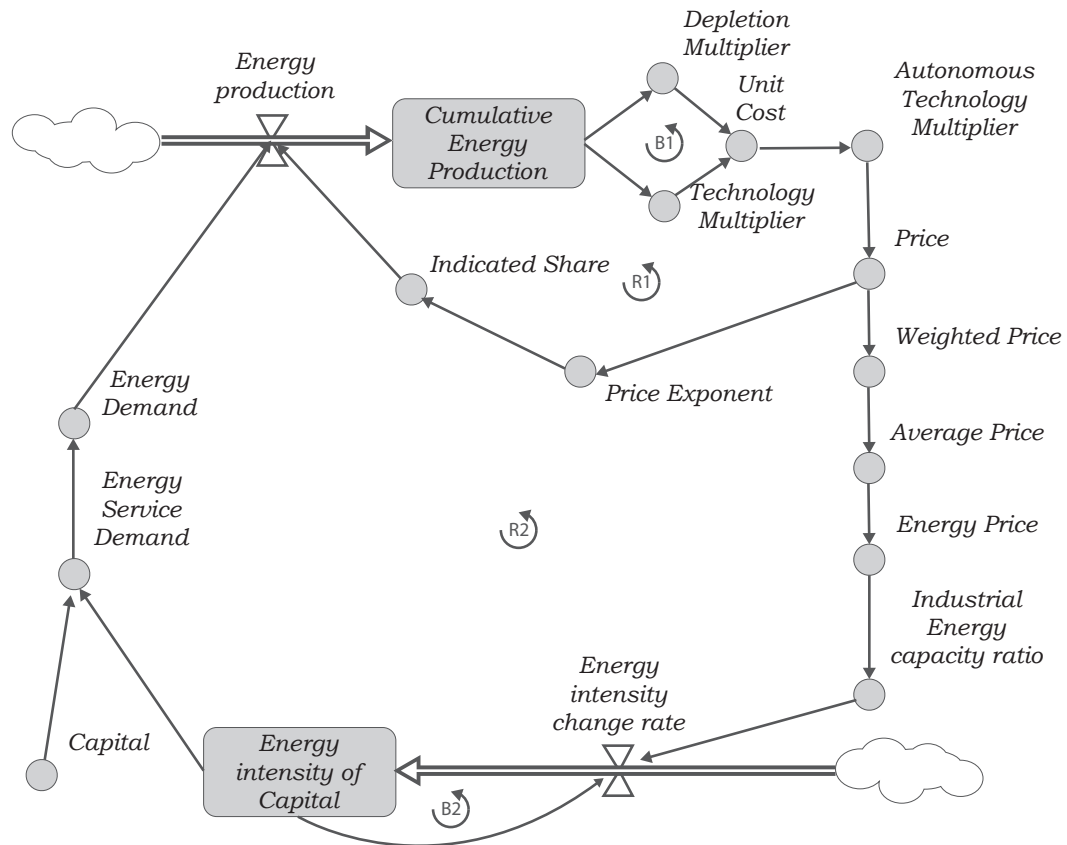


Figure 3.12 – Schematic overview of the energy production system

Three sources of energy are incorporated in the energy sector. Energy can be produced using carbon based fuels, non carbon based fuels and alternative carbon based fuels. The model seeks always to the most optimal energy source to be used in the energy sector. Energy sources are weighted by their price, implicating cheap energy will have more market share compared to more expensive energy sources. The availability of energy per energy source, is influencing the price levels, thereby technology can have significant impact on the way energy is produced. The production of energy is time and resource restricted, implicating that the amount of solar energy that can be produced is restricted by the amount of solar energy per year the sun is providing. Another example can be the production of oil, which is restricted by the availability of oil resources and the production time of oil.

Cheap energy prices result in cheaper energy since the production of "new" energy will be less expensive. This effect is reinforcing the energy production loop and is expressed by R1 in figure 3.12. As cheap energy for the energy production sector is resulting in lower prices for energy, the sectorial expenditure on energy will decrease as well, resulting in more capital available to produce goods and services, resulting in more energy demand (R2).

Since AVEM uses renewable (non-carbon based) fuels and nonrenewable (carbon based) fuels, the production of energy puts pressure to the endowment of resources. Renewable

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energy sources are assumed to be inexhaustible, while nonrenewable energy sources are dependent on the availability of resources. The smaller the availability ratio of a resource will be, the more difficult it will be to produce the particular type of energy from that resource. This effect is expressed as depletion multiplier. On the other hand, the higher the demand for a particular energy source will be, the higher the incentive to innovate on the production of this type of energy to decrease energy prices and improve on the market share. This effect is referred to as technology multiplier.

The energy production in AVEM can be explained using the equations stated below.

$$EP_i = EP_{i,0}(\alpha_{i,r}(\frac{R_i}{R_{i,0}})^{\rho_{i,r}} + (1 - \alpha_{i,r})EII_i^{\rho_{i,r}})^{\frac{1}{\rho_{i,r}}} \quad (3.14)$$

EP_i = energy production

EII_i = effective input intensity

$EP_{i,0}$ = initial energy production

$\alpha_{i,r}$ = resource share

R_i = resource remaining

$\rho_{i,r}$ = resource substitution coefficient

$R_{i,0}$ = initial resource remaining

The coefficient α is chosen such that there is a limit to the rate of energy production, representing the minimum time required to extract the remaining resource.

$$\alpha_{nonrenewable} = (\frac{R_{i,0}}{\tau_r EP_{i,0}})^{\rho_r} \quad (3.15)$$

$$\alpha_{renewable} = (\frac{R_{i,0}}{EP_{i,0}})^{\rho_r} \quad (3.16)$$

τ_r = minimum time to deplete resource

The effective input intensity is depending on the level of technology, capital and variable inputs to production. Thereby it represents the relative effort devoted to resource extraction.

$$EII_i = TE_i(\frac{KE_i}{KE_{i,0}})^{\beta_{i,kv}}(\frac{V_i}{V_{i,0}})^{(1-\beta_{i,kv})} \quad (3.17)$$

TE = energy technology

V_i = variable input (goods)

KE_i = capital

$V_{i,0}$ = initial variable input

$KE_{i,0}$ = initial capital

$\beta_{i,kv}$ = capital share

Since the elasticity of substitution between the resources and other inputs is less than 1, energy production has an upper limit as variable costs approach infinity. Since infinite variable costs are unrealistic, the variable inputs are constrained by limiting the maximum production rate, determined by a maximum practical rate of input (for example solar power per year, in case of solar energy).

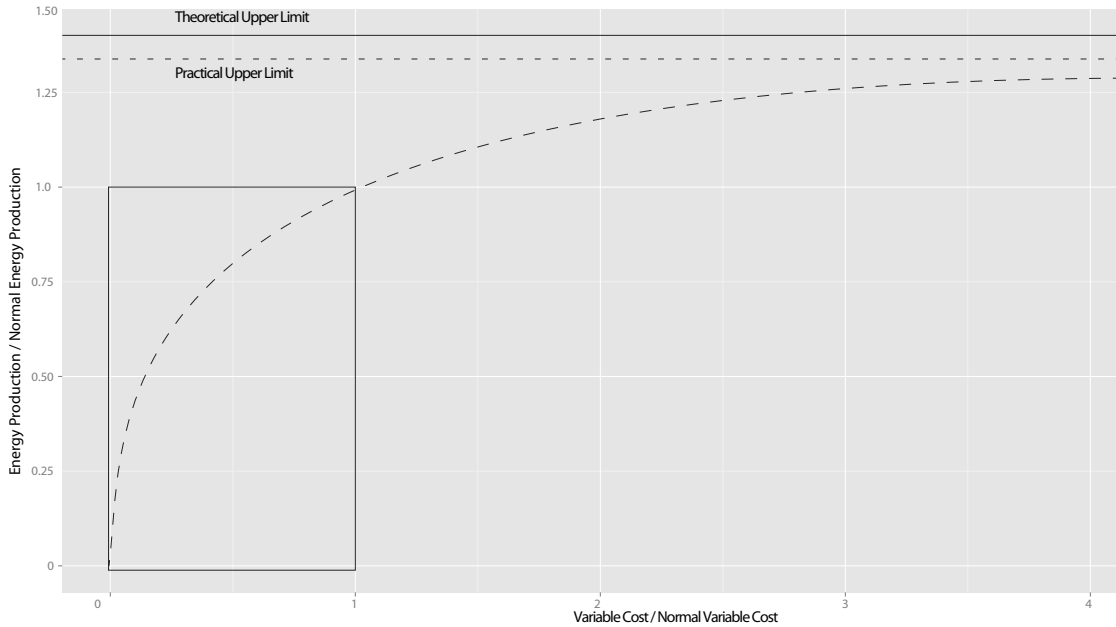


Figure 3.13 – Schematic overview of the energy production limits

Depletion As equation 3.14 implies, there is a limit to the production from depletion and saturation. Depletion represents the diminishing productivity of non-renewable energy production as the resource remaining declines. The opportunity cost of resource depletion is treated as an externality, so the resource depletion path will be suboptimal unless resource owners intervene to restore efficient by imposing a depletion tax, for example [Fiddaman, 1997]. The saturation effect represents the increasing marginal cost of supply for both renewable and nonrenewable energy production as the intensity of effort directed at extracting a fixed resource endowment increases.

As could be expected, if the fraction of the initial resource endowment remaining declines to zero, the production also declines to zero. Adversely, there cannot be energy production if there is no resource available. For a given input of capital, technology and energy input, the energy production declines if there are effects of saturation. This effect is expressed in figure 3.12 as B1. The depletion multiplier as function of the fraction of initial resources is provided in figure 3.14

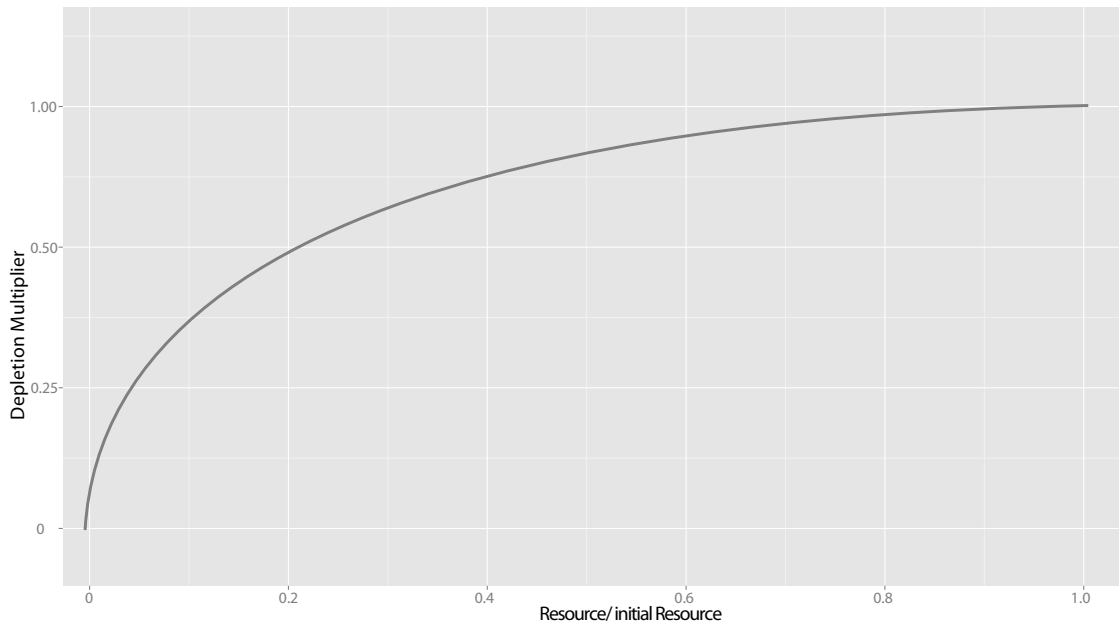


Figure 3.14 – Schematic overview of the depletion multiplier

3.5.4 Emissions

The emissions of greenhouse gases in the model are modelled endogenously. Based on the sources of energy which are consumed by the sectors, the emissions are modelled. Every energy source has its own greenhouse gas content. The product of the source specific energy content and energy consumption result in the energy related carbon emissions. The aggregate of the energy related greenhouse gas emissions form the total energy greenhouse gas emissions. These emissions are combined with the non energy related greenhouse gas emissions in the Total Greenhouse Gas emissions. In order to create a model that is reliable and can be validated using available data, AVEM use carbon dioxide as the only greenhouse gas in the system. The structure of the emissions is illustrated in figure 3.15.

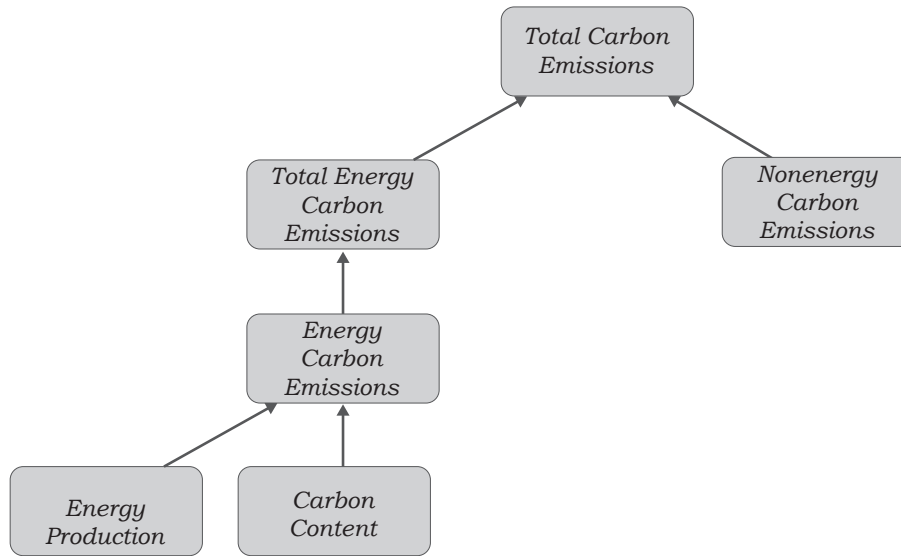


Figure 3.15 – Schematic overview of the emissions system

3.5.5 Carbon Cycle

The carbon cycle is an important system in AVEM. In the carbon cycle, the transport of carbon dioxide is calculated. The climate system can be very sensitive to concentrations of carbon dioxide. Therefore it is essential to know where the carbon content, as a resultant of emissions and forcings, accumulated. Based on principles of Oeschger, the carbon cycle of AVEM is constructed. The carbon cycle is a simplification of the more complex climate systems in FREE or ICAM, however it contains the effect of oceans, which will function as a sink to carbon dioxide.

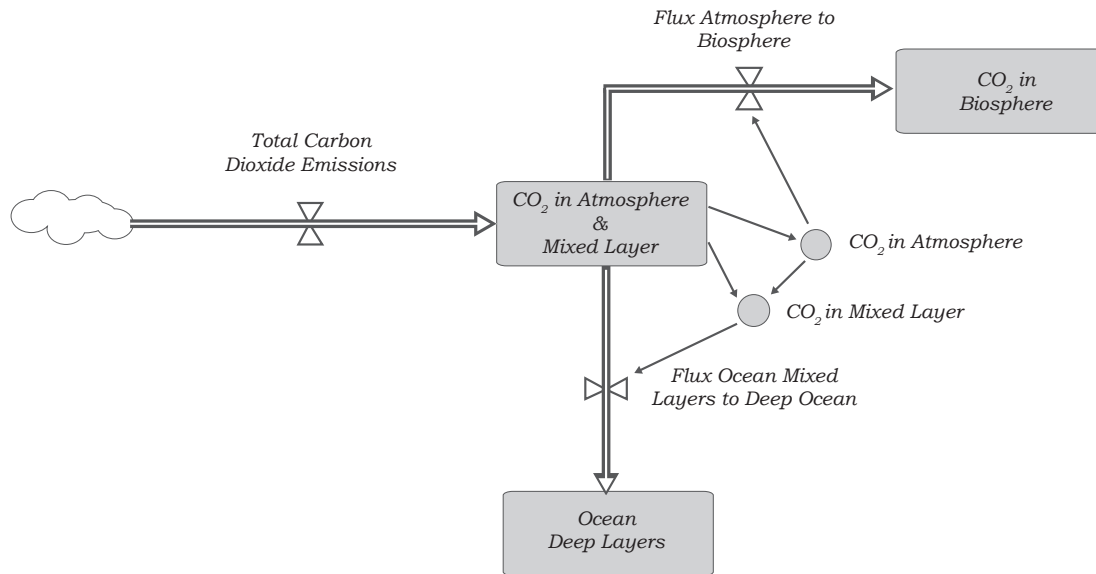


Figure 3.16 – Schematic overview of the carbon cycle [Oeschger and Siegenthaler, 1994]

Figure 3.16 illustrates the schematic representation of the carbon cycle designed for AVEM. The carbon dioxide emissions are fed to the combined atmospheric and mixed layer of the climate system. The total amount of carbon dioxide emissions emitted by the system is expressed as the Net Primary Production (NPP), see 3.18. The amount of carbon dioxide in the atmosphere is dependent on the capacity of the atmosphere and is expressed by equation 3.19. The equilibrium of carbon content in the atmosphere is strongly dependent on the buffer ratio. Since the mixed layer carbon content and atmospheric carbon content are accumulated in the stock variable, the carbon content of the mixed layer is the resultant of the carbon content in the combined layer minus the carbon content in the atmosphere.

$$NPP = NPP_0 + C_{total} \quad (3.18)$$

NPP = net primary production

C_{total} = total CO_2 emitted

NPP_0 = net reference primary production

$$C_a = \frac{C_{am} - C_{m,0} * (1 - \frac{1}{\zeta})}{(1 + \frac{C_{a,0}}{\zeta})} \quad (3.19)$$

C_a = CO_2 in atmosphere

C_{am} = CO_2 in atmosphere and mixed layer

$C_{m,0}$ = reference CO_2 s in mixed layer

$C_{a,0}$ = reference CO_2 in atmosphere

ζ = buffer coefficient

The atmosphere is not only transporting carbon dioxide to the mixed layer, it also feeds the biosphere with carbon content. The biosphere itself is able to decompose the carbon dioxides and use them to produce new biomass. The biosphere residence time is expressing the amount of time required to decompose carbon dioxides. When no carbon dioxides are transported to the biosphere, the biosphere will eventually run out of stock. The transport of carbon dioxide from the atmosphere to the biosphere is expressed by equation 3.20

$$C_b = NPP_0 \left(\frac{C_a}{C_{a,0}} \right)^{\beta_b} - \frac{C_b}{\tau_b} \quad (3.20)$$

NPP = net primary production

C_a = CO_2 in atmosphere

NPP_0 = net reference primary production

$C_{a,0}$ = reference CO_2 in atmosphere

β_b = biostimulation coefficient

C_b = CO_2 in biosphere

τ_b = biosphere residence time

$$C_b(t) = \int NPP(t) - \frac{C_b(t)}{b} dt \quad (3.21)$$

C_b = carbon in biomass

τ_b = biomass residence time

As the concentration of carbon dioxide in the atmosphere is increasing, the transport of carbon dioxides to other components in the climate system will intensity. If the concentration of CO_2 in the atmosphere increases, the amount of CO_2 in the oceans increases as well. However, the time required to set equilibrium will be dependent on the buffer factor. The larger the buffer factor will be, the longer this process will take. The buffer factor, also referred to as Revelle factor, is dependent on the atmospheric concentration of CO_2 itself as well. This will implement that the ocean's capacity to absorb CO_2 diminishes as the atmospheric concentrations rise. The buffer factor is defined as in equation 3.22.

$$\zeta = \zeta_0 + \delta_b \ln \left(\frac{C_a}{C_{a,0}} \right) \quad (3.22)$$

ζ_0 = reference buffer factor

δ_b = buffer CO_2 coefficient

Is saturated situations, the ocean's deep layers absorb the CO_2 from the mixed layer and gradually feed the lower positioned layers, which will function as a "sink" and are modelled as a stock variable. Figure 3.17 provides an insight in the layers of the deep ocean stock variable.

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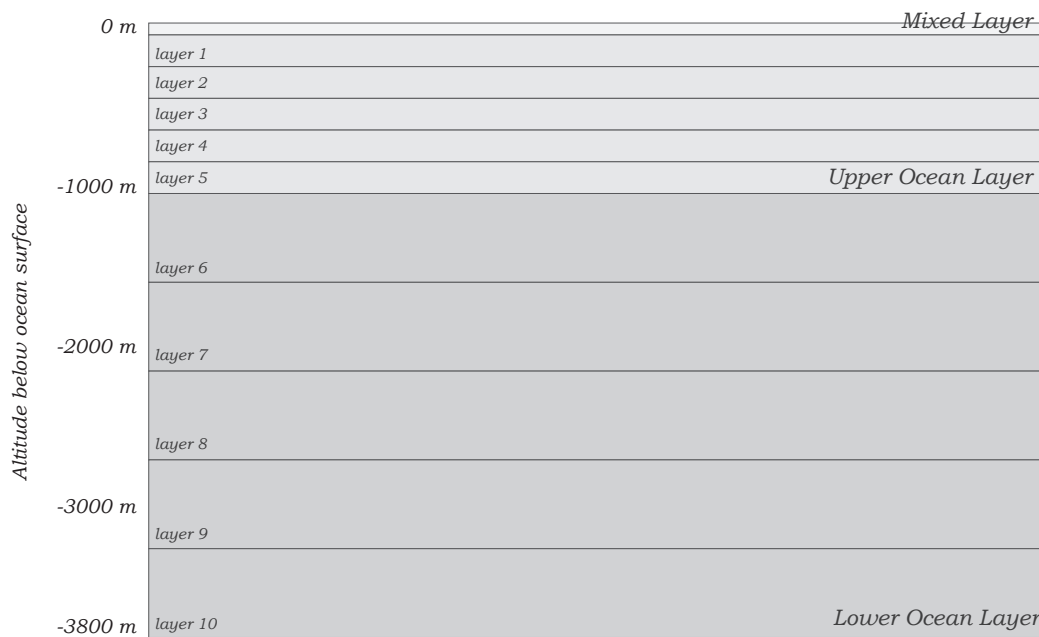


Figure 3.17 – Schematic overview of the layers in the deep ocean stock variable

Within this model, the transport of carbon among ocean layers operates linearly. The flux of carbon between two layers of identical thickness is expressed by:

$$F_{m,n} = \frac{(C_m - C_n)e}{d^2} \quad (3.23)$$

$F_{m,n}$ = carbon flux from layer m to layer n e = eddy diffusion coefficient
 C_k = carbon in layer k d = depth of layer

The depth of the ocean layers is illustrated in figure 3.17 and varies between 75 meters and 560 meters. The basis for the ocean model can be found in Siegenthaler and Oeschger [Oeschger and Siegenthaler, 1994, Goudriaan and Ketner, 1984]. Due to the thickness of particular layers, the time constants, which can be expressed as e/d^2 vary. Table 3.6 indicates the calculated time constants for different ocean layers. These value indicate how many years are required for the carbon from layer n to be absorbed by layer m .

Table 3.6 – Ocean's time constant as function of layer thickness

Layer Thickness	Time Constant
75 meters	1.4 years
200 meters	10 years
560 meters	78.4 years

Commonly, ocean models are compared by their retention of CO_2 by a double emission impulse in the atmosphere. Figure 3.18 illustrates the behaviour of AVEM com-

pared to other models. Since the data for these models was not freely available, the data used to construct the graph is estimated from the figures developed by Fiddaman [Fiddaman, 1997].

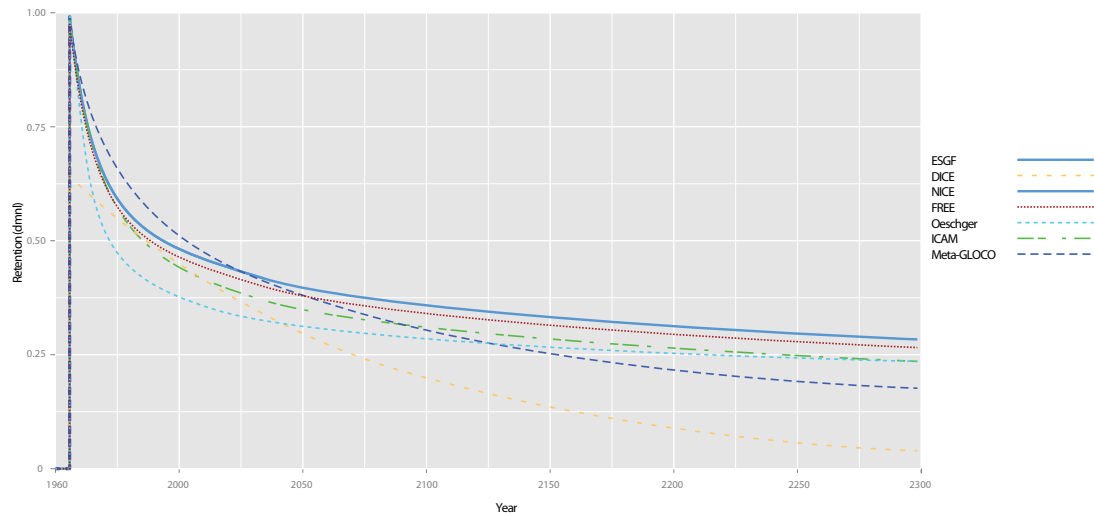


Figure 3.18 – Retention of 2x CO₂ emissions Pulse

Table 3.7 summates all the parameters used in the model. One should notice, the structure as well as the parameter values are obtained from other climate models, which are referred to in the notes section of the table.

Table 3.7 – Carbon Cycle Parameters

Parameter	Alias	Value	Units	Notes
Biomass residence time	τ_b	10.6	year	[Goudriaan and Ketner, 1984, Fiddaman, 1994]
Biostimulation Coefficient	β_b	0.4	dmnl	[Goudriaan and Ketner, 1984]
Buffer CO ₂ coefficient	δ_b	4.05	dmnl	[Goudriaan and Ketner, 1984]
Eddy Diffusion Coefficient	ϵ	4000	meter ² /year	[Oeschger and Siegenthaler, 1994, Fiddaman, 1994]
Initial Net Primary Production	NPP ₀	6e10	TonC/year	[Goudriaan and Ketner, 1984, Fiddaman, 1994]
Mixed Ocean Depth	d_m	75	meter	[Goudriaan and Ketner, 1984, Fiddaman, 1994]
Residence Buffer Factor	ζ_0	10	dmnl	[Goudriaan and Ketner, 1984, Fiddaman, 1997]
Deep Ocean Layer Thickness top 5 layers	d_n	200	meter	[Oeschger and Siegenthaler, 1994]
bottom 5 layers		560	meter	[Fiddaman, 1997]

3.5.6 Climate

One of the main purposes of AVEM is to demonstrate the climate effects of human activities. The model represents the greenhouse gas (/carbon dioxide) emissions disaggregated per sector. The climate system has many indicators to indicate climate change. One of the indicators that are widely used is the atmospheric temperature change and the (deep) ocean temperature change.

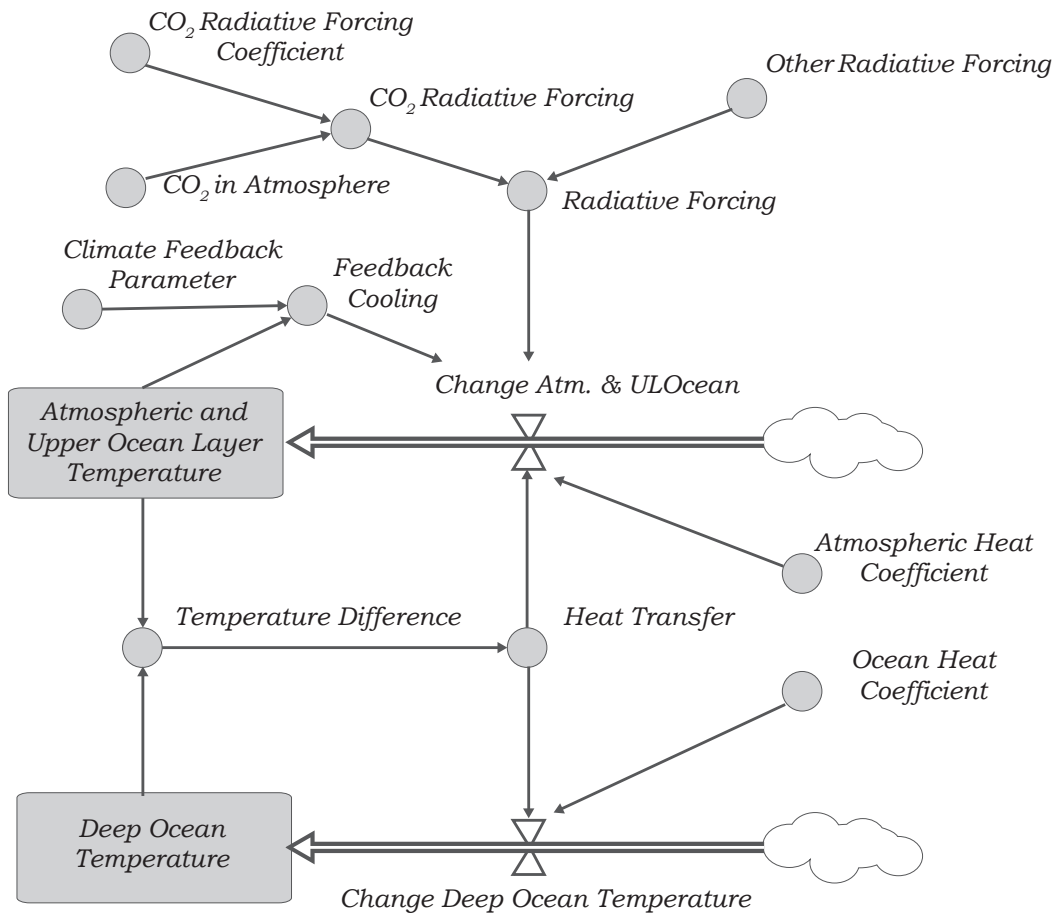


Figure 3.19 – Schematic overview of the climate system

AVEM's climate system is based on the climate system used in DICE. The basic layout of the climate system structure is illustrated in figure B.1. The total amount of CO_2 in the atmosphere is multiplied with the CO_2 radiative forcing coefficient to obtain the radiative forcing induced by CO_2 . The CO_2 induced radiative forcing is combined with the other radiative forcing, induced by other greenhouse gases into the total radiative forcing. The radiative forcing is changing the heat balance of the atmosphere and upper layer of the oceans, as equation 3.24 indicates:

$$\Delta T_{atm} = \frac{(RF - Q_{feedback} - Q_{transfer})}{\kappa_{atm}} \quad (3.24)$$

ΔT_{atm} = Temperature change atmosphere and upper layer

$Q_{feedback}$ = feedback cooling

κ_{atm} = heat capacity atmosphere and upper ocean layer

RF = radiative forcing

$Q_{transfer}$ = heat transfer

The radiative forcing from CO_2 is a logarithmic function of the atmospheric CO_2 concentration. The equilibrium temperature response to a change in radiative forcing is determined by the radiative forcing coefficient, δ , and the climate feedback parameter, λ .

$$T_{equilibrium} = \frac{\delta_{rf} \ln\left(\frac{C_a}{C_{a,0}}\right)}{\lambda \ln(2)} \quad (3.25)$$

$T_{equilibrium}$ = equilibrium temperature δ_{rf} = radiative forcing coefficient
 C_a = atmospheric CO₂ concentration λ = climate feedback parameter
 $C_{a,0}$ = reference atmospheric CO₂ concentration

In order to illustrate the temperature response to a doubling of CO₂ emission impulse, the model shows a response as presented in figure 3.20.

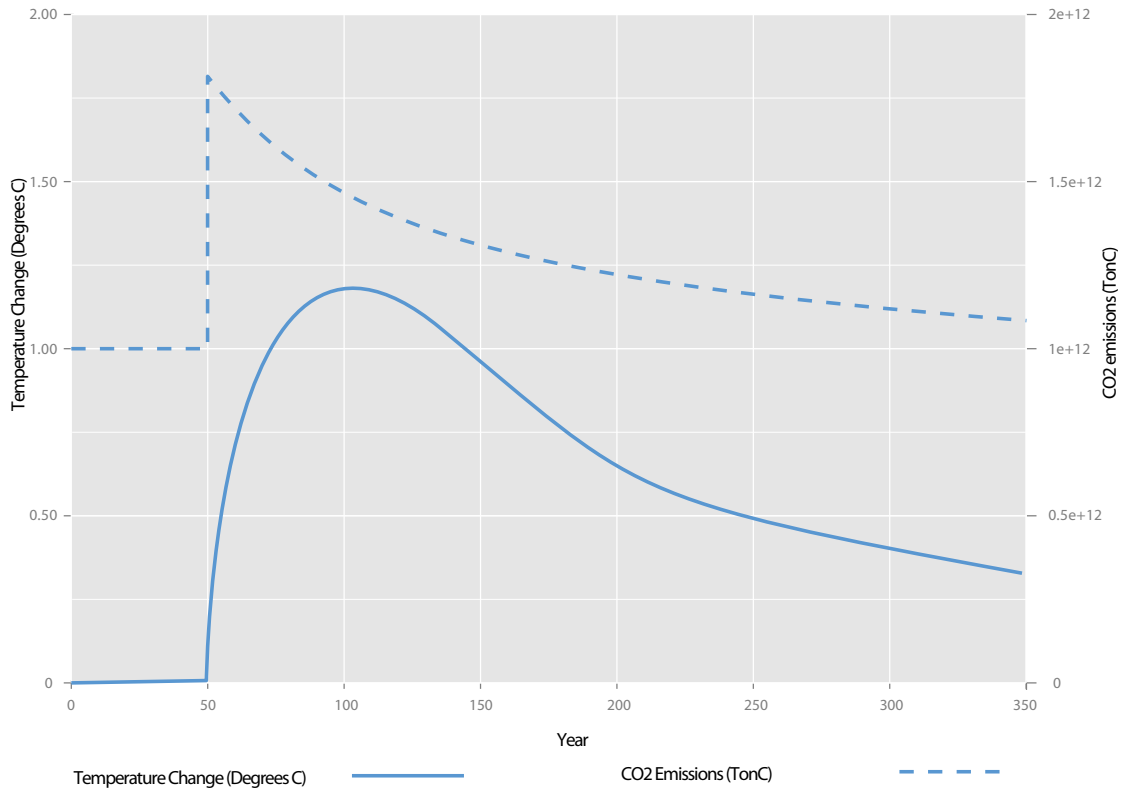


Figure 3.20 – Temperature response as function of a doubling in CO₂ emissons

As could be concluded from appendix B, changes in atmospheric temperature and ocean temperature cause serious problems to flora and fauna. In order to compensate for the effects of climate warming, AVEM introduces a climate damage component. By quantifying the effects caused by climate warming and express them into monetary entities, it is possible to calculate the climate effects and take them into account in the capital system. Nordhaus has developed as method to express the change in temperature as the fraction of economic output that is lost in order to combat climate change. This fraction is expressed by equation 3.26.

$$\mu_{cd} = 1 - \frac{1}{(1 + \kappa_{climatescale} * (\frac{T_{atmos}}{T_{ref}})^{\nu_{nonlinear}})} \quad (3.26)$$

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μ_{cd} = climate damage fraction

T_{atmos} = atmospheric temperature

$\kappa_{climatescale}$ = climate damage scale

T_{ref} = reference atmospheric temperature

$\nu_{nonlinear}$ = climate damage nonlinearity

Higher atmospheric temperature will increase the ratio in the denominator of equation 3.26, thereby reducing the subtracted part, which will increase μ_{cd} , thereby increasing the climate damage cost, which has a negative effect on the effective consumption.

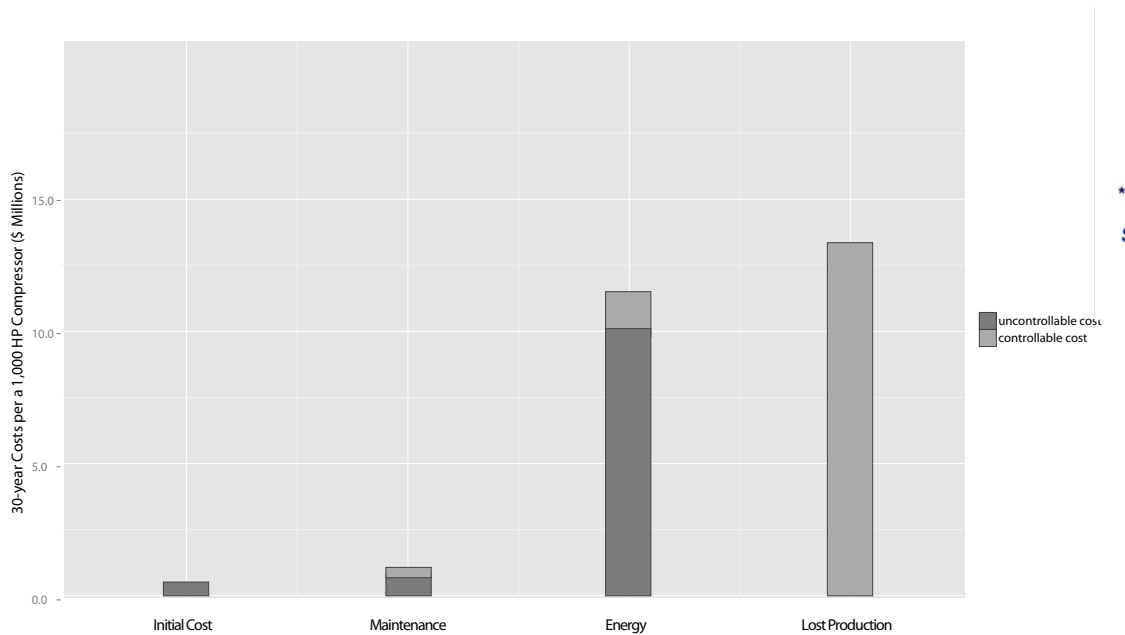


Figure 3.21 – Climate damage fraction as function of time at constant emissions pulses

Figure 3.21 illustrates the effect of emissions on the climate damage fraction. The emissions pulses are constant and do not increase over time. Due to the heat capacity of the atmosphere, the climate damage fraction does not increase rapidly due to the single emissions pulse ($6.7e11$ TonC), while the heat induces by the radiative forcing of a doubling in emissions pulse impacts the heat balance in a way, the atmospheric temperature increases drastically and thereby results in a significant increase in the climate damage fraction. Table 3.8 indicates the climate damage parameters used in the model.

Table 3.8 – Climate Damage Parameters

Parameter	Alias	Value	Units	Notes
Climate damage fraction	μ_{cd}		Dmnl	[Nordhaus, 1993]
Climate damage scale	$\kappa_{climatescale}$	0.013	Dmnl	[Nordhaus, 1993]
Climate damage nonlinearity	$\nu_{nonlinear}$	2	Dmnl	[Nordhaus, 1993]
Reference atmospheric temperature	T_{ref}	3	Degrees C	[Fiddaman, 1994]

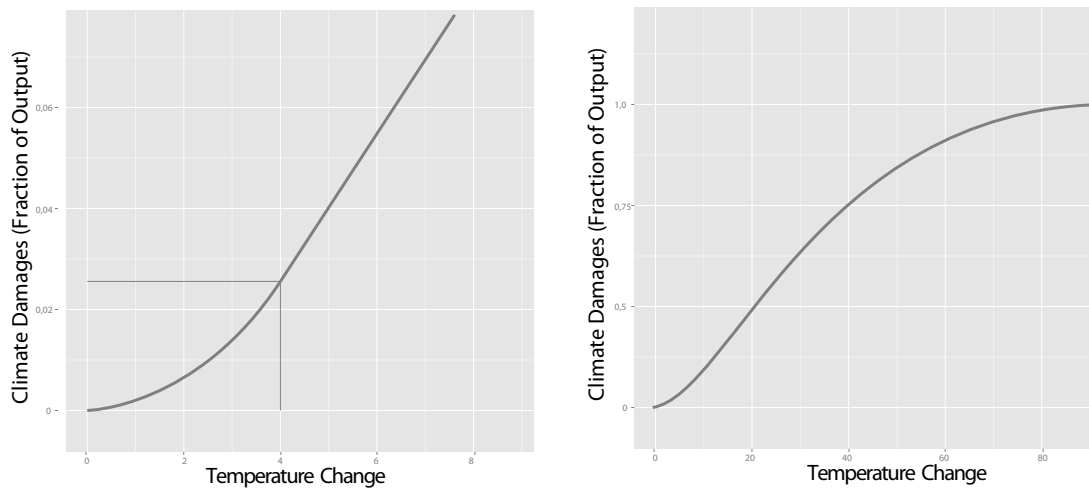


Figure 3.22 – Climate Damage expressed in fraction output relative to temperature change; left: small changes and quadratic behaviour, right: asymptote factor 1 at high temperature changes

Due to the fact radiative forcing is logarithmic, damages are quadratic, the equilibrium damage response to a given concentration of CO_2 is relatively linear [Fiddaman, 1997].

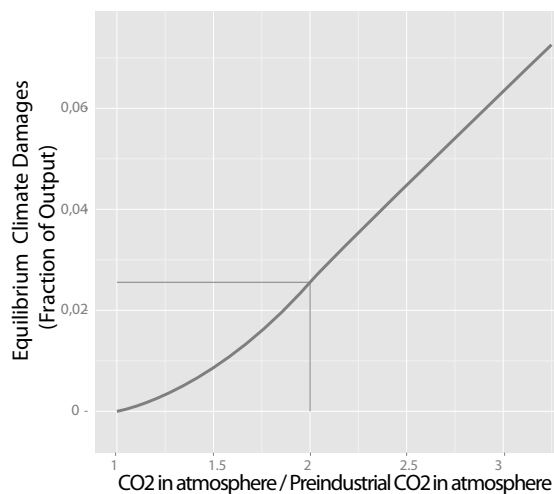


Figure 3.23 – Equilibrium Climate Damage expressed in fraction output relative to change in ratio of current and preindustrial CO_2 concentrations in the atmosphere

3.6 Transport Model

By definition transportation services are market inputs that combine with the traveler’s time to produce a trip to a certain destination. An air trip (Z_a), for example, is a combination of the air-carriers services (X_a) and elapsed time (T_a).

$$Z_a = f(X_a, T_a) \tag{3.29}$$

The same yields for other transport modes (X_b).

$$Z_b = f(X_b, T_b) \quad (3.30)$$

The model is based on two transport modes to keep the focus on aviation, which is weighed for relevant transport services to the other transport mode. The demand for air transport is based on the demand for various transportation services (X_a and X_b) and is derived from the demand depending on the demand for air and other modal transport trips. The basis of the model is based on the principle that a trip can be related directly to an utility that yields to a contribution to the production of a third activity. If the utility required to make the trip is not compensated by the production of the third activity, the trip should not be made. The utility for the trip can be expressed by formula 3.31.

$$Z_i = f(X_i, T_i, Z_a, Z_b) \quad (3.31)$$

In this expression X_i is the other market input for the production of the visit and T_i is the time input involved, which could be considered to be the length of the stay.

The demand for a visit reflects the marginal utility and the marginal productivity of the visit. The combination is expressing the attractiveness of the point of destination. For example, point of destination C can result in an increase of utility (i.o.w. production), while the trip itself is 1/10th of the utility of the production, it can be considered to be more attractive than a point of destination that requires a trip that is of equal level of utility. The marginal utility of the last trip is 0.

The demand elasticity for a factor of production is directly related to the demand elasticity of the product, the elasticity of substitution in production between the factor and other inputs, and the share of the factor in the total cost. Therefore, the demand elasticity of a trip depends, aside from the demand of visits, on the elasticity of substitution between trips and other inputs used in the production of the visit, and the share of the trip in the visit's costs. The optimal allocation of inputs in the production of a visit calls for

$$\frac{\partial Z_v / \partial Z_i}{\partial Z_v / \partial X_v} = \frac{x_v}{z_i} = \frac{\Pi_i - (u_i / \lambda)}{P_v} = \frac{\Pi'_i}{P_v} \quad (3.32)$$

$$\frac{\partial Z_v / \partial Z_i}{\partial Z_v / \partial T_v} = \frac{t_v}{z_i} = \frac{\Pi_i - (u_i / \lambda)}{K_v} = \frac{\Pi'_i}{K_v} \quad (3.33)$$

where $z_i = \frac{\partial Z_i}{\partial Z_v}$ is the marginal input of the trip in the production of a visit, t_v and x_v are the marginal inputs of other time and market goods, respectively, P_v is the price of the other market goods and Π'_i is the trip's total price. The trip price is based on the time and money inputs to produce the trip minus the money equivalent of the marginal utility that is derived from the trip.

The demand for a trip on modal level is depending on the alternatives combined with the urgency to make a trip. Hereby the elasticity of substitution is a rather important parameter. In the optimal condition the marginal rate of technical substitution between

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trips by various modes is equal to their relative prices. This can be expressed by

$$\frac{\partial Z_v / \partial Z_a}{\partial Z_v / \partial X_b} = \frac{z_b}{z_a} = \frac{\Pi'_a}{\Pi'_b} = \frac{P_a X_a + K_{ta} - (u_a / \lambda)}{P_b X_b + K_{tb} - (u_b / \lambda)} \quad (3.34)$$

As the price of the trip is dependent on the equivalent money inputs of the marginal utility of the trip, the selection of the transport mode is dependent on the travellers income and the distance of the trip. The money equivalent of the marginal utility differential equals the difference in marginal money outlays per trip. A change in income will change the marginal utility of income (λ), thereby affecting the slope of the price line and the modal choice.

$$\frac{\Pi'_a}{\Pi'_b} = 1 \Rightarrow u_a - u_b = \lambda(P - a x_a - P_b x_b) \quad (3.35)$$

Based on the money and time inputs required for a trip, one can make the selection based on the ratio of the marginal products of time and money in the production of the trip. Which is expressed by K . Figure 3.24 illustrates a set of transport modes combined with their specific marginal product to a trip. The traveler, aiming at minimisation of costs, chooses mode i if

$$\frac{P_i - P_{i+1}}{T_{i+1} - T_i} = K_{i,i+1}^* < K < K_{i-1,i}^* = \frac{P_{i-1} - P_i}{T_1 - T_{i-1}}$$

Meaning the traveler prefers mode A to B if

$$K > \frac{P_A - P_B}{T_B - T_A} = K_{A-B}^* \quad (3.37)$$

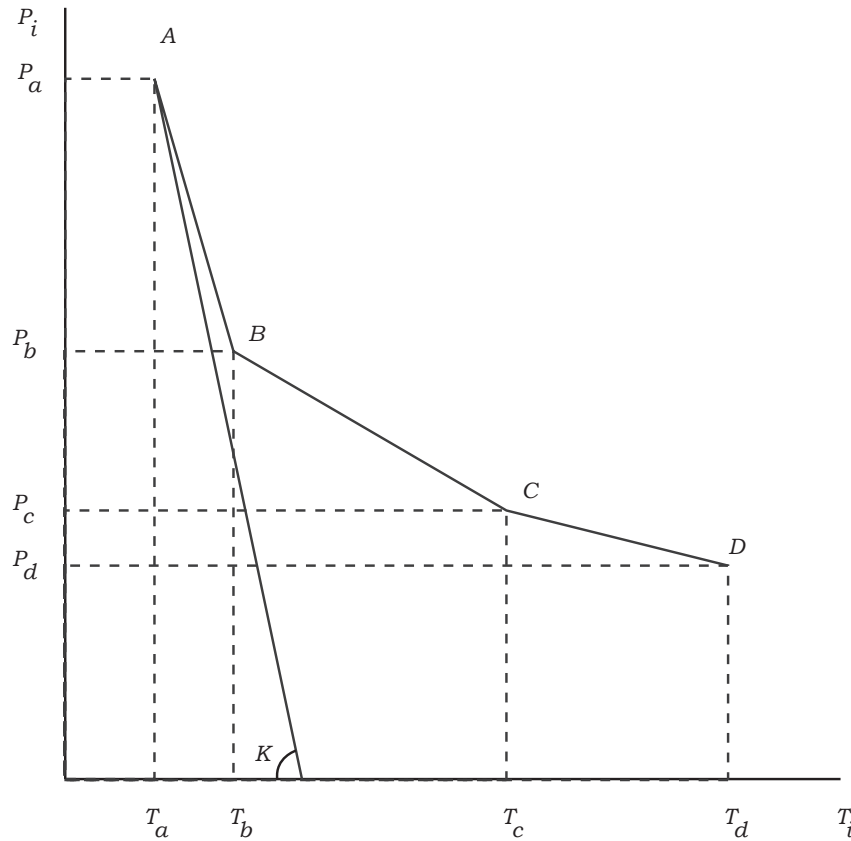


Figure 3.24 – Isoquant of transport modes based combined with the technical substitution ratio

Based on the above expression a couple of remarks can be made. When the price of the faster mode will decrease, travelers will have the tendency to switch from the slower mode to the faster mode. On the other hand, when the price of time increases with income, one would expect that the choice for the faster mode will increase. Households are not expected to be able to substitute their free time for equivalent money, while business travellers can. Therefore the price of time is higher for business trips than for personal trips. The isoquant illustrated in figure 3.24 can be explained based on an example. The traveler's tendency to switch from mode a to mode b is stronger if the marginal rate of technical substitution K^* is smaller. This is the situation in case the slope in the isoquant is smaller. The slope of the isoquant is based on the time intensities of various modes, these intensities change with the distance of the trip.

The production of a trip is always dependent on a time component and a cost component. The relationship between time and costs and the distance of a trip (M) can be approximated by a linear function

$$T_i = \alpha_{0i} + \alpha_{1i}M \quad (3.38)$$

$$P_i = \beta_{0i} + \beta_{1i}M \quad (3.39)$$

$$\Pi_i = (\alpha_{0i}K + \beta_{0i}) + (\alpha_{1i}K + \beta_{1i})M \quad (3.40)$$

Where α_{0i} and α_{1i} stand for the initial time required to travel with mode i and the variable time component relative to the velocity of the mode, respectively. β_{0i} and β_{1i} represent the initial equivalent cost and variable cost, respectively. Move A is preferred above mode B in the situation that the price of time is larger than the marginal differences.

$$K > \frac{(\beta_{0A} - \beta_{0B}) + (\beta_{1A} - \beta_{1B})M}{(\alpha_{0A} - \alpha_{0B}) + (\alpha_{1A} - \alpha_{1B})M} = K^* \quad (3.41)$$

Equivalently, no traveller will use mode A if $T_A > T_B$ and $P_B > P_A$.

$$M < \frac{\alpha_{0A} - \alpha_{0B}}{\alpha_{1B} - \alpha_{1A}} \quad (3.42)$$

The marginal rate of technical substitution K^* is inversely related to the distance of the trip when an increase in the distance increases the time differential ($T_B - T_A$) at a faster rate than the increase in money differential ($P_A - P_B$). In order to use the faster mode A , the trip distance should be at least the minimal distance (M^*)

$$M > \frac{(\beta_{0A} - \beta_{0B}) + (\alpha_{0A} - \alpha_{0B})K}{(\beta_{1A} - \beta_{1B}) + (\alpha_{1A} - \alpha_{1B})K} = M^* \quad (3.43)$$

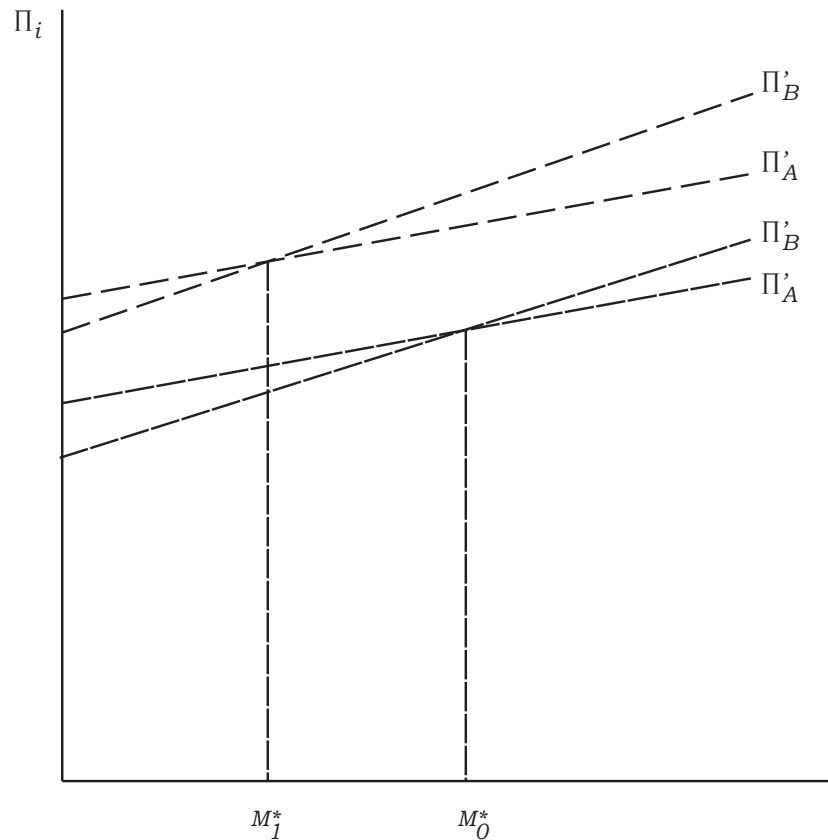


Figure 3.25 – Illustration of switching distances

An increase in income will increase the demand for trips and visits. On the other hand it also increases the price of time and thereby the price of the trips. An increase in income from Y_0 to Y_1 shifts the demand for "trips to point i" from D_0 to D_1 . However, the accompanied change in the price of time raises the price of the trip from Π_0 to Π_1 and shifts the income-consumption curve from C_0 to C_1 . The net income effect X_0X_2 is the difference between the income effect X_0X_1 and the price effect X_1X_2 . The net income effect is directly related to the income elasticity of trips, and inversely related to the trips's price elasticity, the elasticity of the price of time with respect to the income and the time intensity of the mode used [Seyoum, 1976]. Hereby can be concluded that the tendency of passengers to use faster modes increases with its income.

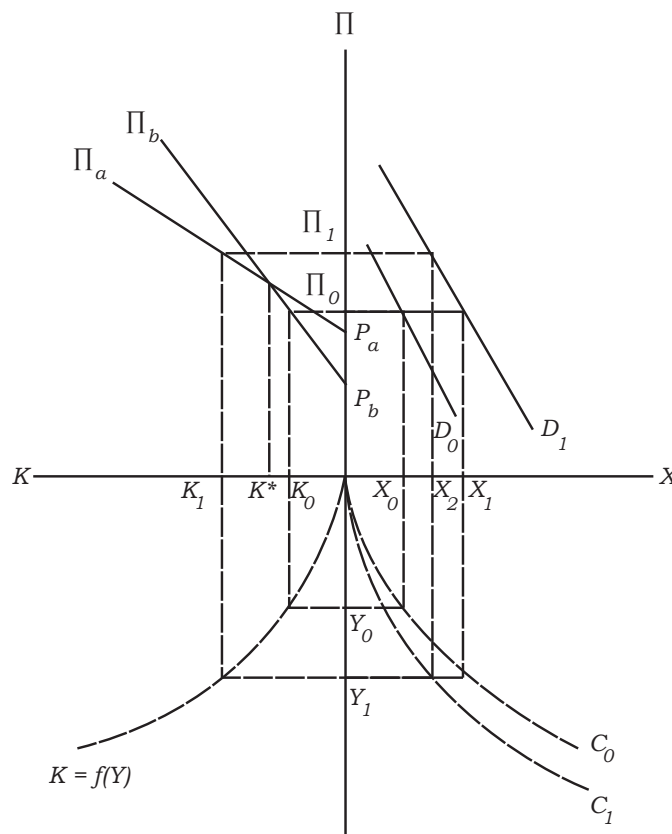


Figure 3.26 – Income effects on transport services demand [Seyoum, 1976]

3.7 Air Transport Model

As explained in section 3.4, the air transport model is closely related to the transport model. The Transport Model uses socio-economic data to simulate the demand for transportation services. In this work only two transport modes are considered, air transport and "alternative" transport. "Alternative" transport is considered to be all the transport modes together, except for air transport. The based on the cost price of air transport and the time required to travel by air, the Transport Model simulates the demand for air transport by calculating its market share.

In order to be able to calculate these two drivers for transport demand, the Air Transport Model, from this moment on referred to as ATM, tries to match the demand for air transport based on its operations. The ATM is constructed based on background information on the air transport industry and uses aircraft specific data as well as generalised airport/runway data to calculate its capacity to provide air transport services.

As a result of the demand for air transport services and its available capacity, the model simulates flight in order to fulfil the demand for air transportation. Operating aircraft on flights result in consumption of energy, allocation of labor, capital and emissions. The ATM combines aircraft specific fuel consumption in order to calculate the consumption of energy, based on the amount of kilometers flown, uses the IAM investment rate to

calculate the costs of capital to order new aircraft and corrects labor costs based on the status of the economy. These are all examples of the way the ATM interacts with the IAM, whether or not using the Transport Model, as illustrated in figure 3.1.

The ATM consists out of three parts, one part is used to calculate the capacity of the global airline industry to provide air transport, while the other part is used to calculate the associated costs to operate the required amount of flights, while the third part is used to evaluate the performance of multiple aircraft for the simulated scenario using a Value Operations Methodology. Figure 3.27 illustrates the structure of the ATM model.

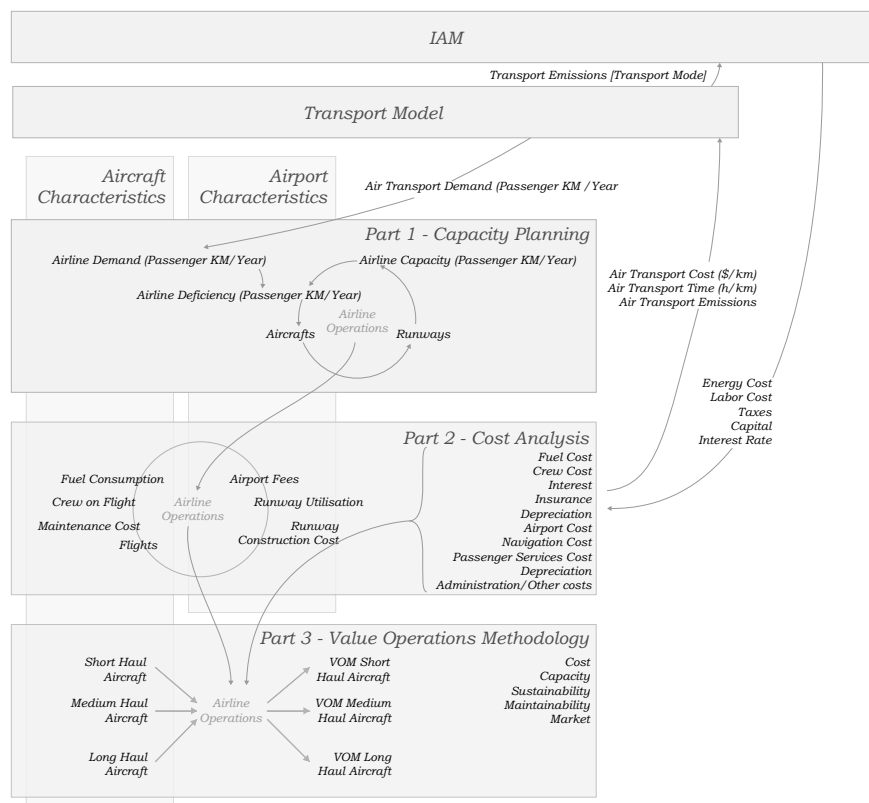


Figure 3.27 – Structural overview of ATM model and its relation to Transport Model and IAM

The ATM is coded object oriented, which enables one to review the performance of three different type of aircraft for the same scenario. In this work the three type of aircraft considered are the Boeing 737-800 (short-haul), Boeing 777-200 (medium haul) and the Airbus A380-800 (long haul). Every structure in the model is therefor modeled along the aircraft characteristics of these three aircraft types. Since the aircraft characteristics influence the airline operations, as will be described in the next sections, this will also impact the capacity planning of the airline (part 1), which in its turn impacts the associated cost of operations (part 2). Eventually the operations are then evaluated in the Value Operations Methodology (part 3).

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3.7.1 Airline Operations

As figure 3.27 illustrates, airline operations are of major importance in the ATM. This work focuses on a global airline which provides all the air transport services required. In order to be able to simulate the air transport movements in this model, there have to be made several assumptions, as listed in table 3.9

Table 3.9 – Assumptions made in the ATM

Airline	Aircraft	Airport/Runway
Global Airline	One type of aircraft operated	One type of runway
No geographical distribution of demand	No effect of stage length on fuel consumption	Lifetime of runway 30 years
No subsidies	Lifetime 30 years	Construction cost 1B\$
Labor cost are inflation corrected	Production time 3 years	Construction time 6 year
No strikes	Financing by IAM capital system	Maximum amount of daily operational hours: 18
Availability of skilled personel	Use of Carbon Based Fuel (kerosine)	Capable of handling all a/c types
Administration cost: 6% of total	Non-carbon emissions related to amount of carbon emissions	

An airline is relying on an extended set of factors that determine the succes of the airline. This section will focus on the simplified operational procedures that the airline follows to perform flights and transport people.

First of all, an aircraft fleet need to be available to the airline. Every aircraft should be operated with pilots, crew and other staff. Depending on the stage length (provided by the Transport Model in the form of a distribution), the airline is able to operate a particular amount of flights per aircraft per year. Depending on the aircraft specific fuel consumption, the airline has to take fuel cost into account. For every flight, the airline has to pay airport handling fees and navigation cost.

Every aircraft owned by the airline (or leased) should be on the airline's balance. Based on interest rates and depreciation rates of the IAM, the airline financial performance can vary over time. The cost of the runways are taken into account to the airport cost. More runways mean higher airport cost.

The ATM models all the cost associated to providing air transport services together in the airline cost. These cost consists out of the following parts:

- Fuel Cost
- Crew Cost
- Interest
- Depreciation
- Airport Cost

- Navigation Cost

- Administration Cost

- Other Cost

Based on the fleet size and amount of runways available, the model calculates the maximum capacity of flights per year. The Transport Model drives the demand for air transport services. The airline should be able to provide the amount of air transport services demanded. By adding a control mechanism, which is known as the capacity utilisation rate, the model calculates its capacity utilisation rate. As in real businesses, there is an optimal capacity utilisation rate, which is assumed to be 0.85. If the demand for capacity is higher than the airline could provide, the airline has to order new capacity. The model will automatically calculate whether these orders should consist out of runway orders or aircraft orders, depending on their individual capacity utilisation rates. In situations of under-capacity, the demand will be higher than the supply of services. This causes the model to congest. Depending on the rate of capacity utilisation, the model will add additional time and cost to the air transport services, based on the congestion cost or time penalties. These additions to the air transport cost and time expenditures, will change the conditions for the Transport Model to calculate the required transport kilometres for air transport. In other words, congestion is a balancing feedback structure to air transport, making it less attractive in comparison to the "alternative" transport mode. Figure 3.28 illustrates the relation of key airline aspects.

Every flight performed involves costs. On the other hand it also involves energy. More flights implicate more demand for energy sources. Since emissions are related to energy consumption, more conducted flights will produce more (carbon dioxide) emissions. The air transport related emissions are normalised to the global emissions, calculated in the IAM. Based on the relative share of carbon dioxide emission in the model, one can evaluate the air transport impact on the climate. The air transport induced emissions are added to the global emissions, to determine the absolute saturation of carbon dioxide emissions in the atmosphere. Based on this level of saturation, the model calculates the climate impact of carbon dioxide emissions.

Based on the tangible and intangible climate impact, calculated by the IAM, the carbon taxes are adjusted to balance the energy demand by increasing energy prices. This will impact the aviation industry since the fuel cost will increase. Higher fuel cost will cause the airfares to raise. This can have negative effects in the Transport Model.

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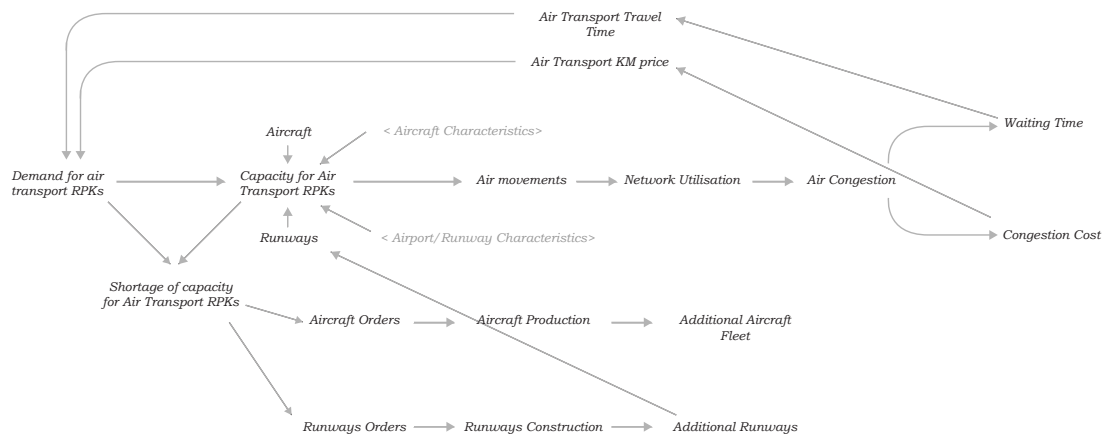


Figure 3.28 – Causality diagram for air transport demand

3.7.2 Capacity Utilisation Rate

The capacity utilisation is the extent to which an airline uses its productive capacity. It is the relationship between actual output that 'is' actually produced with the installed equipment, and the potential output which 'could' be produced with it, if capacity was fully used.

In every business there is an optimal capacity utilisation rate which allows businesses to anticipate on fluctuations in demand, while still being able to overcome the cost of the utilised capacity. Based on the capacity utilisation rate, an airline can make decisions regarding ordering new aircraft or demand for additional runway capacity.

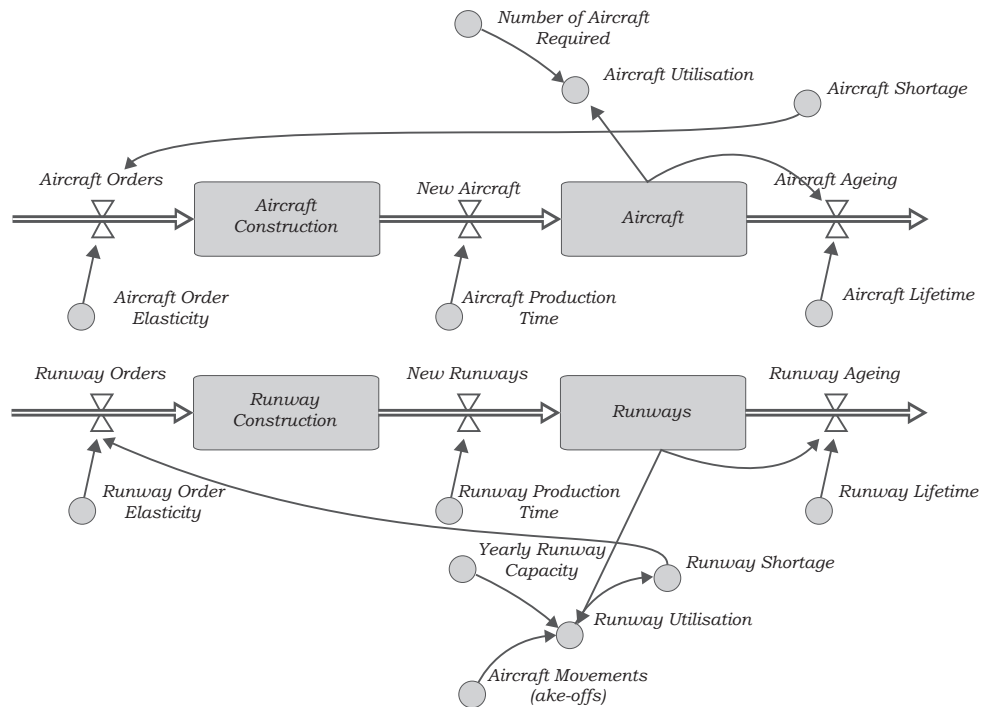


Figure 3.29 – Causality diagram for aircraft and runway capacity corrections

This work uses the Capacity Utilisation Rate to drive orders for new aircraft and runways. Figure 3.29 illustrates the causal loop diagram for the aircraft and runway orders. After an aircraft is ordered, it will be produced. Finally, the produced aircraft could be utilised by the airline and is added to the fleet. Since aircraft do age, aircraft will be discarded from the balance after the aircraft lifetime.

Runways are also subject to ageing. After a couple of decades, after being maintained properly, a runway needs to be replaced as well. Contrarily, the runway could be outdated. New types of aircraft, for example the Airbus A380 require extended runway lengths. Conventional runways from the early 60's are mostly not able to deal with this type of aircraft. This restricts the capacity of runways on global scale. Replacement of this runways could lead to higher capacity.

This work makes the assumption of a desired capacity utilisation rate of 0.85.

3.7.3 Air Transport Cost

The demand for passenger transport kilometers is dependent on the cost of transport and the trip time. If the utility gains are higher than the utility losses, in terms of cost and time expenditures, passengers will travel. As previous section illustrates, pricing is an essential driver for demand. Low prices make the transport mode more attractive compared to other modes. However, situations can occur that show high demand for a transport mode while there is not enough capacity. This implicates that the capacity needs to be

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improved. In the aviation industry this means ordering new aircraft or expanding airports.

In order to be able to calculate the cost price per passenger kilometer for air transport, a cost breakdown is created based on the information that is provided in chapter 1. Air transport costs can be distinguished into multiple types of cost. Combined with data obtained from a cost breakdown by Curran et al. the Indirect Operating Cost (IOC) and Direct Operating Cost (DOC) are provided in table 3.12.

Table 3.10 – *Cost value levers*

Airliner Cost Lever
IOC
Depreciation
Tickets/Sales
Admin/ Other
Staff
DOC
Maintenance
Fuel
Crew
Interest
Insurance
Depreciation
Airport
Navigation
Passenger services

Indirect Operating Cost are cost that are not directly proportional to the amount of kilometers flown with an aircraft. The Direct Operating Cost are directly related to the amount of passenger kilometers flown. In order to see these costs into perspective, figure 3.30 illustrates the relation of the airline costs.

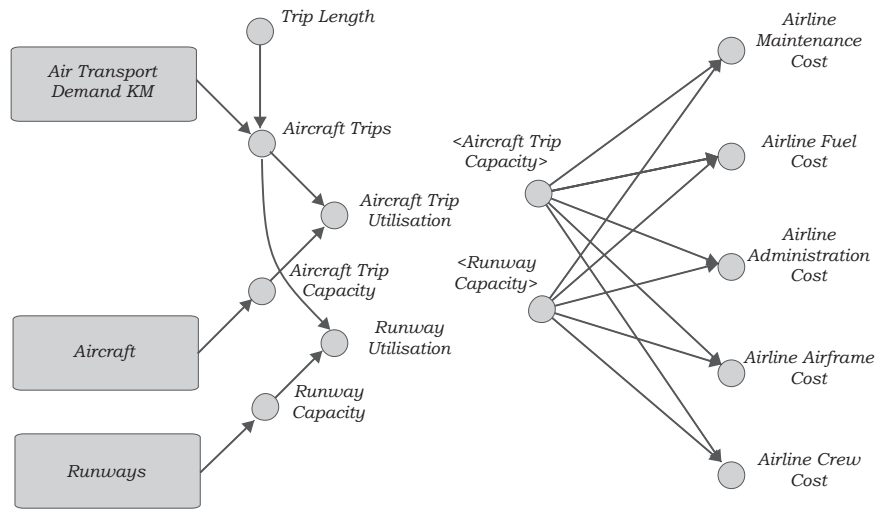


Figure 3.30 – Causality diagram for airline cost and utilisation

In order to support the illustration in figure 3.30, the formulation for the airline costs are provided below.

$$P_{maintenance} = N_i * P_{m_{hours}} * T_{avg} \quad (3.44)$$

where N_i is the number of air transport trips, $P_{m_{hours}}$ the price of maintenance per flight hour and T_{avg} the average flight time per trip.

$$P_{fuel} = N_i * T_{avg} * W_{fuel_{hour}} * E_{jet_{fuel_{kg}}} * P_{energy_{GJ}} \quad (3.45)$$

where P_f is the Airline cost of fuel, $W_{fuel_{hour}}$ the weight of fuel per passenger per hour of flight, $E_{jet_{fuel_{kg}}}$, the energy intensity of a KG of jet fuel and $P_{energy_{GJ}}$ the price of energy per GJ.

$$P_{crew} = N_i * S_{service} * P_{crew_{yearly}} * C_{crew} * T_{avg} \quad (3.46)$$

Where $S_{service}$ is the service level on a flight (business class or economy), $P_{crew_{yearly}}$ the crew salary on a yearly basis, C_{crew} the crew capacity, expressed in number of flight hours per year per person.

$$P_{airframe} = \frac{P_{aircraft}}{T_{lifetime_{ac}}} * N_{fleet} * C_{depreciation}^{relyear} \quad (3.47)$$

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Where $P_{aircraft}$ is the initial aircraft purchase price, $T_{lifetime_{ac}}$ the lifetime of an aircraft and $c_{depreciation}$ the depreciation factor for capital.

$$P_{airline} = P_{maintenance} + P_{fuel} + P_{crew} + P_{airframe} + P_{administration} \quad (3.48)$$

In this work, the cost levers of air transport services, as described above, are related to the system dynamics simulation. Based on the number of flights performed, take-offs and landings, aircraft specific fuel consumption, amount of crew on board and administrative costs, the model calculates the total price per passenger kilometer for every aircraft type, which will be used in the trade-off model of the transport mode selection mechanism.

This chapter describes the development of a Value Operations Methodology (VOM) that is part of the Airline Value Evaluation Model (AVEM). Based on the methodology described in chapter 5, Background on Value Operations Methodology, this chapter will work out the VOM for airlines. The VOM is based on four essential aspects of the aviation industry, cost, sustainability, utilization/capacity and maintainability that form the division of total value to an airliner.

3.8 Value Operations Methodology

The development of a Value Operations Methodology is based on the effort of Curran et al. which in their situation is used to support Value Driven Design (VDD). Despite it is possible to use AVEM for Value Driven Design purposes that are constrained by future socio-economic scenarios, this work will only focus on the performance evaluation of airliners under particular scenarios using VOM. Based on the decisions made by airliners regarding fleet size, aircraft type, trip length, etc, the airliner can be evaluated under different future scenarios.

3.8.1 Value Model Development

Nowadays, the airliner value is not only determined by financial and economic inputs but also by the value for the customer and the value to society. Since these values cannot be compared directly to each other, the model aims to quantify the amount of value added by different aspects and captures the value of an airliner and its operations realisation in terms of value-added. By using this methodology, the chance of missing hidden goals can be diminished. The next sections describe how the conceptual model was set up and which input parameters were identified.

3.8.2 Levers in the VOM Function

The VOM function is partially based on the research conducted by Curran et al. and Doig [Curran et al., 2010, Doig et al., 2003]. The value function for an airliner can be described by four main pillars: Cost, Sustainability, Utilization and Maintainability. Safety should

actually be included in the function, but is excluded from the function. This saves complexity and one can condemn that an aircraft should be 100% safe before it enters the market.

Based on the four pillars, the VOM function is designed. In order to be able to evaluate the performance of airlines over time, the VOM function is converted into an System Dynamic format, thereby making advantage of the benefits of system dynamics modelling, like a graphical user interface, real time monitoring and trend lines. Based on the variables that are used in the model to express the different aspects of the airline industry, the VOM function adopts values that are used in the VOM function as is designed in next sections.

Airliner Value Levers

The most value for an airliner is added when the costs are as low as possible and the revenues as high as possible. This is only possible when the operational availability is high and the market is willing to use the airline services. Lower airliner costs can be used to lower airfares to gain more market share. More sustainable aircraft can be less costly, due to lower taxes on emissions, but can also be beneficial for the reputation of the airliner.

Based on the tradeoff conducted by Curran et al. table 3.11 illustrate the division of total value for an airliner.

Table 3.11 – *Airliner Value Model used in AVEM*

Value in Airliner Design	Percentage
Cost	33%
Sustainability	33%
Utilization	17%
Maintainability	17%

Costs

The cost pillar for airlines can be divided into two categories, Indirect Operating Cost (IOC) and Direct Operating Cost (DOC). A study into general airliner cost models of Boeing, ICAO, Curran and MIT resulted in the 13 items listed in table 3.12

The percentages above indicate how much percent a certain item of the airliner will contribute to the reduction of these costs. These numbers are therefore relative, not absolute [Curran et al., 2010].

Airline Utilisation

Revenue generation is critical for airlines, herein airline utilisation is important. Airline utilisation determines how much time the aircraft is used to generate revenue. In order to operate at high utilisation rates, the number of flights per day needs to be as high as

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Table 3.12 – *Cost value levers and weight factors*

Cost Lever	Weighting Factor (percentage)
IOC	
Depreciation	9,3%
Tickets/Sales	11,1%
Admin/ Other	6,5%
Staff	3,4%
DOC	
Maintenance	9,3%
Fuel	16,0%
Crew	11,8%
Interest	7,2%
Insurance	0,8%
Depreciation	6,9%
Airport	6,0%
Navigation	4,4%
Passenger services	7,3%

possible, the block hours per aircraft should be as high as possible and the turnaround time as low as possible. Curran states that the turnaround time of an aircraft is determined by the number of passengers in the aircraft. Therefore the turnaround is assigned the highest weighting factor, see table 3.13

Table 3.13 – *Utilization Levers used in AVEM [Curran et al., 2010]*

Utilization Levers	Percentage
Daily Hours	20%
Block Hours	20%
Stage Length	20%
Turnaround Time	40%

Airline Maintainability

Maintainability of an airliner relates to all aspects of an airliner that relate to the production and the maintenance of the airliner [Curran et al., 2010]. Based on a study on airliner lifecycle cost, a set of six aspects are determined. Of which one is cost, however this aspect is already used in the cost pillar. For this reason, the cost lever of maintainability is taken out of the list, which could be found in table 3.14

Environmental Quality

Based on a study of Curran et al. the environmental quality of an airliner can be determined using three pillars, flight procedures, aircraft and engine design, and production. According to the study, the production is determined to be of 20% importance in the

Table 3.14 – *Maintenance Levers used in AVEM [Curran et al., 2010]*

Maintenance Levers	Percentage
R&D	13,6%
Production	54,5%
Ground equipment + initial spares	15,9%
Special Construction	11,4%
Disposal	4,6%

model. The production can on its turn be divided into two levers, recyclability and pollution during production. Flight procedures such as taxiing, take-off, cruise and landing contribute for 18,5% to the value of environmental quality. Changes in cruise procedures do have the largest effect on the environmental quality of an airliner. Thereby, during a flight an aircraft is almost 100% in cruise mode.

Aircraft design and engine design are also important levers in the environmental quality value determination. Hereby carbon dioxide is together with noise the most important component. Based on numbers published in the study on determination of weight factors in the environmental quality value lever, table 3.15 indicates the important aspects for the environmental pillar.

Table 3.15 – *Environmental value levers and weight factors*

Environmental Lever	Weighting Factor (percentage)
Flight Procedures	
Taxiing	0,1%
Take-Off	0,5%
Cruise	17,3%
Landing	0,6%
A/C and engine	
CO ₂	20%
Noise	30%
Production	
Recycle	10%
Pollution during production	10%

Passenger Satisfaction

Where the previous pillars of the airliner value could be related to the System Dynamics model, the passenger satisfaction could not. The passenger satisfaction is based on the continent value method, that is based on a market survey.

Based on the numbers presented in the work of Curran et. al., it can be concluded that passengers prefer speed (19%) over onboard service (5%) and the comfort of the aircraft (4%). The stated percentages are scaled to 100% and subdivided further into items.

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The speed component can be divided into boarding options (20%) and boarding/check-in-time (47,5%). The airline services are divided into hand baggage size (2,4%), hand baggage weight (2,4%), baggage size (2,4%), baggage weight (2,4%), on board entertainment (1,0%), catering (2,4%), shopping (2,4%) and seat reservation (2,4%). The comfort of an airliner is determined by the seat pitch (14,3%) [Curran et al., 2010]. Table 3.16 shows the percentages per item.

Table 3.16 – Customer satisfaction value levers and weight factors

Customer satisfaction Lever	Weighting Factor (percentage)
Speed	
Boarding options	20,4%
Boarding/Check-in-time	47,5%
Services	
Hand baggage size	2,4%
Hand baggage weight	2,4%
Baggage size	2,4%
Baggage weight	2,4%
On board entertainment	1,0%
Catering	2,4%
Shopping	2,4%
Seat reservation	2,4%
Comfort	
Seat pitch	14,3%

3.8.3 The VOM function

in the section Methodology in chapter 2.1.1, a hedonic formulation is presented that connects the variation in cost to the variation of characteristics. It is used to define the percentage change in price the stakeholder is willing to pay for an adjustment in the value lever x . This value model is based on Keeney's representation of theorems for quantifying values using utility functions [Keeney, 1992b, Curran et al., 2010]. Based on the principles of Fishburn, the additive utility function only exists when the attributes are additive independent to each consequence x if there exists a corresponding number u indicating the value [Fishburn, 1964]. The proof for this function is provided in Fishburn 1965 [Fishburn, 1964].

$$u(x_1, \dots, x_n) = \sum k_u u_i(x_i) \quad (3.49)$$

The VOM function used in AVEM can be described as:

$$\Delta V = \alpha_c(C_1/C_0) + \alpha_u(U_1/U_0) + \alpha_m(M_1/M_0) + \alpha_e(E_1/E_0) + \alpha_p(P_1/P_0) + \epsilon \quad (3.50)$$

Part III

Evaluation and Application on Air Transport Sector

4 Validation

Air transportation services are offered all around the world and its demand determined by driving forces such as demographic development, socio-economic development and technological change. Their future evolution is highly uncertain. To support airlines to be able to explore future pathways, AVEM is developed in order to simulate how the future might unfold and to evaluate how driving forces may influence airline businesses. Not only aviation industries can be affected by a changing future, other industries can as well. Therefore AVEM includes a submodel that is able to model the development of other industries as well. This submodel focuses on the consumption of energy and associated emissions. Thereby one can see how the aviation industry relates to the other industries with respect to emissions and pollution. Nowadays the air transportation industry is responsible for nearly 2% of the total anthropogenic greenhouse gas emissions, if this share will grow in the future, governments and organisations can put up new measures to limit the emissions induced by air transportation. By relating the aviation industry to other industries, the relative contribution to climate change can be observed and policy measures can be evaluated using AVEM. Therefore it is important to not only simulate air transport industry but take into account all the industries in the world.

In this chapter the development of scenarios is described that will be used to evaluate the performance of airlines within changing socio-economic environment. The scenarios comprise production structures, depletion, endogenous technology, population growth, economic fluctuations and the climate system as described in chapter 3.4.

By 2150 the world will have changed in ways that are difficult to imagine - as difficult as it would have been at mid 19th century to imagine the changes of the 150 years since. Each scenario assumes a distinctively different direction for future developments, such that the three scenarios differ in increasingly irreversible ways. They cover a wide range of key future characteristics such as demographic change, economic development, and technological change. For this reason, their plausibility or feasibility should not be considered solely on the basis of an extrapolation of current economic, technological and social trends.

In the baseline the three scenarios could be described as listed below:

- Scenario A
describes a future world of very rapid economic growth, global population that peaks mid century and declines thereafter, and the rapid introduction of new and more efficient technologies. Scenario A focuses on the development of alternative and new energy sources in the future.
- Scenario B
describes a very moderate growth of population and economy, regional focus and extrapolated use of carbon based energy sources.
- Scenario C

describes diminishing population growth, but growing prosperity, whereby future generations become more wealthy relative to their predecessors. The scenario focuses on environmental protection, using taxes.

Figure 4.1 illustrates in more detail how the scenarios will look like with respect to the subsystems in AVEM.

Table 4.1 – Scenario description

System	Scenario A	Scenario B	Scenario C
Population	Linear growth, asymptotically at 2150	Linear growth, top around 2100	Slow growth, peak at 2100
Factor productivity growth	Always greater than zero, but growth stops slowly	Asymptotically zero, so that economic growth eventually stops	Always greater than zero, but asymptotically towards zero around 2100
Capital Elasticity of Output	Putty-putty, with low moderate capital-energy and high inter-energy substitution elasticities	Putty-clay, with slow behaviour adjustments	Putty-clay, with slow behaviour adjustments
Behavior	Rapid adjustment to optimal factor balances	Moderate adjustment to optimal factor balances	Fast adjustment to optimal factor balances
Energy technology	Learning curve	Static	Learning curve
Taxes	Moderate	Moderate	Progressive, carbon taxes
Energy Sources	Alternative energy sources	Low energy source substitution	High energy source substitution
Globalization	International focus	Regional focus	International focus
Welfare evaluation	Time discounting of social welfare	Intergenerational equity	Intergenerational equity

4.1 Validation of Airline Value Evaluation Model Subsystems

This section will focus on the validation of the IAM systems that are used to simulate future pathways for the air transport industry. As chapter 3 illustrates, the Transport and Air Transport Model are closely related to the systems in the IAM. Therefore the systems within the IAM are validated by using the scenarios picked in previous section.

4.1.1 Population

Over the last five decades the world population has expanded significantly. Based on historic numbers provided by the world data bank, the population growth rate has been around 0.012. In accordance with this data, AVEM uses the pre-2010 growth rate as basis for future population expansion. Literature studies provide information about world population sizes varying from 8 billion people to 11 billion people. By adjusting the population growth rate by the population growth decline rate, the future expansion of demographic size can be controlled. Figure 4.1 illustrates the simulated population sizes for the three scenarios. Table 4.2 indicates the corresponding parameter values.

As one can see in the figure, the scenario B and C have a asymptote around 2100 on respectively 7.8 billion and 8.7 billion people. Scenario A projects an even larger population size. The size of the world population has a large impact on other systems in AVEM. According to figure 3.2, population has a direct impact on the economy and welfare. The energy orders placed by the energy system are driven by population size. As a validation step, the data from the world data bank [Ida,] are used. Since the model is configured based on the data from the world data bank, the first 5 decades in the graph match the evolution of population size closely. Besides of being configured based on the world data bank, population size is considered to be a exogenous variable, so it is not surprising the simulated population growth is matching the historic data.

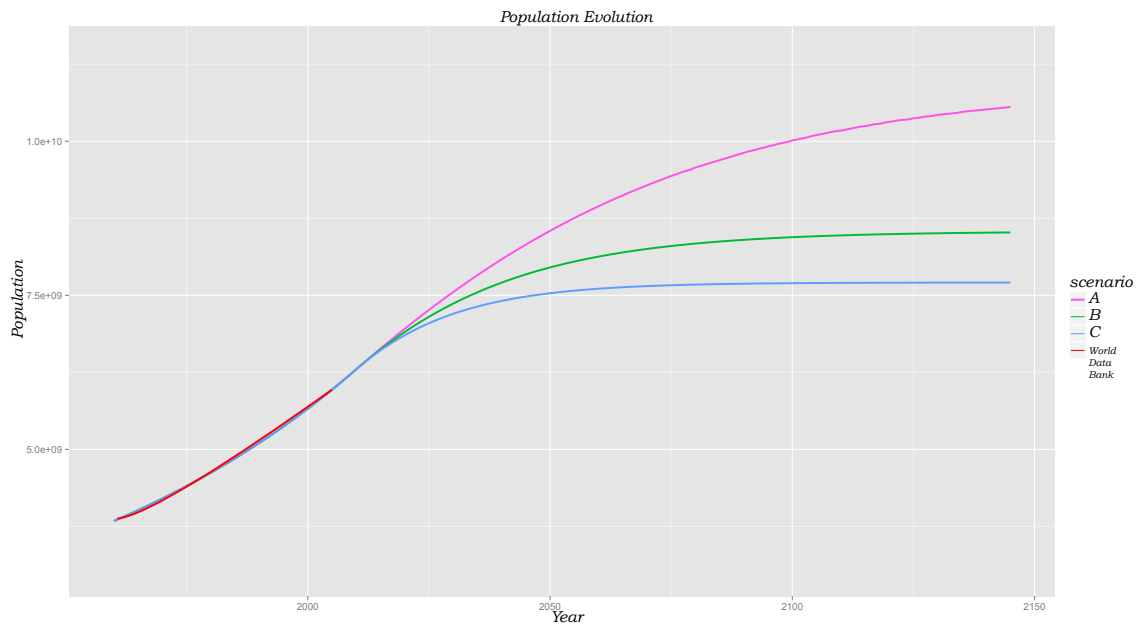


Figure 4.1 – Evolution of population size under different scenarios

4.1.2 Factor Productivity Growth

Factor productivity is a measure that determines the level of economic output and can be interpreted as the level of technology. Factor productivity is used as a factor that relates the capital input and labor input to economic output. High factor productivity causes

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Table 4.2 – Parameter values for future population growth expressed per scenario

Parameter	Scenario A	Scenario B	Scenario C
Population Growth Rate before 2010	0.012	0.012	0.012
Population Growth Rate after 2010	0.012	0.012	0.012
Population Groth Rate Decline Rate	0.015	0.037	0.055

higher levels of economic output at equal levels of capital and labor input. The factor productivity growth rate describes how the factor productivity will be impacted towards the future. Over the last couple of decades, the factor productivity growth rate was 0.0152 [Nordhaus, 1993], while the factor productivity rate decline rate was 0.014. Hereby could be concluded that the factor productivity growth declined over the last decades, implementing the level of technology to slow down. Scenario A describes a rather positive pathway with respect to the factor productivity as the factor productivity growth rate decline rate is somewhat smaller than it was in the last decades [Nordhaus, 1993]. Scenario B and C describe a future that has a slightly higher factor productivity growth rate decline rate, meaning that the level of technology is advancing less progressive. Hereby the behaviour of the factor productivity growth is asymptotical at zero around 2100.

Figure 4.2 illustrates how the factor productivity behaves in different scenarios. Scenario A focuses on high population growth and increasing technology levels, while scenario B is less extreme and focuses on moderate population expansion while the rate of innovation slows down, causing the factor productivity to flatten. Scenario C however, describes a stop for population growth, while the prosperity grows. The level of technology is a bit less optimistic compared to scenario A, so is the factor productivity, which slows down and behaves asymptotically around 2150.

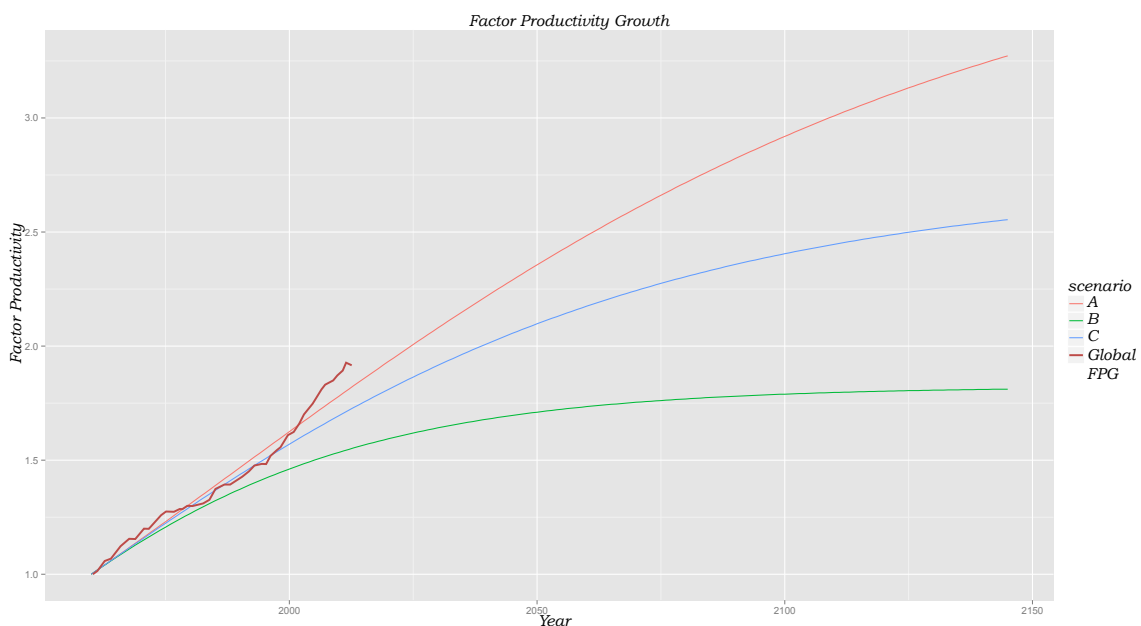


Figure 4.2 – Evolution of population size under different scenarios

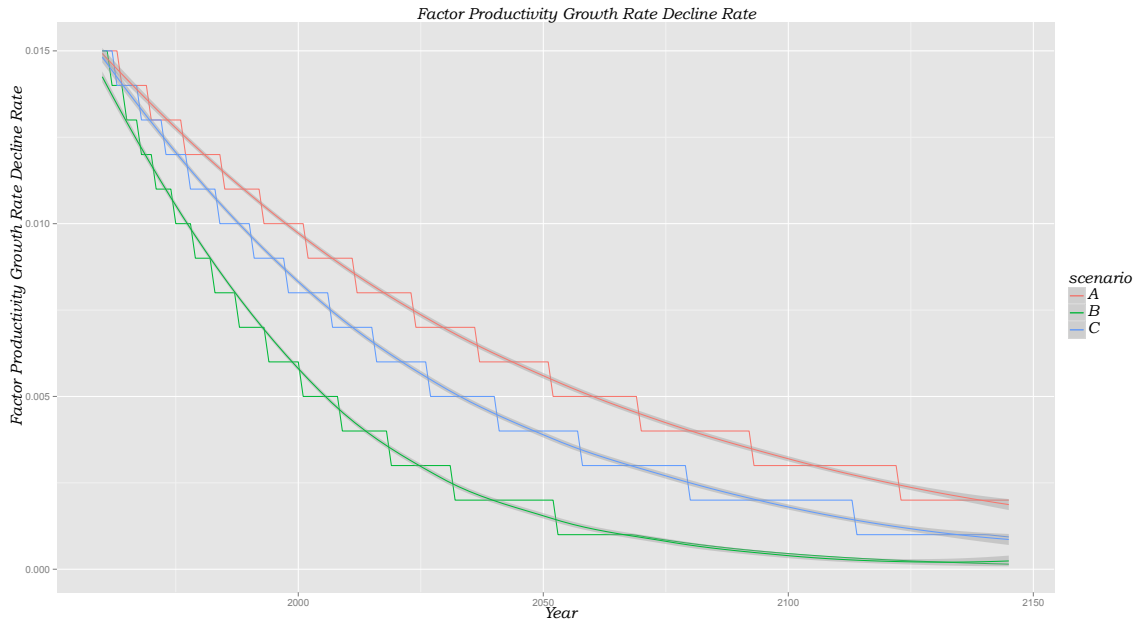


Figure 4.3 – Evolution of factor productivity growth rate decline rate

Table 4.3 – Parameter values for factor productivity growth expressed per scenario

Parameter	Scenario A	Scenario B	Scenario C
Factor Productivity Growth Rate	0.014	0.019	0.023

Output Elasticity of Capital

The economic output produced is determined using a Cobb-Douglas production function. This function states that the total economic output is the product of the factor productivity, labor and capital inputs. Labor and capital are put to the power of the output elasticity of capital, which determines how much the economic output will be affected by 1% increase in capital, while the labor input stays constant. The output elasticity of capital is essential for the production of economic output, which is used for many systems in model. Consumption for example is a product of output, while the energy demand is driven by consumption.

High output elasticity of capital means labor is less effective to produce economic output, while capital is more effective. High output elasticities of capital implicate that capital is more effective to create more capital, increasing the utility of investing more of the effective capital available to people to be able to produce more capital. Conversely this effect cause the consumption to become less attractive, meaning less utility, which is used in the model to express the level of welfare and prosperity. On the long term, the increasing amount of capital available will force the system to increase utility as well, an effect that is illustrated in figure 4.6. Figure 4.4 and figure 4.5 illustrate the effect of changing output elasticity of capital values for scenario A and B/C respectively.

VALIDATION

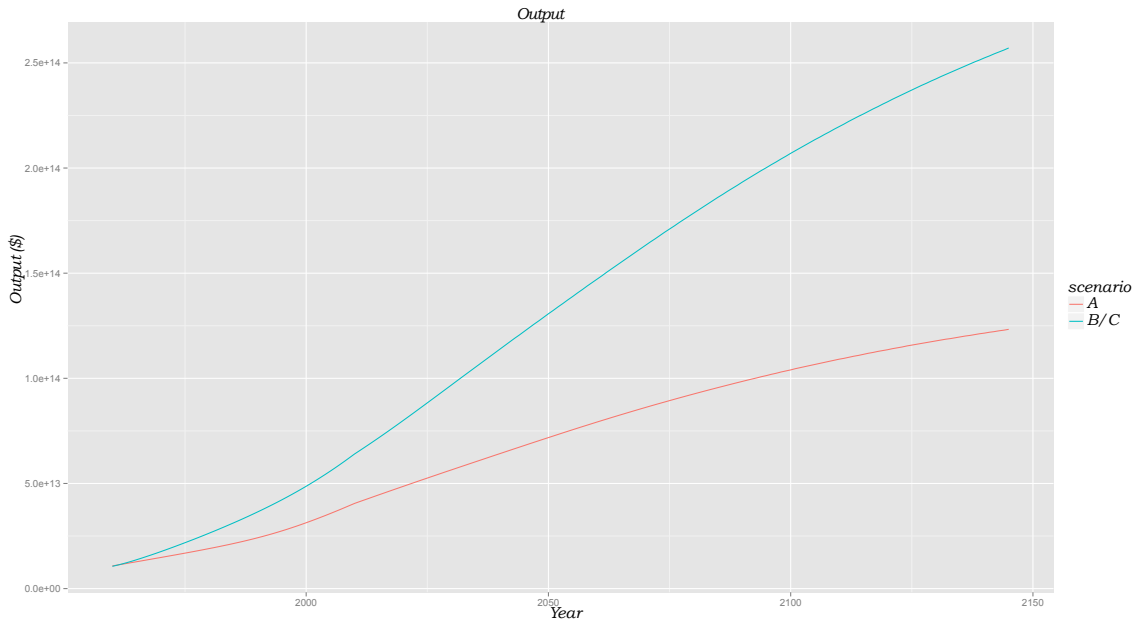


Figure 4.4 – Evolution of economic output. Output elasticity of capital 0.1 for Scenario A, Output elasticity of capital 0.3 for scenarios B and C

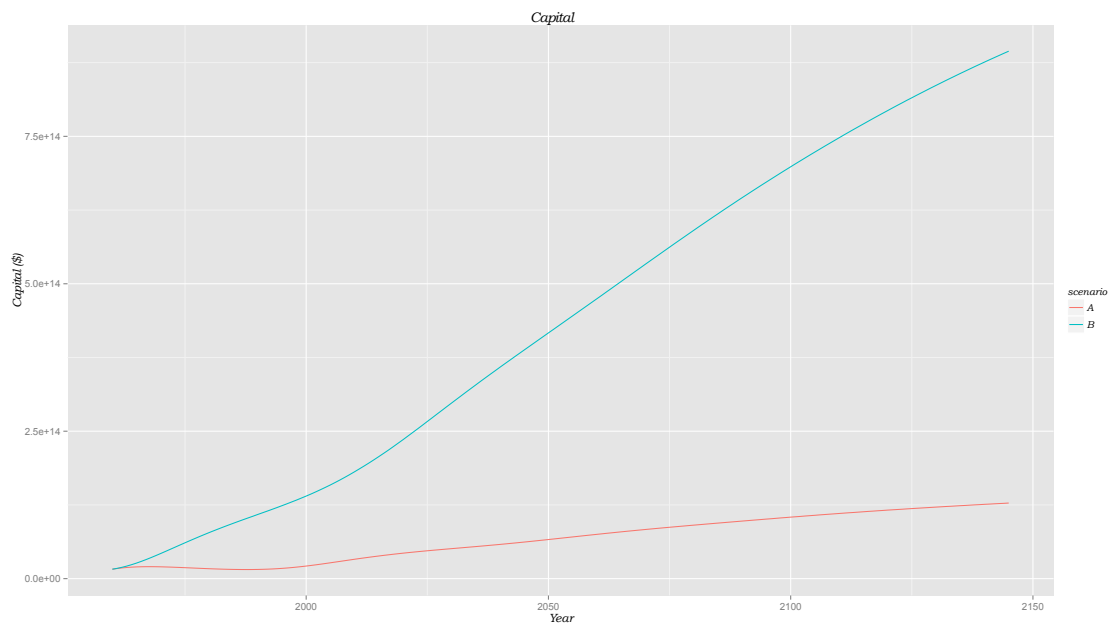


Figure 4.5 – Evolution of capital. Output elasticity of capital 0.1 for Scenario A, Output elasticity of capital 0.3 for scenarios B and C

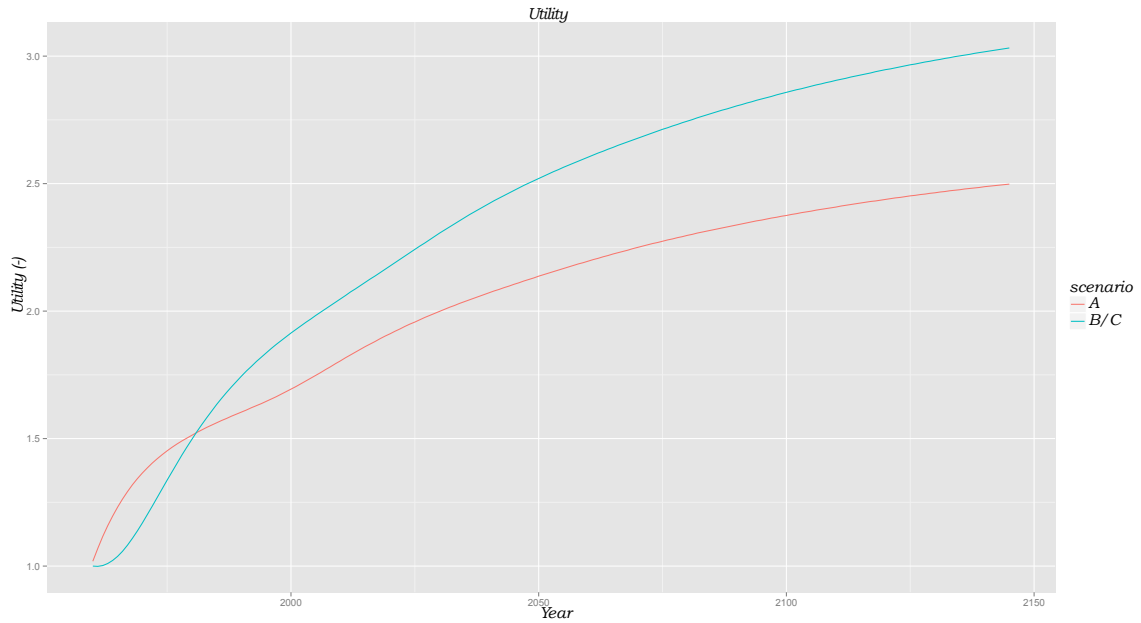


Figure 4.6 – Evolution of utility. Evolution of economic output. Output elasticity of capital 0.1 for Scenario A, Output elasticity of capital 0.3 for scenarios B and C

4.1.3 Energy Technology

Depletion of energy sources is not the only process affecting energy production costs. Technological improvements reduces the cost of energy production. Historically, the improvements in technology have offset the effects of depletion [Fiddaman, 1997], though this can not continue forever. The effects of depletion are increasing over time as resources become more scarce. Energy technologies are not supposed to offset the increasing effect of depletion on the energy production costs. Advances in technology cause the efficiency of energy production to increase. This effect is modeled exogenous to the model, meaning that energy technology behaves autonomously. As a result of the energy technology, the energy price will be lower in the near term. However, lower energy prices lead to more rapid depletion, which will increase the production cost of energy. Table 4.4 provides the learning rates per energy source, expressed as fractional reduction per doubling of experience.

Table 4.4 – Learning rates per energy source, expressed as fractional reduction per doubling of experience

Parameter	Scenario A	Scenario B	Scenario C
Technology Learning Rate Carbon Energy Sources	0.20	0.15	0.05
Technology Learning Rate Alternative Carbon Energy Sources	0.10	0.05	0.05
Technology Learning Rate Noncarbon Energy Sources	0.05	0.10	0.15

Based on the learning rates, which express the energy technology, the energy prices will change towards the future. In figure 4.7 the evolution of energy prices is provided. Car-

bon based energy is in all scenarios the cheapest option. High learning rates will cause the energy price to decline, shifting the transition point for other than carbon based energy to the left.

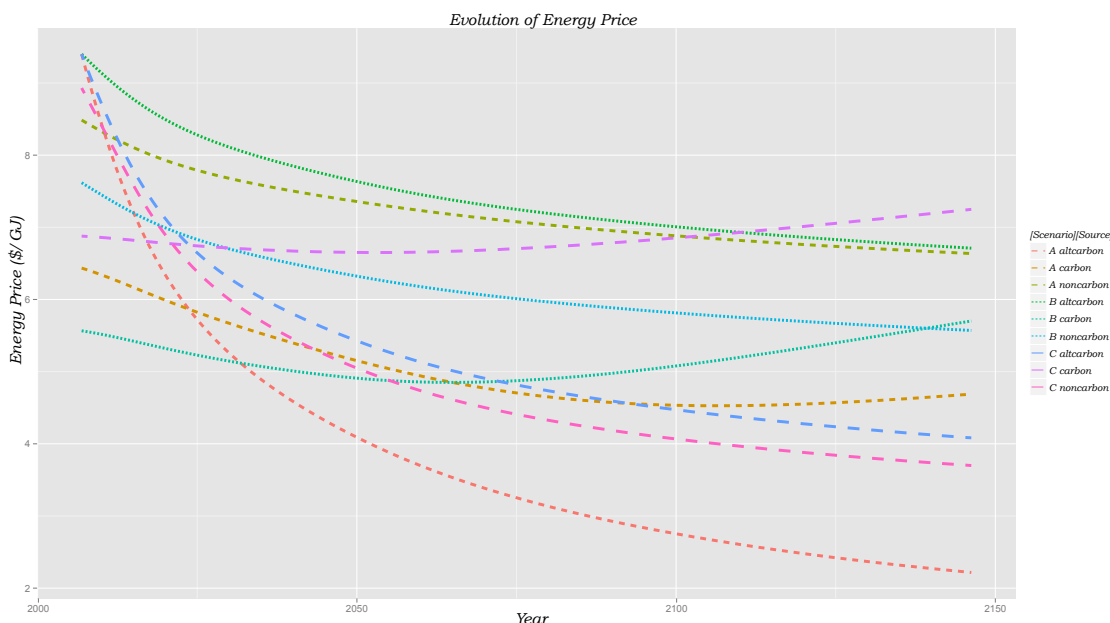


Figure 4.7 – Evolution of utility. Evolution of economic output. Output elasticity of capital 0.1 for Scenario A, Output elasticity of capital 0.3 for scenarios B and C

Figure 4.8 illustrates the total demand for energy under different scenarios. As one can observe, scenario A - rapidly growing world population, increasing wealth and focus on carbon based fuels - shows the largest increase in energy usage. Since carbon based energy is the cheapest and best available energy source, the energy price can be rather low. The level of energy technology simulates the demand and cause the depletion effect to grow. Thereby the scarcity of carbon based energy sources shifts, and other energy sources become more attractive. Around 2025, the energy price for alternative carbon based fuels is equal to carbon based energy sources. The carbon tax, introduced in scenario A, causes the energy price to rise, but still does not offset the price for non carbon based fuels, which is significantly higher.

Scenario B does not focus on energy policy, causing the energy price to increase over time due to depletion. The transition point for other energy sources is reached around 2140. Non carbon based fuels are becoming less expensive over time, but are not able to gain market share as the other two energy types are less expensive. Since scenario B is not subject to any tax policy, the energy prices for carbon based energy are rather low. Scenario B simulates a future where no emphasis is put on energy saving measures. The relatively low factor productivity and decreasing population, cause the increase in demand for energy to flatten.

The focus of scenario C is specifically on environmental friendly development, where special emphasis is put on the development of non carbon based fuels and high taxes on carbon emissions (75\$/TonC). This causes the energy price for carbon based energy to increase immediately, while alternative carbon based energy and non carbon based

energy prices are becoming more affordable. The transition point for non carbon based energy therefor is rather near in the future, 19 and 25 years ahead respectively. Due to the relatively low energy prices due to energy technology and progressive tax policy, the demand for energy increases in the first instance and stabilises over time.

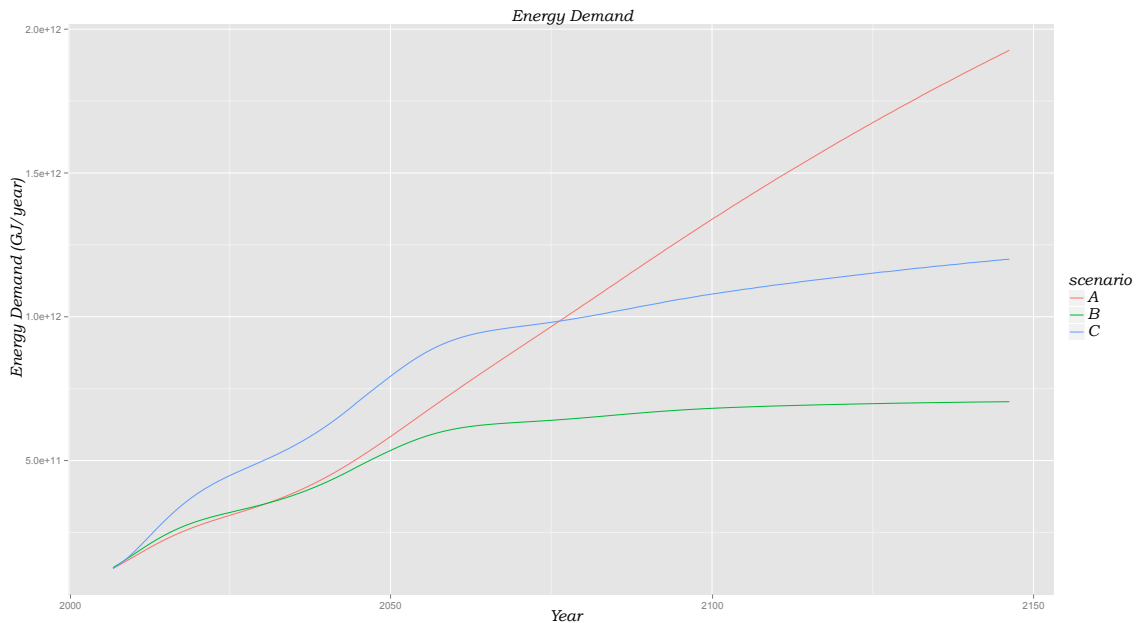


Figure 4.8 – Demand for energy, expressed in GJ/year

4.1.4 Carbon Cycle

Carbon is a critical part of AVEM. It is generated by the production and consumption of energy, it is absorbed by the atmosphere and associated components of the climate system. On the other hand carbon dioxide concentrations in the atmosphere are subject to taxes, which affects the energy price, thereby the ability to produce goods and services, which on their turn affect welfare in the form of utility. The carbon cycle is models in AVEM as an endogenous system. The scenarios reviewed in this sector are subject to different carbon dioxide emission. Figure 4.9 illustrates the total amount of carbon dioxide emissions in the atmosphere. Keep in mind that the net increase in carbon dioxide emissions is the result of new emitted carbon dioxides minus the uptake of carbon dioxide by the biosphere and oceans. As figure 4.10 provides the scenario specific total production of carbon dioxide emissions in the atmosphere, one can see significant differences in the emission scenarios. The carbon dioxide uptake of the mixed layer and biosphere is provided in figure 4.11 and 4.12.

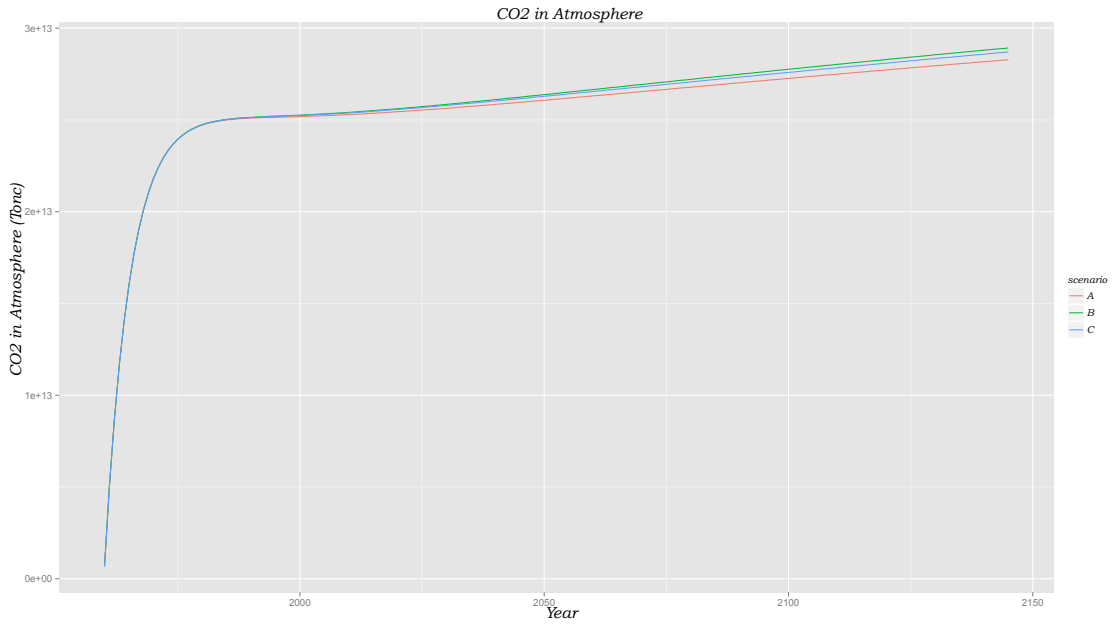


Figure 4.9 – Carbon dioxide emissions in the atmosphere

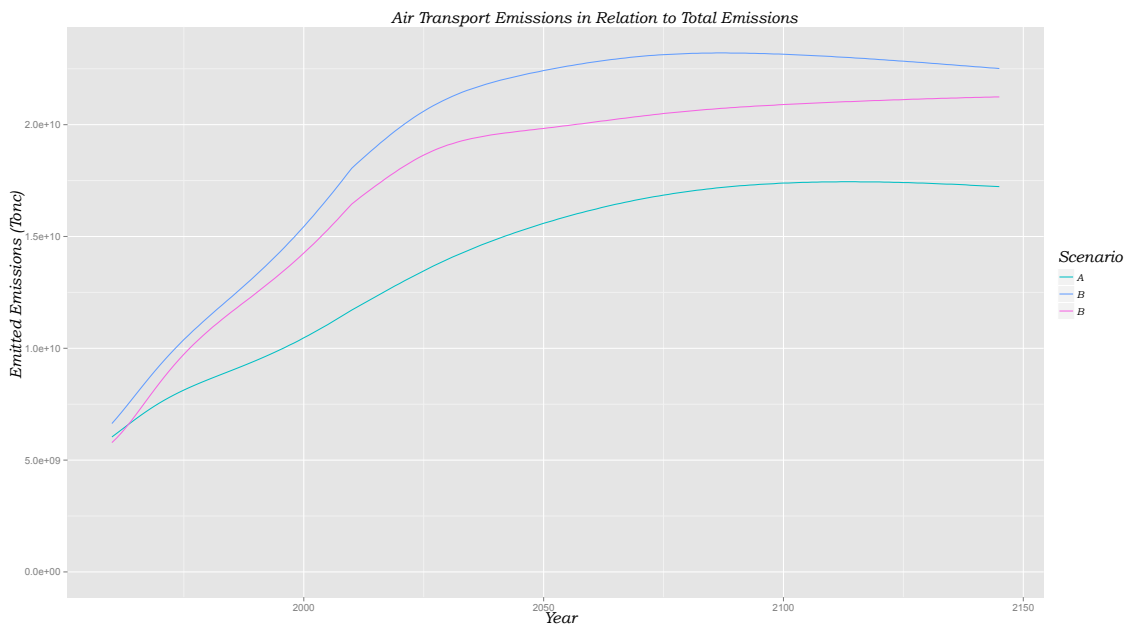


Figure 4.10 – Total production of carbon dioxide emissions

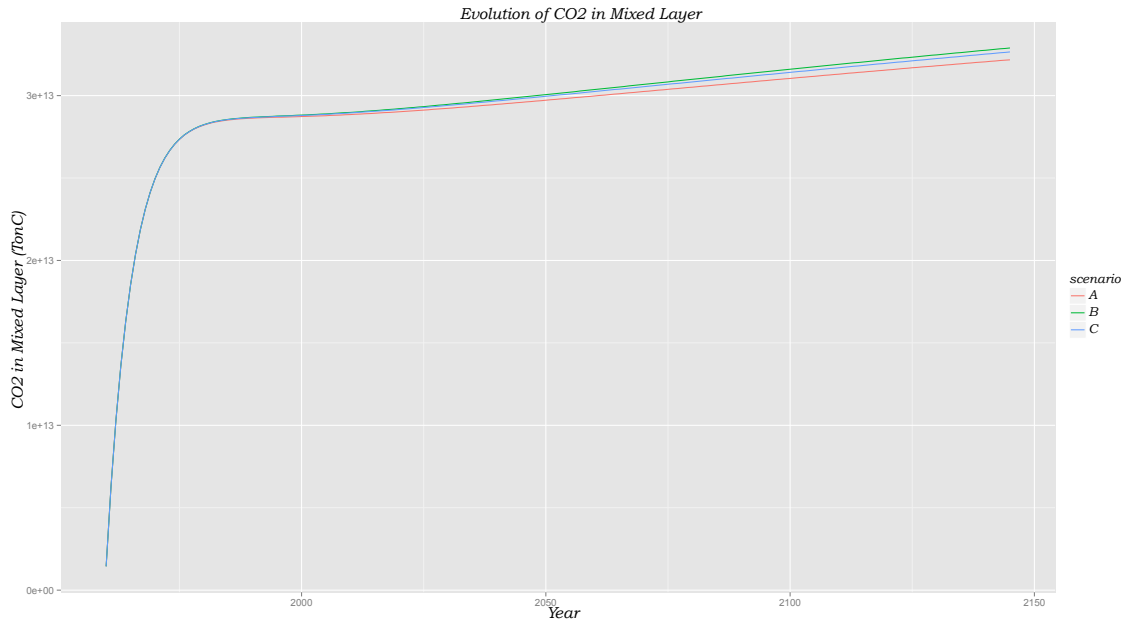


Figure 4.11 – Amount of carbon dioxide emissions in mixed layer

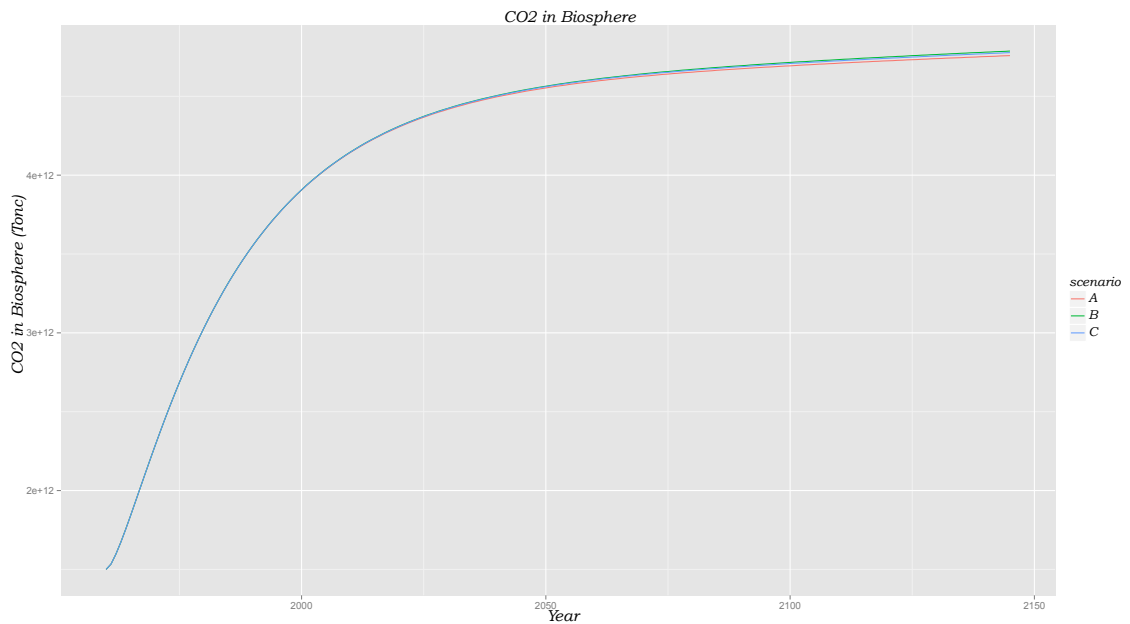


Figure 4.12 – Amount of carbon dioxide emissions in the biosphere

As stated in section 8.7, the oceans are a sink for carbon dioxide emissions from the mixed layer. The ocean is modeled in 10 layers, each transporting carbon content to the layer located below. This causes a flow of carbon dioxide towards the bottom of the ocean. Since the ocean transport of carbon dioxide consists out of 10 layers, only the oceanic carbon dioxide transport of scenario is plotted in figure 4.13. As one can see layer 1-9 show almost similar behaviour, while layer 10, which is the bottom layer in the ocean functions as a sink. However, due to saturation, layer 10 is not able to absorb more carbon

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dioxide from higher layers. Layer 1-9 show a tendency towards saturation as all carbon content in the layer accumulates.

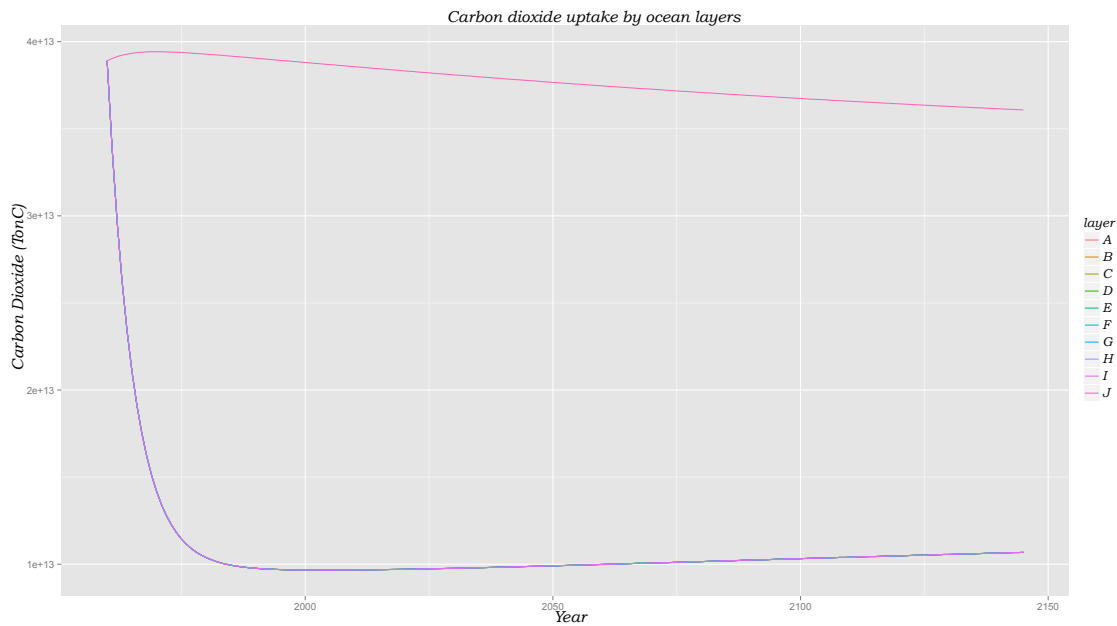


Figure 4.13 – Accumulation of carbon dioxide in ocean's layers

The carbon dioxide absorbed by the oceans reacts in the salty water and affects the heat balance of the ocean. As the oceans have an enormous heat capacity, this process evolves slowly. Figure 4.14 illustrates the deep ocean temperature change for all three scenarios.

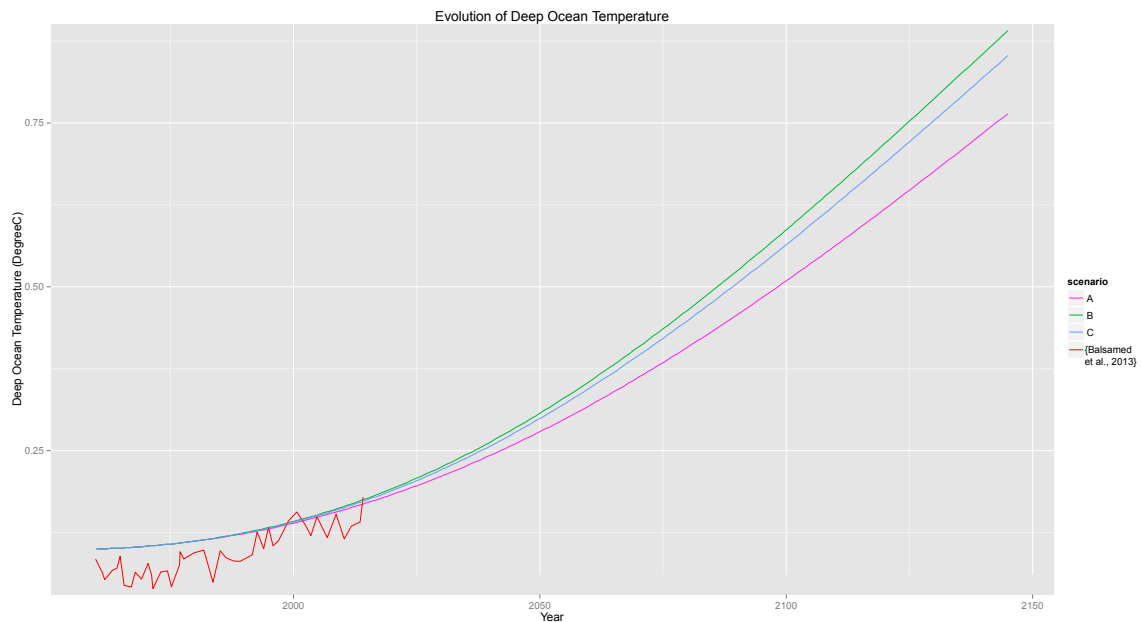


Figure 4.14 – Deep ocean temperature

Where the ocean has an enormous heat capacity, the atmosphere's capacity is signifi-

cantly smaller. Thereby changes in carbon dioxide concentrations will have stronger impact on the atmospheric temperature. In AVEM radiative forcing is used as a metric to express the decrease in heat capacity for the atmosphere. The radiative forcing in AVEM is based on the effects of a saturating carbon dioxide concentrations in the atmosphere and other non-carbon dioxide greenhouse gas concentrations. The Figure 4.16 illustrates the atmospheric temperature increase due to the carbon dioxide emissions.

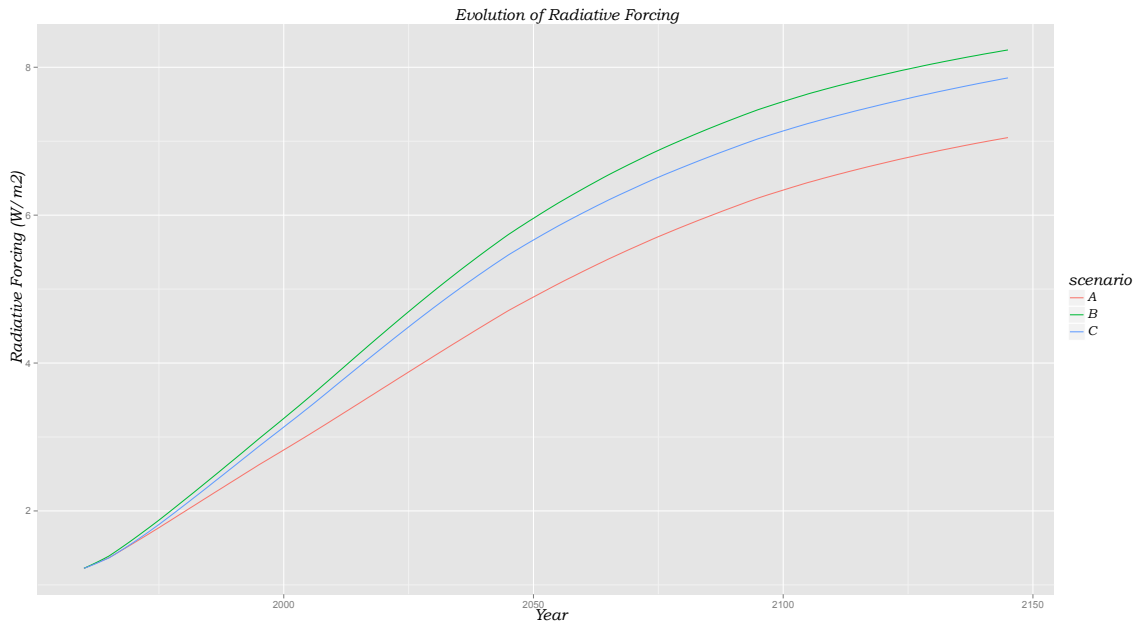


Figure 4.15 – Radiative forcing

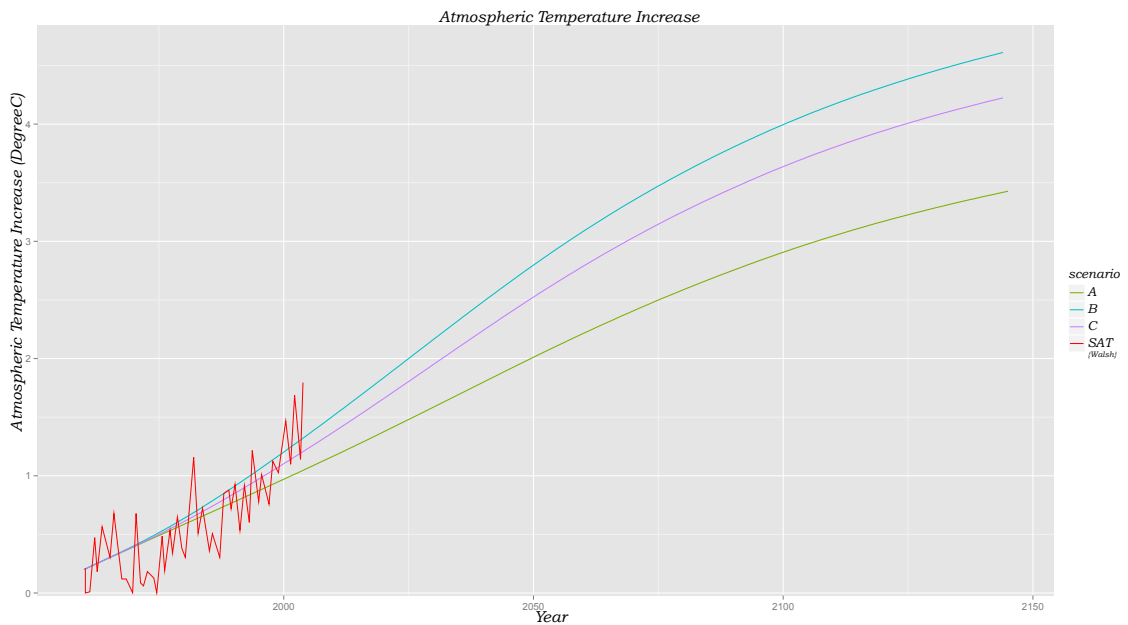


Figure 4.16 – Atmospheric Temperature increase, validation based on Walsh [wal, 2008] research Pacific Marine Environmental Laboratory, Seattle, WA

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As one can see in the graphs above, there is a correlation between the amount of radiate forcing and the temperature increase in the atmosphere. Based on the thermodynamic laws described in the chapter on climate system, this behaviour is expected. Compared to the study performed by Balsamed et al., 2013, the Deep ocean temperature is indeed increasing, however empirical studies show that the rate at which the deep ocean temperature rises is less aggressive.

4.1.5 Climate Damage

Increases in atmospheric and oceanic temperature do have dramatic effects on human well-being, flora and fauna. As one can read in Appendix A, for society, human health effects from increases in temperature are likely to include increases in heat-related illnesses and deaths, especially in urban areas. The changes in sea level, precipitation and patterns of streamflow can damage the infrastructure and property, thereby demolishing roads, bridges and utilities. The more intense the climate changes, the more severe the effects of these changes can influence the ecosystems. The climate effects are simulated in AVEM as tangible as well as intangible effects. The tangible effects of climate change, in this situation global warming, are related to the economic output of society. Thereby the climate damage fraction indicates the amount of effect tangible climate damage will have on the economy. The climate damage fraction is expressed as the output lost to combatting climate change ($1/\text{DegreeC}^2$). Figure 4.17 illustrates the climate damage fraction for all three scenarios.

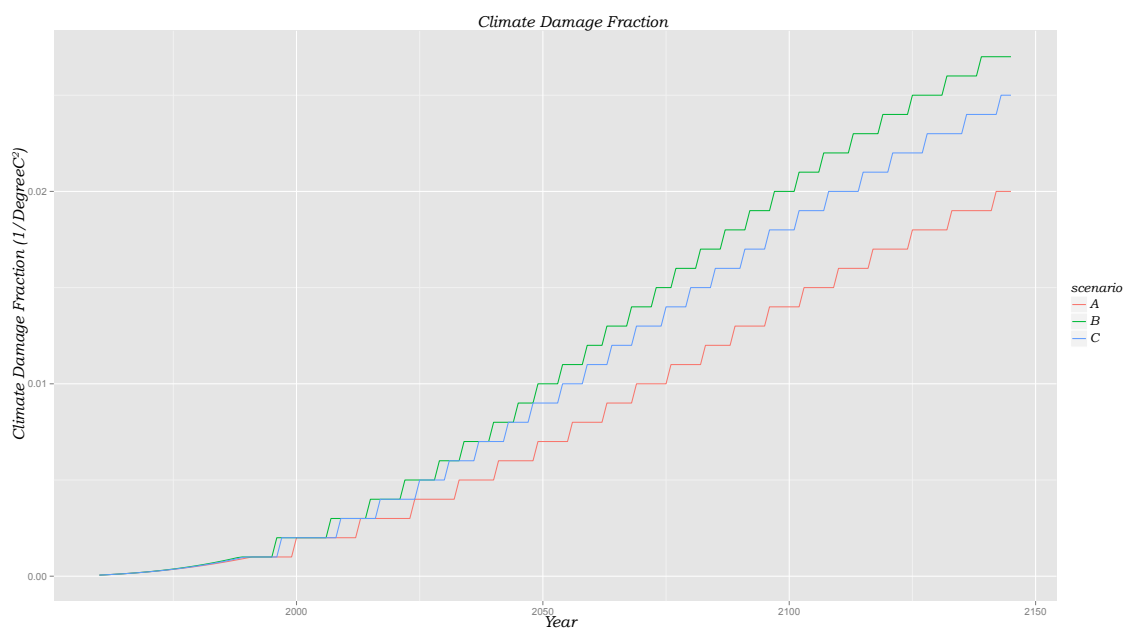


Figure 4.17 – Climate Damage Fraction

4.1.6 Welfare

One of the difficult parts of scenario evaluation is the criteria used for evaluation[Fiddaman, 1997]. In general there are two issues - the extend to which tangible (consumption of goods) vs

intangible (environmental services or health) factors contribute to welfare, and the relative weight assigned to the welfare of generations distant from another in time. The level of welfare provides no direct feedback to the rest of the model. The utility in this AVEM model is measured in terms of marginal utility gain with respect to increasing income. As figure 4.18 shows, the marginal utility of higher income diminishes faster when the output elasticity of capital increases. Figure 4.19 illustrates the utility per capital. Higher utility is in this situation better than lower utility. As one can see is scenario A better in the short term, but less favourable in the long term. This could have to do with the increasing population size which has to share the total utility. On the other hand the utility in scenario A decreases due to the lower output elasticity of capital. Which means that an equal amount of capital produces less new capital in situations where the output elasticity of small compared to a situation where the elasticity is high -as scenario B and C. The capital formation in scenario A is therefore lower and so is the effective consumption per capita.

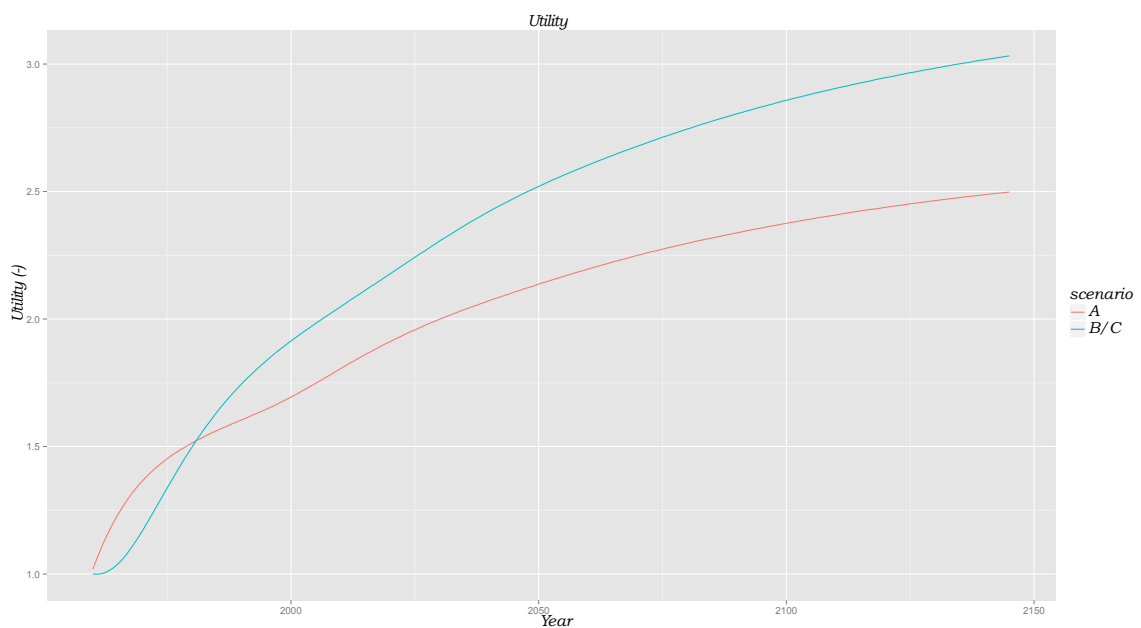


Figure 4.18 – Marginal Utility

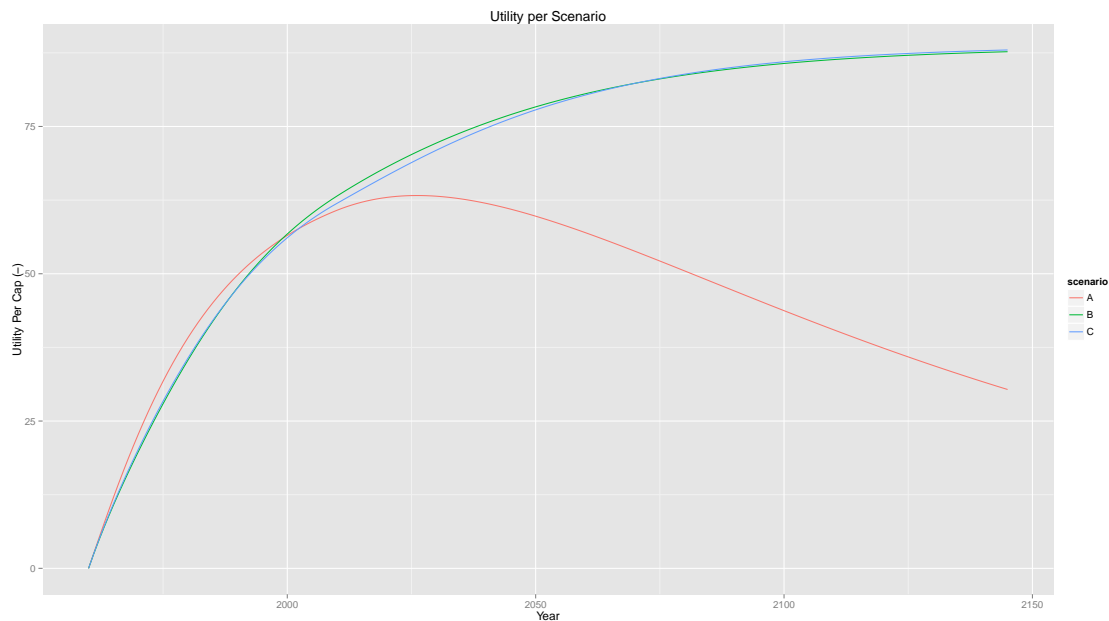


Figure 4.19 – Utility per Capita

Airline Validation After evaluating the three scenarios in previous chapter, this chapter will focus on the effects of changing socio-economic circumstances on airliner businesses. By evaluating the three scenarios for three types of aircraft, the small but efficient Boeing 737-800, the wide-body Boeing 777-200 and the Airbus A380-800.

As previous chapter provides essential information on population sizes, economic well-being, emissions and climate system, this chapter will evaluate the effect of the systems on the aviation industry.

4.1.7 Aircraft and Airport Characteristics

Simulating businesses and future pathways does only make sense if the data used in the simulation is correct and adequate. In previous chapters emphasis is put on the structural relations between key variables in the air transport industry. This section will focus on the characteristics used to describe aircraft and airliners.

In the light of operating cost, it is essential to know how an aircraft is listed, the wages used in the industry, fuel consumption, airport fees etc. In the table below, table 4.5 and table 4.6, the characteristics used to describe aircraft and airliners are shown.

4.1.8 Airline Demand

Air transportation provides the movement of people and goods, enabling economic growth. Thereby transportation is essential to society. The selection of mode of transport is based on the convenience, price and speed. Additionally availability is also an important condition. However, in AVEM two types of transport mode are identified, air transportation

Table 4.5 – Aircraft Characteristics

Parameter	Boeing 737-800	Boeing 777-200	Airbus A380-800
Number of classes	2	3	3
Passenger seats (people)	162	400	535
Seat pitch (inches)	29	31	31
Fuel consumption (kg/hour/pax)	23.85	14.73	12.54
Aircraft weight (kg)	79,000	290,000	540,000
Stage length (nm)	2200	4800	6800
Turnaround time (hour)	0.8	1.3	2
Cruise speed (kmh)	780	905	945
Initial airframe cost (m\$)	76	261	414
Flight attendants	6	12	16
Crew salary	12,000	12,000	12,000

and "other" transport mode, which embraces every transport mode in general except for air transportation services.

AVEM makes a tradeoff whether to select the air transport mode or the other transport mode based on time required to cover a particular distance and the associated pricing. AVEM uses the tradeoff that the fastest or cheapest mode is selected. The market share for a particular distance is calculated by weighing time versus price. This will result in the distribution of market share per transport mode per trip distance. In order to determine the mode specific demand for transport km, the total transport demand is simulated by the model. This results in figure 4.20.

Table 4.6 – Airport Characteristics

Parameter	Airport used in AVEM
Runway construction cost (m\$)	1,000
Airport cost per enplaned passenger (\$)	8
Runway length (m)	3,400
Airport daily operational uptime (hour)	18
Airport optimal Utilisation	0.92
Runway lifetime (year)	30
Airport construction time (year)	3
Administration costs (percentage of total cost)	6%

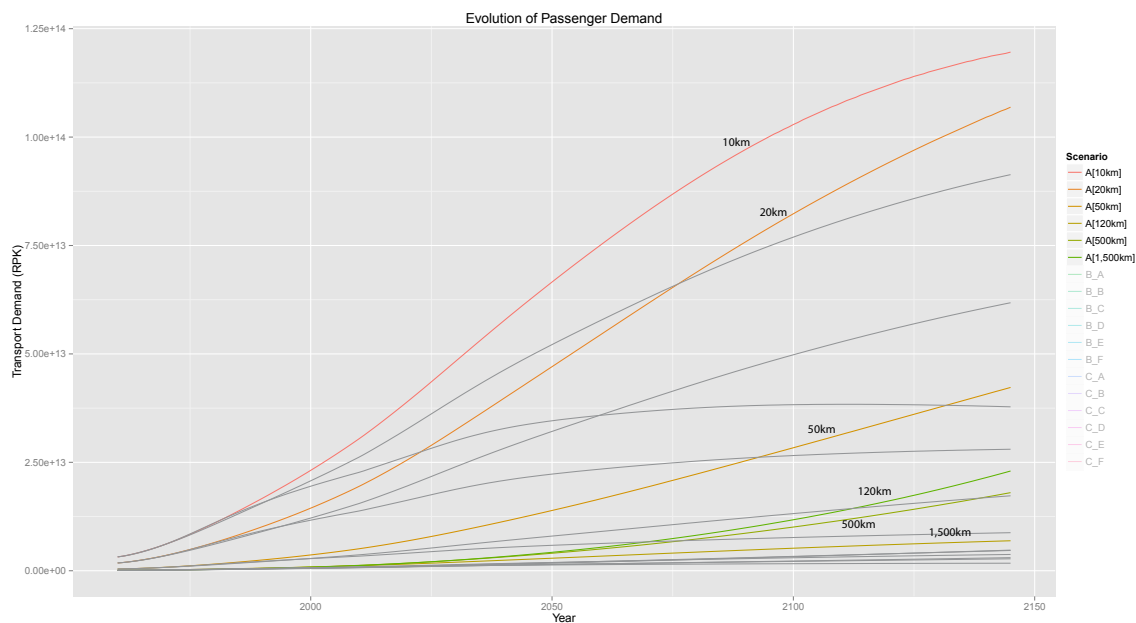


Figure 4.20 – Transport Demand per Distance

Based on the market share per trip distance, the model provides the total amount of passenger kilometers for air transportation. The RPKs are used in the model to simulate the amount of flights conducted and associated costs and time. For all three scenarios the total passenger km demand is different. The transport demand for air transportation services is not per definition equal to the amount of RPKs flown. Therefore the airliner can be restricted by capacity problems, financial or political constraints. The constraints can be adjusted per scenario, but are in general equal to each other to make a fair comparison.

The three aircraft types are simulated simultaneously to the scenario, whereby there is no difference between socio-economic circumstances. The RPKs per aircraft type under

a scenario can be seen in figure 4.21.

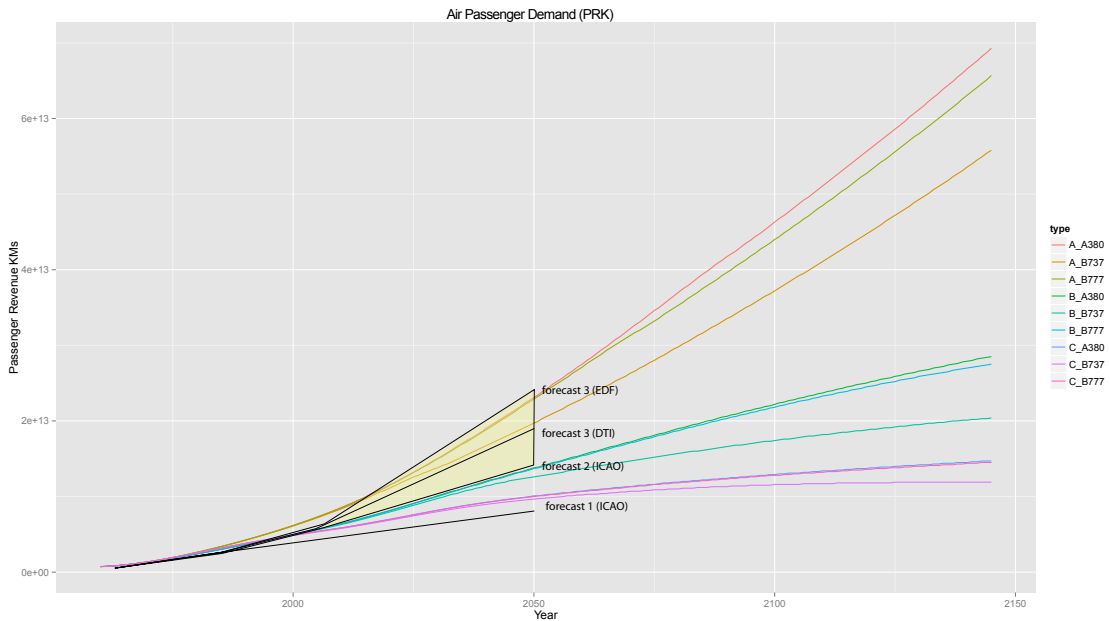


Figure 4.21 – Transport Demand per Aircraft Type

Figure 4.21 illustrates the increasing demand for trips. The demand is driven by population size increase, increasing wealth and utility. Combined they are responsible for the growth in passenger kms. Based on the demand for passenger km, the airline allocates its fleet and runways. In normal situations the utilisation of assets - runways and aircraft-should not exceed 90%. If the maximum utilisation of one of the assets is almost reached, the model will start placing orders to produce new aircraft or construct new runways. Every runway and aircraft is subject to asset specific constraints, which can be found in table 4.6, 4.5. Based on the constraints and structural relations, the model simulates the development of airliners.

Figure 4.21 plots also the forecasts made by the EDF, DTI and ICAO institutions. As one can see from the plot, the external forecasts match scenario A and B. For 2015 some predictions assume 5.700 billion, for 2050 a likely range could be 14,000 to 23,000 billion (ICAO/EDF forecast for medium economic growth). Thereby they assume a world population of about 10 billion in 2050. This means that the average Earth's citizen will go 1400 to 2300 km per year by airplane. This numbers match accurately with the assumptions and simulations made in this thesis work [Uherek, 2005].

The cost and time constraints involved in the production and construction process of aircraft and runways is providing feedback to the model by increasing cost price of tickets and fees. This will change the tradeoff for passengers to use air transport services or other mode transportation. For example, when an airline has to increase the number of runways operated, the landing fees, administration cost and depreciation cost will increase, this increase in cost is compensated by an increase in airfares.

4.1.9 Utilisation

Utilisation is an important aspect in simulating air transport demand. Not only it put restrictions to the amount of flights that can be conducted, it also regulates new orders for aircraft and runways. Over capacity, so under utilisation, will increase costs to airlines which do have negative effects on the performance of the airlines. The utilisation of assets in the future is rather difficult to predict. AVEM uses an optimal utilisation of assets in order to stabilise the capacity and enable air transportation in right quantities. Figure 4.23 and figure 4.22 illustrate the amount of aircraft and runways per aircraft type per scenario required.

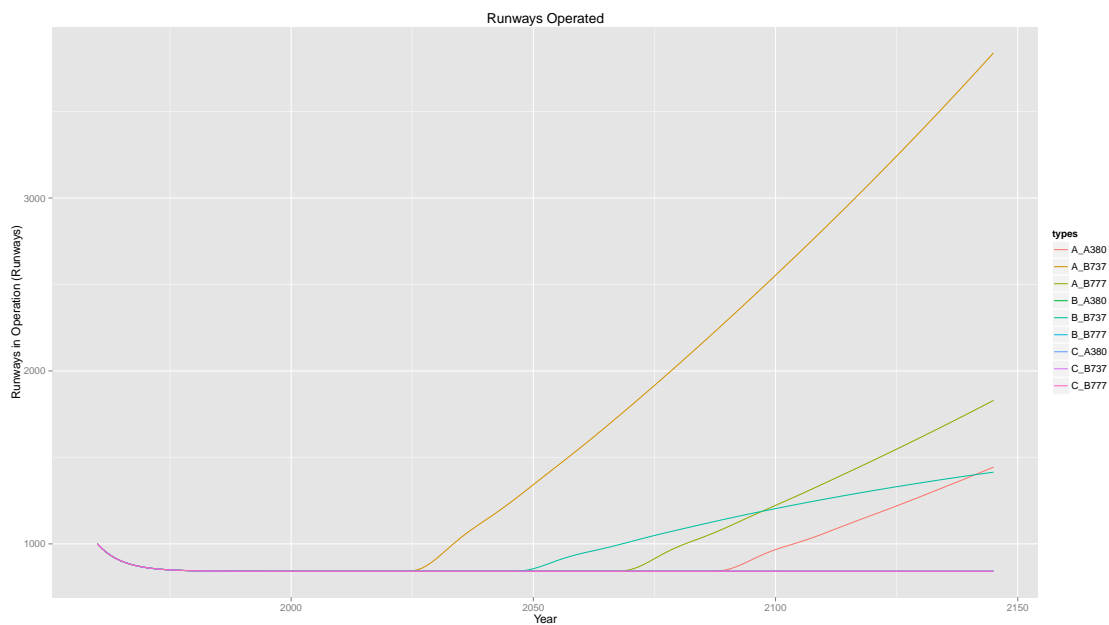


Figure 4.22 – Runways operated

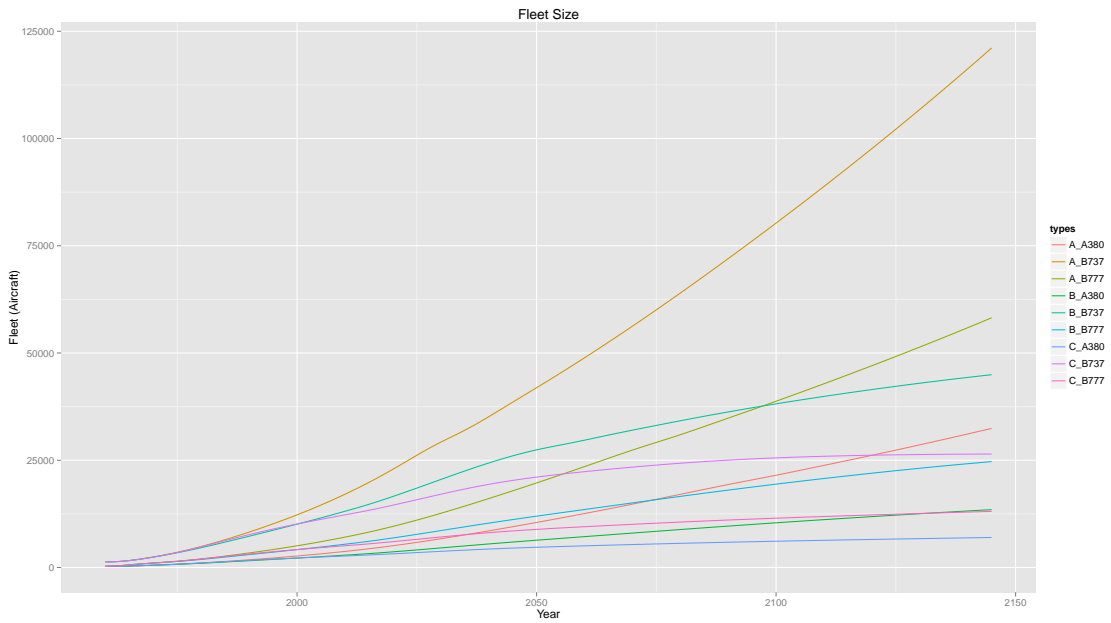


Figure 4.23 – Number of aircraft operated

As one can see in the figures above, the runway capacity before 2025 is sufficient. Thereafter, the runways are at maximum capacity and new runways need to be constructed. On the other hand, there is a shortage of aircraft from the beginning. Therefore the airlines will place new orders for aircraft. Since the lead time is nearly three years for an aircraft, there is a delay in the number of aircraft in an airlines fleet. Figure 4.24 and 4.25 illustrate the number of orders for new assets.

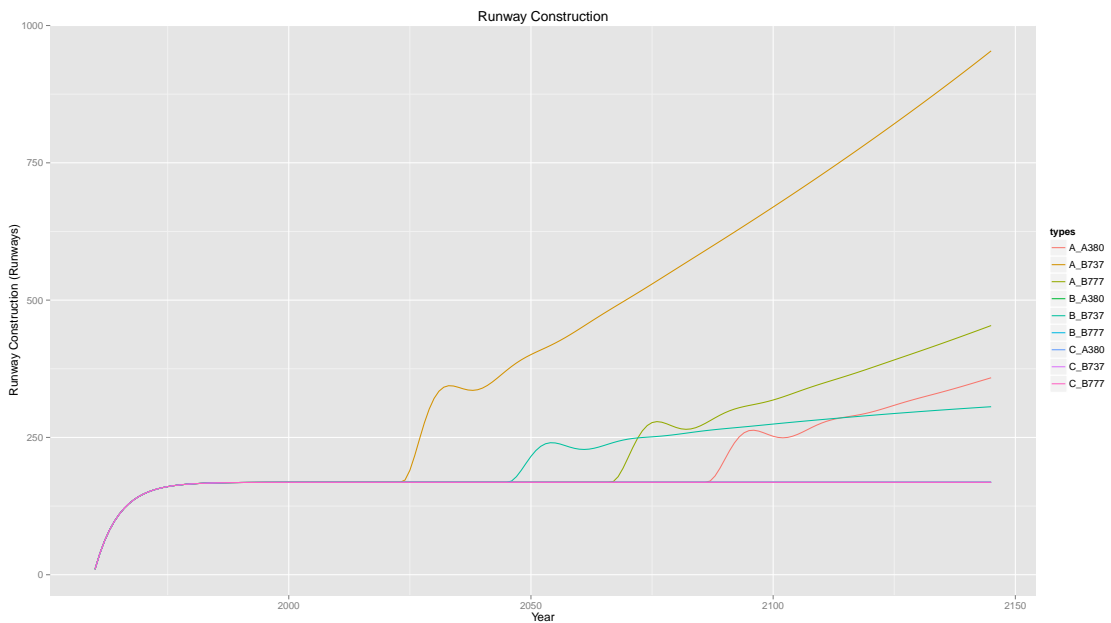


Figure 4.24 – Number of runways under construction

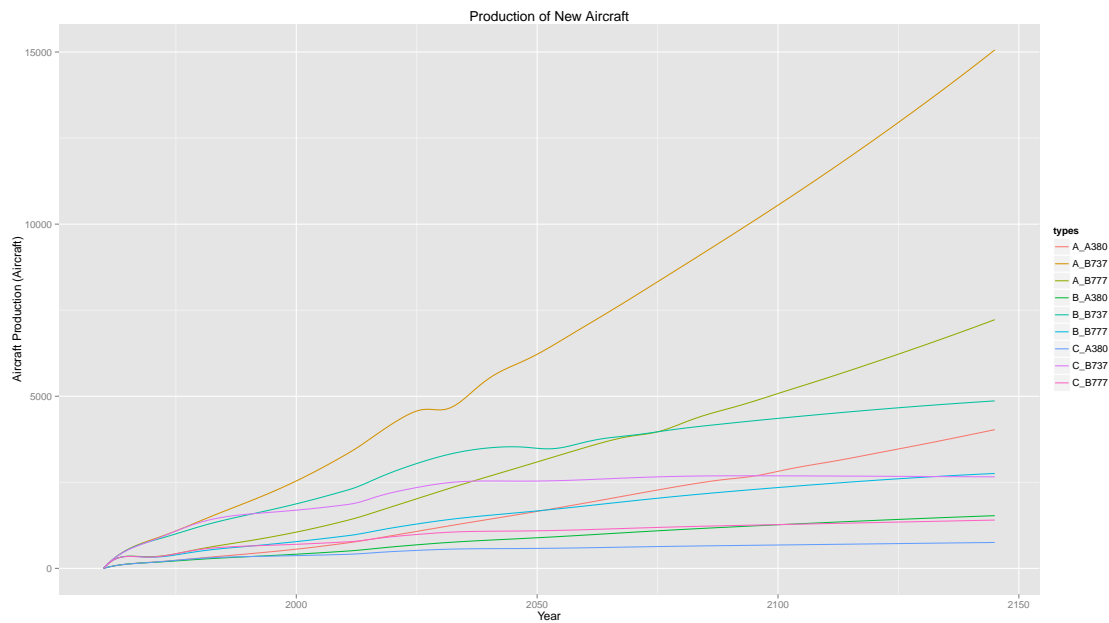


Figure 4.25 – Number of aircraft in production

4.2 Validation of the Airline Value Evaluation Model through application on Airline Businesses

The validation of the value model is established by comparing three types of aircraft that will be used in AVEM as well. The basis for the comparison is the Boeing 737-800 operated by KLM-Air France, in practice this could be any other aircraft. Availability of operational data is the only requirement for the selection of an aircraft that can be used as reference aircraft in this model. The values used in the validation of the value function are obtained using AVEM. Based on the structure of variables in the model, particular outcomes can be obtained. Since the validation of the aircraft is based on absolute data, so not normalised to passengers or capacity, the values can look somewhat off. The real value of the aircraft can be obtained after entering the aircraft characteristics in AVEM and running the model for a particular demand for flights.

According to Doganis short haul flights generate more profit than long haul flights [Doganis, 2001]. On the other hand the number of wide body aircrafts operated increases every year. Therefore the Boeing 777-200 is chosen as the competing aircraft. For convenience, the Airbus A380 is used as third competitor. This aircraft is known for its capacity, and is designed for long haul flights. Based on the three aircraft types the comparison is made for every value level. In order to evaluate the value for the three aircraft types, real life data is used. KLM-Air France operate the Boeing 737-800, Boeing 777-200 and the Airbus A380-800 [Guru, b, Guru, a, Guru, c]. This is convenient for comparison, since the operational method is comparable [Curran et al., 2010].

4.2.1 Comparison of Aircraft Types

In this case the Boeing 737-800 is compared to the more recent Boeing 777-200. Additionally a long haul, high capacity aircraft as the Airbus A380 is added to the comparison.

4.2.2 Cost related to the aircraft

The cost related to operating an aircraft are strongly dependent on the type of airliner and its procedures. In order to make the best comparison, it is beneficial to select an airliner which operates both the Boeing 737-800, Boeing 777-200 and Airbus A380. However, there is no airliner that operates all three aircraft. Therefore KLM and Air France are selected as reference airliners.

The cost for an airliner can be divided into Direct Operational Cost(DOC) and Indirect Operational Cost (IOC). The Direct Operational Cost (DOC) are a perfect indicator for the operational efficiency of an airliner. The direct operational cost can be found in both the airliner's annual reports and the aircraft manufactures. The insurance costs and interest costs are related to the retail price of the aircraft. As the model uses constant 2005 USD to express the inflation corrected value of assets, the list price of the aircraft will be expressed in constant 2005 USD as well. The PV of a Boeing 737-800 is 84.4m\$, while the Boeing 777-200 is listed 261.5m\$ and the Airbus A380-800 at 414m\$, [?], [Airbus, 2010]. The depreciation costs and for the aircrafts can be considered more expensive for both the Boeing 777-200 and the Airbus A380. The Boeing 777-200 is 210% more costly than a Boeing 737-200 which is almost 4 times less expensive than an Airbus A380-800.

Aircraft operating weight is important for the determination of the airport fees. The Boeing 737-800 weights 74,840kg (operating takeoff weight). The Boeing 777-200 and the Airbus A380-800 are respectively 247,000kg and 560,000kg. The airport fees therefore are in both situations higher, having a disadvantage with respect to the Boeing 737-800.

The fuel price per passenger per nautical mile is used to value the value for the fuel component in direct operating cost. The Boeing 737-800 offers the most efficient miles at the price of 8.17 cents per passenger, while the 777-200 and A380-800 cost 11.64 cents and 11.37 cents respectively [Planccs.com,].

The values provided in table 4.7 are based per flight and are not normalised per passenger. This will cause different values for the aircraft in real life situations, where relative pricing is taken into account.

4.2.3 Aircraft Utilization

Aircraft utilisation is strongly dependent on the stage-length of an aircraft as well as the turnaround time on the airport. The Airbus A380-800 is known to have an turnaround time of 90-110 minutes and having an average stage length of 8,000nm. The Boeing 777-200 average stage length is assessed to be 6,800nm and the turnaround time of 85 minutes. The smaller Boeing 737-800 has a turnaround time of 40-45 minutes. This is significantly faster than both other aircraft. The average stage length of the Boeing 737-800 is 2200nm. Due to the higher stage lengths of both the Boeing 777-200 and the Airbus A380-800,

Table 4.7 – Cost value levers and assigned values

Cost Lever	Boeing 737-800	Boeing 777-200	Airbus A380-800
IOC			
Depreciation	1.0	2.47	3.302
Tickets/Sales	1.0	1.0	1.0
Admin/ Other	1.0	1.48	1.56
Staff	1.0	1.48	1.56
DOC			
Maintenance	1.0	0.42	0.35
Fuel	1.0	0.7018	0.7185
Crew	1.0	1.48	1.56
Interest	1.0	0.323	0.188
Insurance	1.0	0.323	0.188
Depreciation	1.0	0.299	0.188
Airport	1.0	0	0.133
Navigation	1.0	0.302	0.133
Passenger services	1.0	1.0	1.0

the utilisation of the aircraft is higher. Depending on the average stage length of flights and the turnaround time on the airport, the maximum number of flights per day can be calculated. On short flights, aircrafts with small turnaround times are in advantage, while on longer stage lengths high capacity aircraft are in advantage. In both situations a tradeoff needs to be made whether to select a high capacity aircraft with relatively longer turnaround time or a smaller and faster (with respect to turnaround time) aircraft. This is dependent on the type of flights demanded.

Table 4.8 illustrates the values assigned to each aircraft per aspect.

Table 4.8 – Assigned Values for Utilization Levers

Utilization Aspects	Boeing 737-800	Boeing 777-200	Airbus A380-800
Flights per Day	1.0	1.0	1.0
Block Hours	1.0	1.88	2.22
Stage Length	1.0	3.09	3.63
Turnaround Time	1.0	0.52	0.45

4.2.4 Sustainability

The level of sustainability of an aircraft is determined by a set of aspects. Recyclability, noise production, fuel consumption, emissions, and more. The use of high-tech materials such as Glare resulted in new opportunities for aircraft with respect to fuel saving, higher capacity aircraft. A good example is the use of Glare in the Airbus A380-series.

New high by-pass engines reduce the noise during landing and take-off, while better ignition of jet fuels resulted in less pollutants. The sustainability of the aircraft can be assessed on static level as well as dynamic. The difference between both options is the static assessment will focus on the initial production of the aircraft and recyclability, while in

4.2. VALIDATION OF THE AIRLINE VALUE EVALUATION MODEL THROUGH APPLICATION ON AIRLINE BUSINESSES

the dynamic assessment emphasis is put on operating the aircraft. Based on the number of movements and flown kilometers, the aircraft will perform differently. The dynamic assessment can only be made by running AVEM.

Based on a report on noise monitoring at Leigh in september 2012, average noise level bands are assigned to a variety of aircraft. Based on this list, the Boeing 737-200 is considered to be relatively silent (63,0dB) compared to a Boeing 777-200 (64,2dB) and Airbus A380-800 (70,0dB)[Peters, 2013].

Recyclability of an aircraft is becoming more and more important. To reduce the human footprint on the environment, more and more produces need to be recycled. Based on documents published by Airbus and Boeing, trends can be observed regarding recyclability of aircraft after lifetime. The Boeing 737-800 is a rather old aircraft, not specifically designed to be recyclable. The Boeing 777-200 and the Airbus A380-800 however are. Based on a study conducted by Yang et al. the Boeing 777-200 is assigned to have a value of 1.12 for recyclability, while the Airbus A380 achieves slightly higher values, due to use of more reusable composites and material, 1.15 [Yang et al., 2012].

Also during the production process of the aircraft a significant difference could be made with respect to the footprint on the environment. Airbus for example put special emphasis on the reduction of energy consumption (29.7%), water discharge (57.9%), waste production (43.3%), CO_2 emissions (34.2%) and VOC emissions (49.2%) [Airbus, 2014]. The pollution during production is therefor relatively less harmful to the environment and is assigned to have a value of 1.2. The Boeing 777-200 is assigned to have a value of 1.0, since the production processes of both aircraft types are similar to each other.

The efficiency during take-off, cruise, landing and taxiing are governed by the Specific Fuel Consumption (SFC). The Boeing 737-200 reference aircraft has a SFC_{TO} (take-off), SFC_C (cruise) of 0.779, 2.07, 2.730 and 0.277 respectively [Curran et al., 2010]. The C_{lift}/C_{drag} ratio of the Boeing 777-200 is 11,58% better than the Boeing 737-800[?], 17,26 vs 19,26. The Airbus A380 has a Lift to drag ratio of 17.43. This makes the Airbus nearly 1% more efficient during cruise than the Boeing 737-800 [Ramba et al., 2005].

Table 4.9 – Environmental value levers and assigned values

Environmental Aspects	Boeing 737-800	Boeing 777-200	Airbus A380-800
Flight Procedures			
Taxiing	1.0	0.1%	0.1%
Take-Off	1.0	0.5%	0.5%
Cruise	1.0	1.15	1.01
Landing	1.0	0.6%	0.6%
A/C and engine			
CO_2	1.0	1.28	1.223
Noise	1.0	0.9812	0.8948
Production			
Recycle	1.0	1.12	1.15
Pollution during production	1.0	1.0	1.15

4.2.5 Market Requirements

The three assessed aircraft do meet market requirements on different ways. The seat pitch for both long haul aircraft is set on high density (31 inch), while the seat pitch for the Boeing 737-800 is set at 30 inch. Hereby all aircraft are operated in a tri-class configuration, except for the Boeing 737-800, which is operated double class. All aircraft are operated with catering and shopping capabilities.

As the Boeing 737-800 is a short-haul aircraft, the amenities on board are relatively sober. KLM offers AC power for laptops and telephones in world business class only. With respect to catering, it offers prepared sandwiches for breakfast, lunch and dinner, as well as a variety of beverages. Depending on the length of flight, these will be served hot meals as well. On board of the Boeing 737-200 there is no entertainment system[Guru, b].

The KLM operated Boeing 777-200 is provided with a Personal Audio Visual on Demand service, which is available in multiple languages. The screens used in the economy class are 9 inches while the business class screens are 10.4 inches. As for the 737-200, the 777-200 offers power supply in the World Business Class. The type of food offered during flights is depending on the type of flight, intercontinental or continental, but is offered in all classes. For infants, KLM offers bassinets for infants up to 6 months old[Guru, c].

As the KLM doesn't operate the Airbus A380-800, the services provided by Air France are used for the comparison of the A380-800 in this work. Every seat on this plane has a personal entertainment system with multiple radio stations and a variety of video channels and movies. Power supplies are available in every class except for the economy class. Depending on the flight's departure time, duration and class of service, Air France offers breakfast, snack or dinner. Meals are provided on all long-haul flights. The amenities for infants are the most elaborate in the A380-800, offering bassinets and skycots for infants under 1 year old, baby changers on all flights, and special baby food (on request)[Guru, a].

The KLM claims to be able to board a Boeing 737-800 in 17 minutes [Reed, 2013], while research has shown that boarding an A380-800 takes 22 minutes [Harkirat, 2007], and 20 minutes for the Boeing 777-200 [estimation].

Based on the set of market requirements, provided in table 3.16, all aircraft are assessed and the results are provided in table 4.10.

4.3 Airline Value Evaluation

The performance of an aircraft type under different scenarios is simulated by AVEM. Based on the aircraft and airport characteristics, the model simulates air transport demand, utilisation and eventually conducted flights. The model simulates the air transport industry from the perspective of three types of aircraft, the Boeing 737-800, the Boeing 777-200 and the Airbus A380-800. These three aircraft types are different from each other, while they have other flight characteristics, capacity, airport handling fees, etc.

The Value Operations Methodology part in AVEM distinguishes three categories with

Table 4.10 – Customer satisfaction value levers and weight factors

Market Requirements	Boeing 737-800	Boeing 777-200	Airbus A380-800
Speed			
Boarding options	1,0	1,0	1,0
Boarding/Check-in-time	1,0	0,85	0,76
Services			
Hand baggage size	1,0	1,0	1,0
Hand baggage weight	1,0	1,0	1,0
Baggage size	1,0	1,0	1,0
Baggage weight	1,0	1,0	1,0
On board entertainment	1,0	1,5	1,5
Catering	1,0	1,0	1,0
Shopping	1,0	1,0	1,0
Seat reservation	1,0	1,0	1,0
Comfort			
Seat pitch	1,0	1,03	1,03

respect to aircraft/airliner value assessment: Utilisation, Sustainability and Cost. The next sections will focus on the aircraft specific value on a variety of aspects. Only the most interesting value assessments are treated, the other less relevant value assessments are placed into the appendices.

4.3.1 Utilisation

Utilisation of airliners will be subject to the variation in flight lengths as a function of turnaround time and cruise speed. Based on the average flight legs, the utilisation can be higher or lower, based on the average number of maximum flights that can be conducted per year. Figure 4.26 provides the value for utilisation for the three aircraft types for scenario A. The Boeing 737-800 is normalised to itself and used as a reference aircraft, which results in a steady line.

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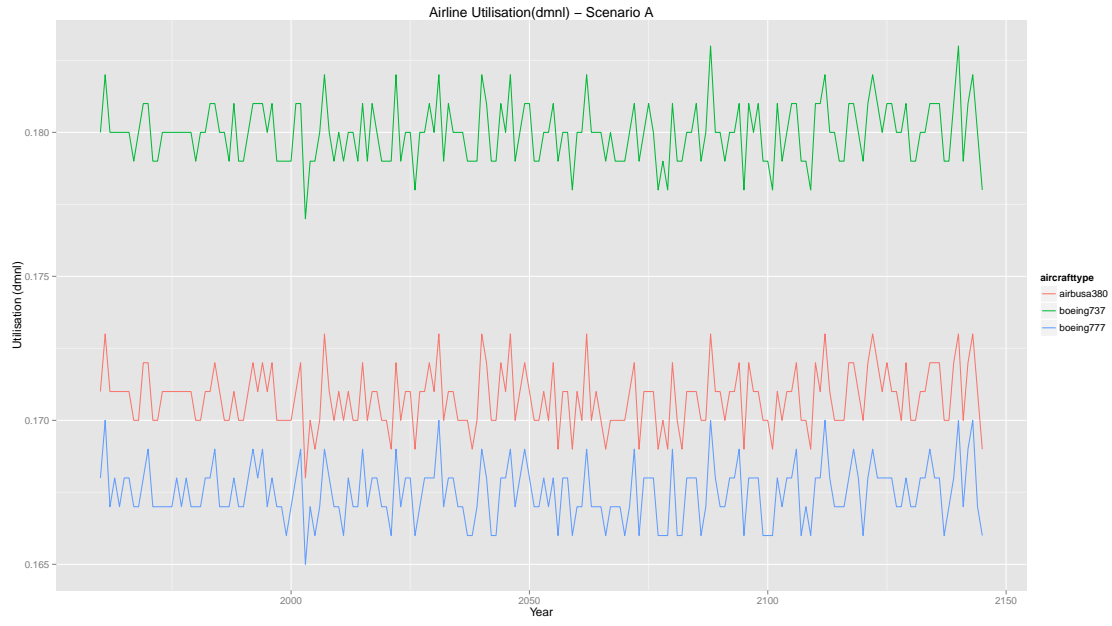


Figure 4.26 – Value for Airline Utilisation - Scenario A



Figure 4.27 – Value for Airline Utilisation - Scenario B

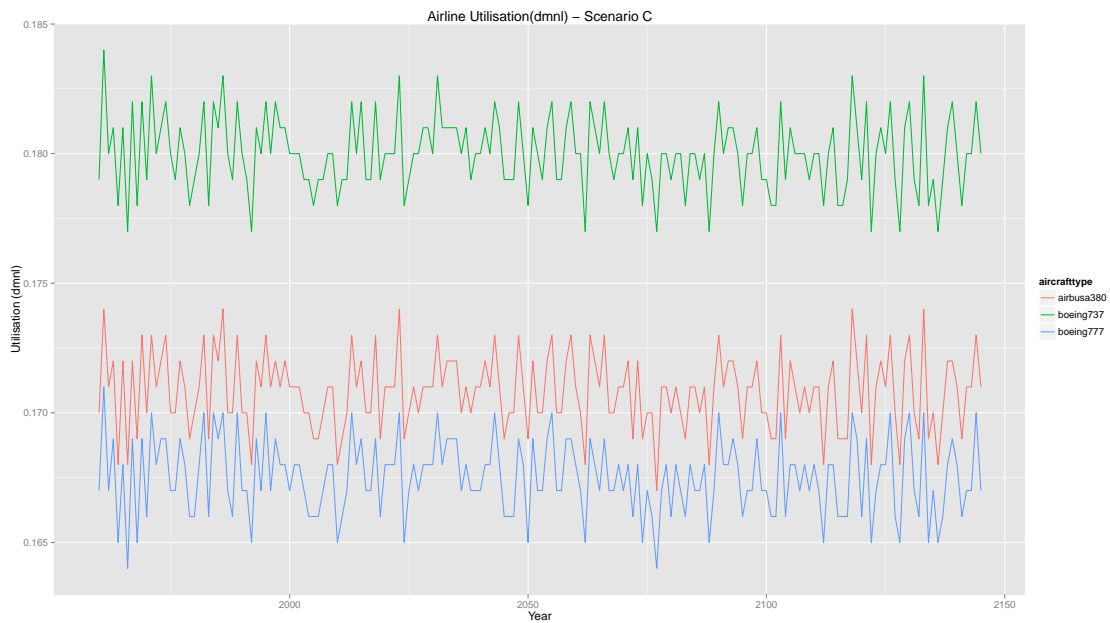


Figure 4.28 – Value for Airline Utilisation - Scenario C

The utilisation value for the Boeing 737-800 is larger than the other two aircraft. This has to do with the turnaround time of the aircraft and the capacity. Based on the typical flight legs, smaller aircraft such as the Boeing 737-800 perform better. In situations of longer flight legs, larger, high capacity aircraft types will perform better. Since Scenario A and C do have a slightly higher international focus, the trip lengths will be larger compared to scenario B. This results in the relative better performance of the Boeing 777-200 and the Airbus A380-800.

4.3.2 Sustainability

The vastly expanding knowledge regarding use of composite and new materials in aviation industry helps to improve the recyclability of an aircraft as well as diminish the pollution during production. Lower weights result in less thrust specific fuel consumption (TSFC), implying higher efficiency. The Boeing 737-800 is with respect to TSFC the most efficient aircraft, however, it is an short-haul aircraft, which cannot directly be compared to the large medium and long haul aircraft as the Boeing 777-200 and the Airbus A380-800. The Boeing 737-800 fuel consumption equals 14.73 kg/h, while the Boeing 777-200 and Airbus A380-800 consume 15.88 and 15.93 kg/h respectively. This makes the Boeing 777-200 and Airbus A380-800 more efficient relatively, due to the increase in weight for long haul fuel demand. The sustainability lever is normalised to the amount of air traffic passenger kms. Since the Boeing 737 is becoming more expensive compared to other transport modes, the share of air traffic relative to the total transport demand decreases. Thereby the total amount of air transport km decreases as well, resulting in a lower impact to the climate system. Therefor, AVEM is modeled to express the sustainability lever per passenger km. This results in less advantage of the Boeing 737-800 compared to a non-passenger-km-indexed value.

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In AVEM the fuel consumption and associated carbon dioxide emissions are incorporated into the comparison. The total flight demand needs to be fulfilled by the three types of aircraft. As the Airbus A380 and Boeing 777 are capable of transporting more passengers over a longer distance, there are less transport cycles required. The expelled noise is also taken into the comparison. Based on the number of take-offs and noise levels, the model calculates the amount of noise pollution. Figure 4.29, 4.30 and 4.31 provides an overview of the aircraft specific performance under the three scenarios in the light of sustainability.



Figure 4.29 – Value for Airline Sustainability - Scenario A



Figure 4.30 – Value for Airline Sustainability - Scenario B



Figure 4.31 – Value for Airline Sustainability - Scenario C

Splitting up the levers for airline sustainability, one can see that the fuel efficiency of the Boeing 737-800 is the highest (2.68 litres per 100 kilometres) in comparison to the Airbus A380-800 and the Boeing 777-200 (2.9 litres per 100 kilometres and 2.89 litres per 100 kilometres, respectively). The Boeing 777-200 performs best in terms of H₂O emissions (1.028 vs 1 (Boeing 737-800) and 0.976 (Airbus A380)). Due to the lower number of cycles on airports, the Airbus A380-800 has a lower aggregated noise penalty (advantage of app. 5% compared to its competitors). In absolute terms, the Boeing 737-800 performs best (63 dB vs 64.2 dB (Boeing 777-200) and 70 dB (Airbus A380-800)).

4.3.3 Cost

Airliners are by nature cash flow businesses, in order to sustain in short term as well as long term, airlines are required to evaluate their expenses and to take measures where required. The Value Operations Methodology evaluates the cost performance of three types of aircraft under changing conditions- the scenarios. The cost value changes for an aircraft is subject to time. This means that the value assigned by AVEM can change under changing conditions. For example, an increase in fuel prices due to carbon tax measures, can impact the financial performance of an airlines, so the cost lever value decreases.

Figure 4.35, 4.36 and 4.37 illustrates the performance of three types of aircraft under different scenarios. As for the other plots, the Boeing 737-800 is used as reference aircraft and is therefore constant. The incorporated weighing factor of 0.36 is therefore assigning a constant value of 0.36 to the cost value of the Boeing 737-800.

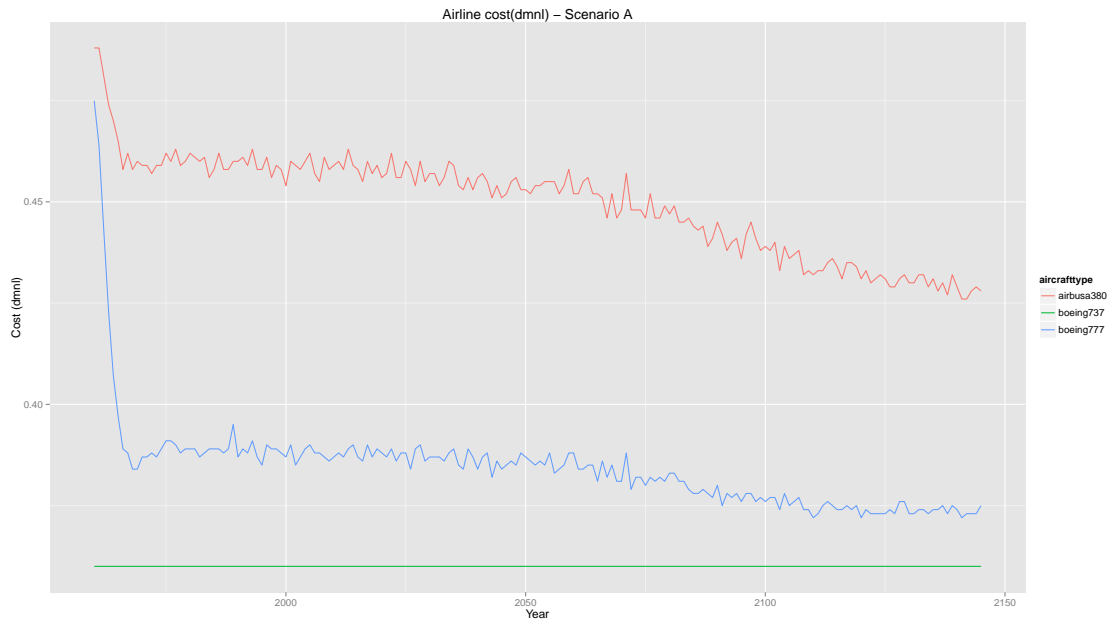


Figure 4.32 – Value for Airline Cost - Scenario A

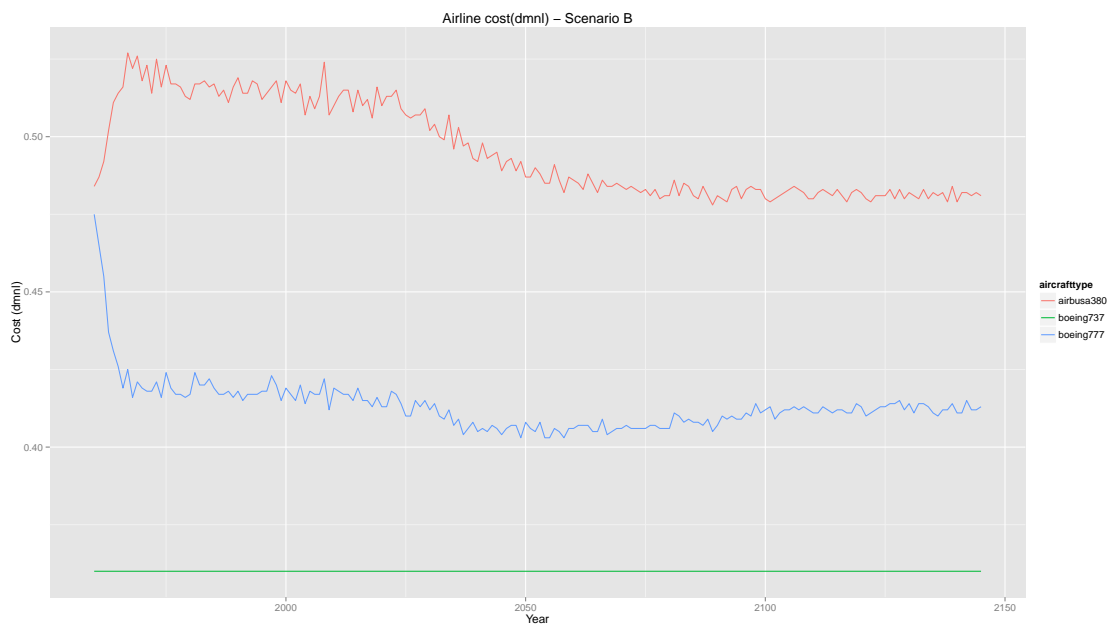


Figure 4.33 – Value for Airline Cost - Scenario B

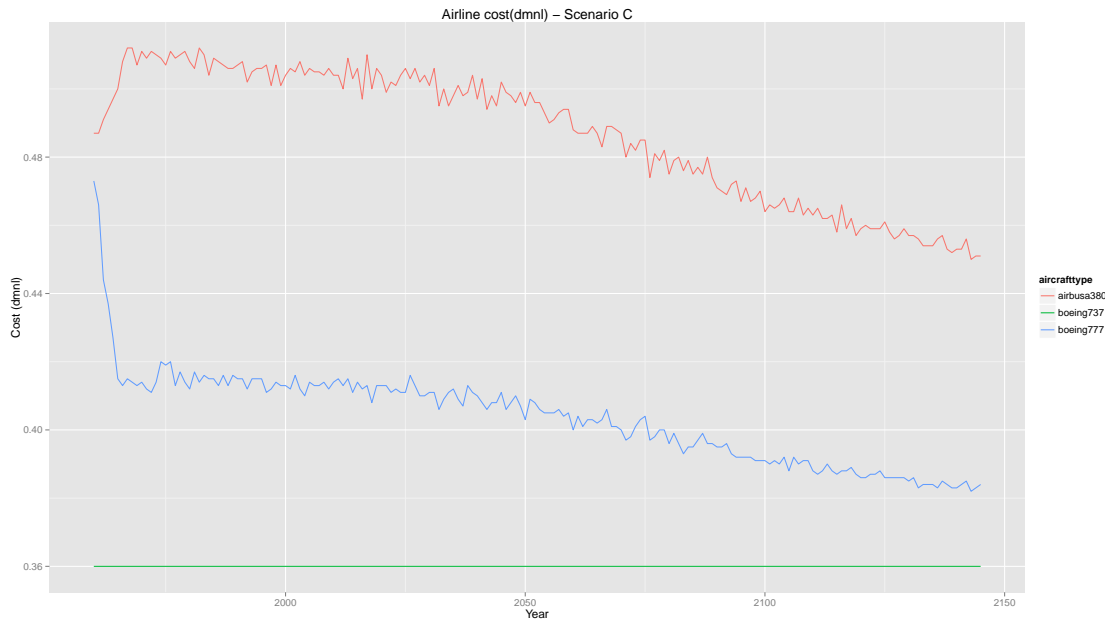


Figure 4.34 – Value for Airline Cost - Scenario C

As one can see in figure ?? advantages of operating an Boeing 777-200 or an Airbus A380-800 are significantly. However, after a couple of years, this advantage diminishes. This has to do with the fuel prices, which decreased over the first 3 decades of the simulation, as well as the interest cost for aircraft. Since the airliner is required to order new aircraft to match the demand for air transportation services, the interest cost rise extremely. The interest component in the cost is significant, but equal to all types of aircraft, since the demand for air transport services expands. This implies that the fuel prices do have the largest impact on the drop in value for the cost lever for the Boeing 777-200 and the Airbus A380-800. The energy technology in scenario A and C are subject to a learning curve, where Scenario B uses a static energy technology. This results in relatively higher fuel prices. The taxi policy of scenario C puts extra pressure on the fuel prices, increasing the cost of the airliners. Thereby the Airbus A380 and Boeing 777 are subject to a drop in cost performance value. The Boeing 737-800, which performs lowest in the comparison in terms of cost over the simulation horizon, is becoming slightly better performing as the environment changes. This could mainly be assigned to energy technology, and emphasis on alternative energy sources and taxes. In terms of operational value of cost, the larger Airbus A380 and the Boeing 777 obtain higher value due to relatively less handling fees, administration cost and interest rates. Besides due to the higher capacity, both aircraft are able to transport more passengers, resulting in higher value for the tickets component.

4.3.4 Total Value

Based on the three dynamic pillars- utilisation, cost and sustainability- and the two static pillars -market requirements, safety- the total value for an aircraft is determined. By combining all levers, the result is a value that describes the performance of an aircraft/airliner under a variety of conditions. Figure 4.35, 4.36 and 4.37 illustrate the total value per aircraft under a particular scenario. As one can see, the performance is different by

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time, this has to do with the changing socio-economic situations, taxes and technological developments.



Figure 4.35 – Value for Airline - Scenario A



Figure 4.36 – Value for Airline - Scenario B

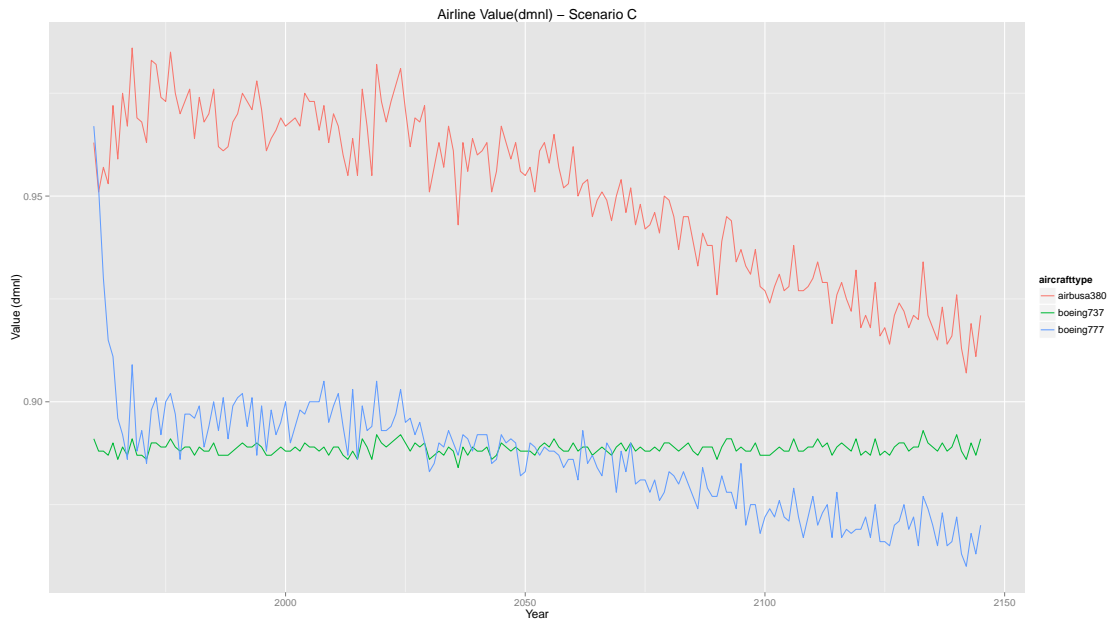


Figure 4.37 – Value for Airline - Scenario C

In all three scenarios, the airbus A380 added the most value to an airline. However, the degree of added value differs per scenario. In a future where economic growth and population is increasing and the focus of energy technology is on alternative energy sources, the value added by an Airbus A380 is significantly lower than the other two scenarios. Due to the lower score on sustainability, the Airbus A380 and Boeing 777 perform worse compared to the fuel efficient Boeing 737. Since the focus of scenario A is on mitigation of the climate system, the Boeing 777 scores directly lower value compared to the Boeing 737-800. Scenario B however, shows a relatively higher score for the Airbus A380 compared to the others. A conservative scenario, as scenario B is, focuses less on new energy technology and alternative energy sources. This is in advantage of the Airbus. The Boeing 777 performs similar to the 737, however the levers of score differ. The cost efficiency of the 777 is better compared to the 737, but is compensated for by the higher sustainability value of the 737. This makes the Boeing 777 score similar to the 737. Due to the lower capacity and turnaround times of both aircraft, it is more likely the aircraft will fit better in changing strategies for airliners. The Airbus A380 can be considered to be more efficient on long leg flights, however not every flight conducted is a long leg flight, reinforcing the need for smaller, short turnaround time, aircraft. Scenario C shows the effect of a progressive carbon tax climate as well as a stable economic climate. The cost for airlines will increase significantly in this scenario, due to higher fuel prices and crew cost. This puts special pressure on the cost lever of airlines. In all three aircraft, the effect is noticeable. Since the Boeing 737-800 is the smallest aircraft, consuming less fuel per passenger km, it is less subject to fluctuations in fuel and crew cost. The Putty-Clay productivity function in Scenario C, implicates that ordered assets should be kept at the balance of an airline, even if there is no demand for flights. The more flexible aircraft as the Boeing 737-800 is, profits of this economic climate.

Based on a scenario exploration, performed using AVEM, the Airbus A380 performs best on short term. The air transport industry is booming and people do have the tendency

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to travel more frequent and further. A long-haul aircraft as the A380 fits perfectly in this scope. However, the economy will change after 2050, since the energy prices become even more influential, putting pressure on the willingness to travel. Merging markets and higher levels of welfare will still feed the demand for air traffic, however the relative share of air traffic will diminish compared to other transport modes. More flexible and less expensive aircraft as the Boeing 777-200 and especially the Boeing 737-800 will benefit in long term.

5 Sensitivity Analysis

AVEM consists out of 444 variables and parameters. Nearly 80% of the variables and parameters in the model of functional or structural form and initial conditions of state variables. The remaining parameters, are subject to significant uncertainty, so it is important to assess their impact. Ideally, one would identify the parameters which contribute most to variation in the optimal performance of airliners over the full parameter space of the model. However, this is computationally infeasible.

Another approach is to evaluate the relative sensitivity of key model variables to variation in individual parameters. If the model output is linear in all of the parameters, this approach would provide full understanding, but this is extremely unlikely, especially since AVEM is partially based on non-linear structures. This method can provide a gradient of the model's response to each parameter.

For this analysis, each key model variable is varied by +/- 10%. A few parameters with initial values of zero were varied by an absolute value of 0.1. The results were then ranked according to the variation induced in four target variables, Energy CO_2 emissions, Gross Output, Discounted Utility, Temperature and Air Transport Demand. The measure of variance was the sum of the squares difference between the perturbed and baseline trajectories, $\Sigma[X_p(t) - X_b(t)]^2$.

For each variable, the results were then ranked in descending order. Since each variable's gradient was tested in two directions, the direction with the greater absolute value was used for the ranking. Trivial or redundant variables are omitted from the ranking. The sensitivity analysis is performed at two points in the parameter space, where scenario A is used as the basis for the analysis.

Table 5.1 shows a set of key parameters in the model. These parameters are sorted based on their gradients around the initial conditions of scenario A. As in other Integrated Assessment Models, the factor productivity and population growth decline rate are among the most sensitive parameters [Fiddaman, 1997], [Nordhaus, 1993]. In general the exogenous variables appear to be the most sensible.

In order to indicate the relative impact of a change in parameters, relative to the abstract ordering as shown in table 5.1, a set of tornado diagrams is provided in figure 5.1, 5.2, 5.3, 5.4, 5.5, each indicating the impact induced by a change in parametric value compared to the five output variables in AVEM.

SENSITIVITY ANALYSIS

Table 5.1 – Parametrical Sensitivity

	Emissions	Utility	RF	Output	VDD	Air Transport Demand
Carbon tax	1	19	1	3	19	18
Population Gr. Rt. Decl. Rt.	2	3	4	1	2	2
Energy share of Capital	3	6	17	7	9	11
Climate sensitivity	4	17	5	6	8	15
Preindustrial co2	5	18	2	4	6	14
CO2 transfer	6	16	3	5	7	12
Energy depletion	7	7	16	18	5	5
Consumer inequal aversion	9	1	6	8	4	3
Rate of time preference	14	2	7	9	10	7
Biosphere residence time	8	8	8	10	11	8
Cost per km (air)	10	9	9	11	12	9
International focus	11	10	10	12	13	19
No. flights per crew per yr.	13	12	12	14	14	6
Saving adjustment time	15	13	13	15	15	10
speed air	16	14	14	16	16	13
jet fuel eff	12	11	11	13	18	16
trip length	17	15	15	17	20	17
Factor product	18	5	18	2	3	4
Output Elasticity	19	20	19	20	17	20
Frac Autonomous Technology Rt.	20	4	20	19	1	1

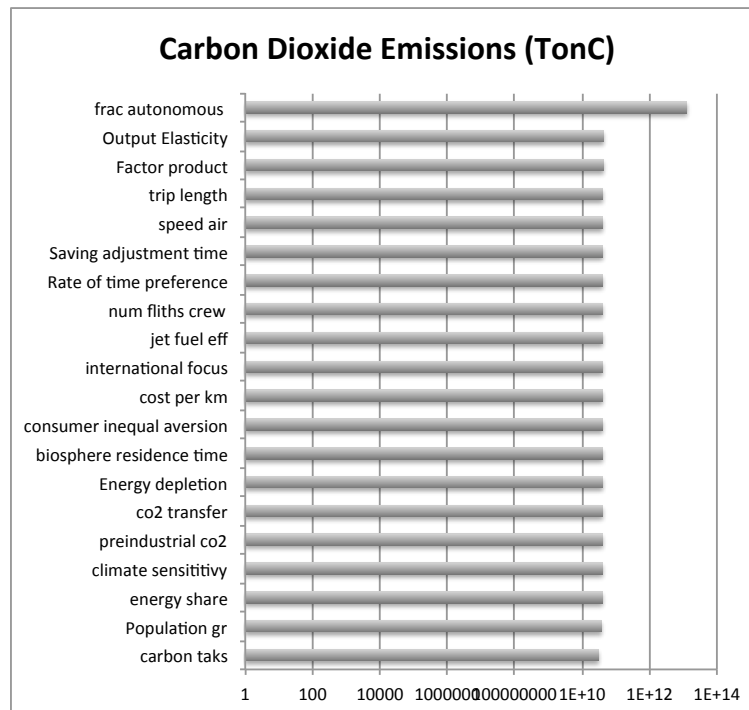


Figure 5.1 – Impact of key model parameters to Emissions (TonC/Year)

As figure 5.1 illustrates, the fractional autonomous efficiency rate has an enormous impact on the level of carbon dioxide emissions, thereby being expressed in a logarithmic scale. This has to do with the way the fractional autonomous efficiency rate is defined, small variations in this value do have major impact. The other parameters do effect the amount of carbon dioxide emissions less drastically, however increasing the carbon tax has a positive effect on the amount of emissions, which can be considered significant. This is in line with the expectations of scientists. Since the sensitivity analysis investigates fluctuations of 10% on top of the parameters describing a scenario, the impact on emissions is relatively invariant. Thereby the analysis is performed at the end-run of the model, only illustrating the final output relative to the original (scenario based) output.

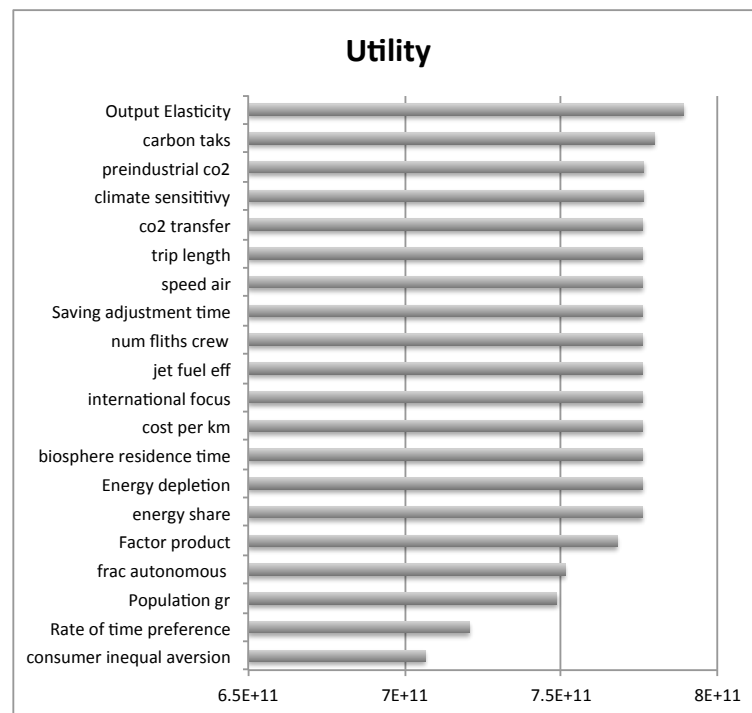


Figure 5.2 – Impact of key model parameters to Utility (dmnl)

As figure 5.2 illustrates, the utility is strongly affected by the consumer inequal aversion, rate of time preference, population growth rate, fractional autonomous, and factor productivity parameters. These parameters are directly related to the utility variable in the model. As expected these parameters do impact the output of utility. The output elasticity of impacts the utility variable as well since an increase in output elasticity results in more production, which will grow faster in contrast to the over variables that do affect utility, thereby having a positive effect.

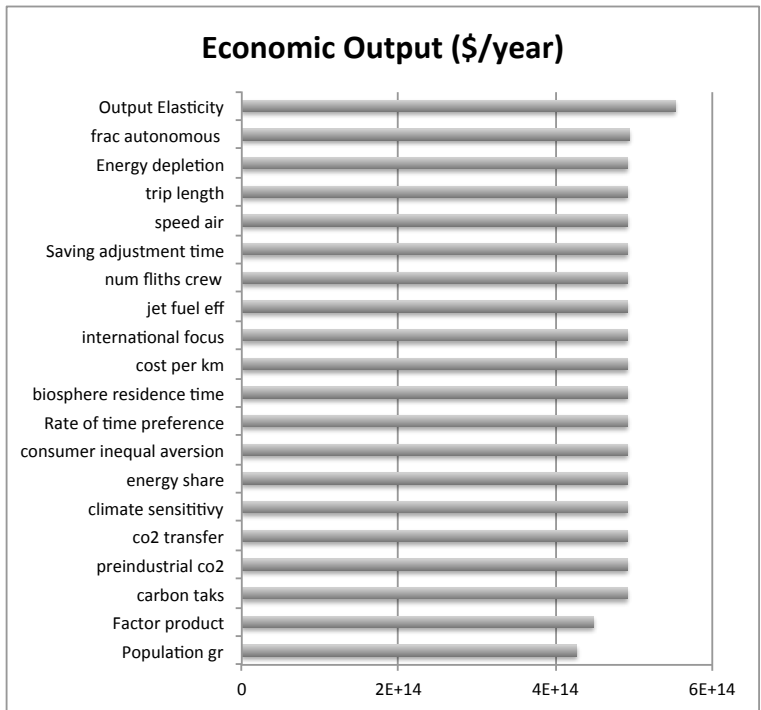


Figure 5.3 – Impact of key model parameters to economic output (\$/year)

As for utility, the economic output is affected by the output elasticity parameters of the model. Since the utility is directly related to economic output, it can be expected that the economic output is affected too. Thereby the factor productivity rate and population do have significant impact on the economic output as well. Carbon tax has also an impact on the economic output, however, scenario A (on which this sensitivity analysis is based) has a focus on alternative energy sources. This makes the impact of carbon taxes smaller than in conventional scenarios.

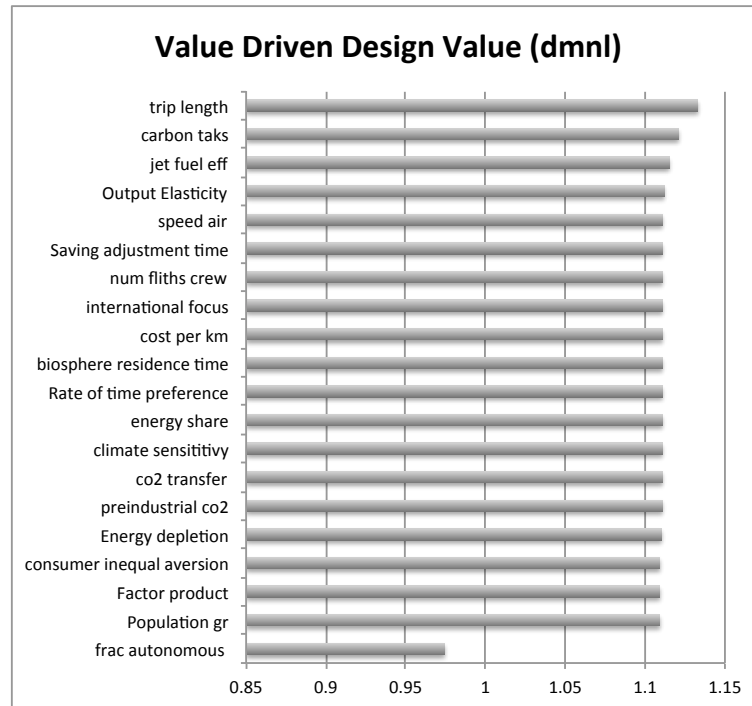


Figure 5.4 – *Impact of key model parameters to Value Driven Design Value (dmnl)*

The value driven design diagram shows interesting behaviour of the model. As expected the value operations methodology is focussing on economic performance of an airline, the environment, capacity and market requirements. As expected, the value scores for airlines are thereby strongly affected by the trip length of a leg, since this impacts the utility drastically. Carbon tax is also a parameter having significant impact on cost lever and environmental lever. The fractional autonomous growth rate is the indicating the level of an energy source is able to become more energy efficient. A reduction in the fractional autonomous parameter impacts the fuel efficiency of an airline, so the airline in the obtained a sub 1 score on the VDD index.

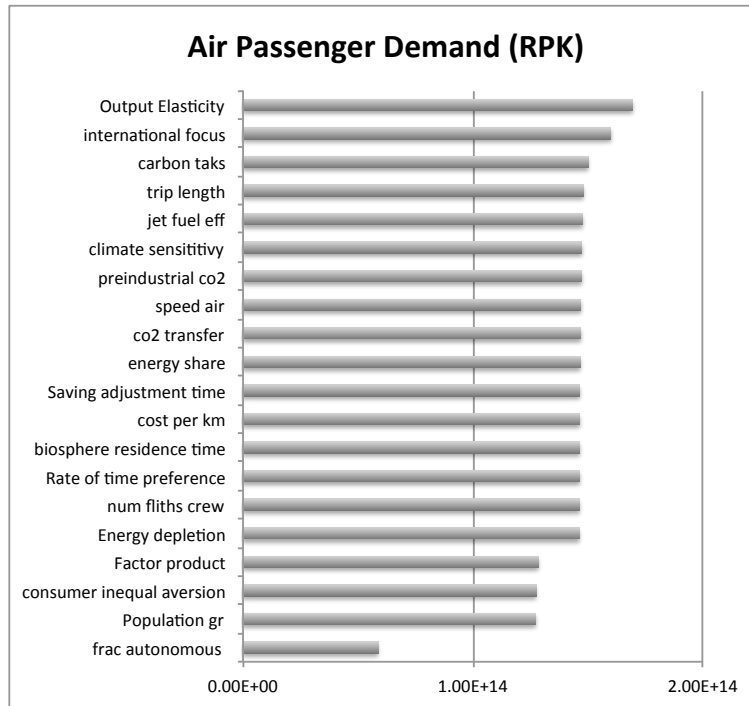


Figure 5.5 – Impact of key model parameters to Air Transport Demand (RPK/year)

The simulated air passenger demand is impacted by the parameters as expected. The output electricity of energy is impacting the economic situation, thereby driving the air passenger demand most. The level of international focus is also impacting the demand for air transport, so does carbon tax. A reduction in taxes has a positive effect on the demand, since the fuel prices are lower, making the air fares better affordable, thereby increasing the potential for gaining utility, which is the un-capitalized driver for air demand. As for the VDD diagram, the fractional autonomous rate impacts air demand as well, since it increases the air fares, thereby decreasing the potential to gain profits. A smaller population growth rate impacts the demand for air transport as well. More inequality in welfare results in a smaller air passenger demand, since the amount of people that are able to fly differs, people that are able to move by air transport cannot compensate the decrease in demand by making more air transport movements. The rate of time preference is likely to impact the demand for air passenger demand, however it is not impacting that much, this seems to be strange, since more valuable time should result in higher penalties for slower transport modes. An explanation could be in the level of time preference scenario A uses. In this situation the time preference is at such a level, people are not even likely to travel long distances by alternative transport modes, since their critical transition point is already reached. A varying in the time preference rate therefor will not imply a significant output variation.

5.1 Multivariate Sensitivity

The parametrical sensitivity analysis is unfortunately unsatisfying since the model behaviour is non-linear, and univariate sensitivity analysis neglects potentially critical in-

teractions among variables. Additionally, the analysis makes no use of subjective information about the relative uncertainty of various parameters; it merely identifies parameter which, if they were uncertain, might have a substantial impact.

While it is beyond the scope of this work to conduct a full scale uncertainty analysis on the model, a preliminary exploration of the multivariate parameter sensitivity of the model is presented in this section. The multivariate parameter sensitivity in this section is based on an analysis performed by Thomas Fiddaman and Peter Nordhaus. They have identified a set of uncertain distributions, which are useful to this analysis. The assigned key parameters are largely based on their work. Nevertheless, AVEM is structurally based on their models, which make the uncertainty distributions meaningful to AVEM. The parameter distributions are summarised in table 5.2

Table 5.2 – Parameter Distribution

Parameter	Distribution	Min	Max	Mean	SD
Population Gr. Rt. Decline Rt.					
	Normal	0.0027	0.033	0.019	0.0106
Frac Tech Gr. Rt. Decline Rt.					
Climate Sensitivity	Normal	0.002	0.024	0.011	0.077
Biostim Coefficient	Normal				
Climate Damage Scale	Normal	0	0.7	0.4	0.1
Initial Resource Oil/Gas	Normal	0	0.032	0.013	0.011
	Normal	2e13	4e13	3e13	3e12
Eddy Diff Coefficient					
	Normal	3300	5000	4000	300
Frac Autonomous Energy Eff Improvement Rate	Normal	0.001	0.023	0.011	0.076
Capital Energy Subst Elasticity	Normal	0.4	0.95	0.7	0.1
Energy Substitution Coefficient	Normal	1.05	3	2	0.33
Fractional Depletion Recovered	Uniform	0	1		

The variation of the key model variables and their distributions show significant changes in model output. The economic output for example varies, which is attributable to variation of population size, factor productivity as well as the autonomous technology coefficient. The climate damage on its turn has a smaller effect on the economic output. Table 5.3 summarises the uncertainty of key variables in the AVEM simulation. In fact, a Monte Carlo simulation could be used to assess whether the model is close to the deterministic simulation values. Unfortunately, the Anylogic version (Educational) that is used to build AVEM does not support multivariate Monte Carlo simulations. Therefore table 5.3 only provides minimum and maximum values to the key model variables, and normal standard deviations, means and medians omitted from the table initially. In order to provide an estimation of the uncertainty, the table is enhanced with data from other

SENSITIVITY ANALYSIS

models, which use similar structure for economic output, and emissions.

Table 5.3 – *Uncertainty of Key Model Variables*

Key Variable	Min	Max	Mean	Median	Norm. SD	Determ.
Economic Output in 2150 (10e11\$/year)	107	609	271	239	0.427	236
Energy carbon dioxide emissions in 2150(TonC/year)	4.5	38.4	23.4	22.3	0.422	24.8
Ocean Temperature increase in 2150 (DegreeC)	0.72	0.94				
Temperature increase in 2150 (DegreeC)	1.83	2.94	3.75	3.67	0.241	3.8
Airline Performance Value (Airbus A380)	1.11	1.23				

6 Conclusion

Over the last decades the air transport industry has become a crucial part of modern society, enabling economic growth by providing transportation services of people and goods. As the air transport industry is strongly intertwined in our society, the dependencies of the industry with respect to other systems in the world are becoming more stringent. Variations in global economy, demographics, climate system and other transport modes can harm the industry significantly. Airlines need to make strategic decisions to sustain their businesses in short- and long-term. Organisations as the IATA help airlines to formulate proper strategies and help to optimise their performance. Despite IATA's knowledge, the world's future can unfold in many scenarios, introducing new risks and opportunities.

To cope with the risks and opportunities, this work focuses on the development of a tool to validate airline performance within the scene of the global system. Since the airline industry is strongly relying on systems as the economy, population, energy, etc. By relating the air transport industry to the global "system" simulated, using an Integrated Assessment Model, the behaviour of airlines can be evaluated.

Based on an Integrated Assessment Model, describing the global systems based on physical, chemical and mathematical relations, the Transport Model calculates the demand for passenger kilometers. Based on the capacity of accommodating the demand for passenger kilometers, the model balances its global kilometer demand between two transport modes. Based on the modalities capacity, energy prices, GDP, population, welfare and other socio-economic variables, the model calculates modality specific costs and time per passenger kilometer. For every time step in the model, the demand is calculated. Every system within the model is recalculated to mimic realistic behaviour.

Based on the scenario exploration and validation of airline performance, can be concluded that the validation of strategy and effect of future pathways on the air transport industry can be assessed by a model as AVEM. This work validated the economic as well as the non-economic performance of a global airline business based on three types of aircraft. In this work an efficient short-haul aircraft (Boeing 737-800) is considered as well as a medium-haul Boeing 777-200 and a long-haul Airbus A380-800. The Airline Value Evaluation Model is found to be a suitable tool to:

- Provide a coherent framework for organising and assessing knowledge about the scene in which the air transport industry operates.
- To help differentiate among (airline) policy options.
- To understand which of the many uncertainties about the modeled system are most important.
- To help inform the research planning process.
- To garner qualitative judgements and insights into the interaction of components

of the modeled systems.

The Value Operations Methodology used in this work provides an interesting insight in the added value for an airline from aircraft perspective. Based on this information, an airline can select the proper aircraft for a particular "future". The Airbus A380 seemed to be the obvious winner, however the focus on sustainability and economic prosperity can unpack adversely eventually. High carbon taxes and personnel cost will have a negative impact on both the A380 as well as the total air traffic industry. The long haul Airbus A380 is efficient on long flight legs, however, in the future people will travel more and more regionally. In this situation the long turnaround times and high capacity make the aircraft inflexible on short-haul flights. Besides, airline's fleet can be considered as putty-clay, implicating a bought aircraft cannot be blacked from the company's balance. This has financial consequences for the airline in terms of maintenance, interest, depreciation and other costs associated with aircraft. This work provides a scenario, in which the ideal airline's utilisation rate drops below 0.85, that illustrates this effect clearly. This effect introduces additional cost, that could be avoided by operating more flexible aircraft, such as the Boeing 777-200 and Boeing 737-800. Therefor the Boeing 737-800 illustrates that short- to medium-haul, short turnaround time, fuel efficient aircraft turn out to be adding the most value to airlines.

Based on the validation effort that has been made in previous chapters, it can be concluded that a holistic model can help airline businesses to assess their performance in the future. AVEM is structured in a way it is able to deal with high-level global issues, such as welfare generation or energy demand, that help form a flexible research platform to evaluate the performance of industry specific issues. This work focuses mainly on the application of AVEM on the air transport industry, but in fact other (transport)industries can be evaluated as well using AVEM. The multi-level object-oriented platform structure, as AVEM is, allows researchers to simulate real world situations without having the need to fall back on extrapolation of historical data to generate scenarios, due to the proven mathematical, economic and bio-geophysical structures that form the basis of AVEM.

6.1 Future Work

Despite the capabilities of the AVEM, there are a variety of additional features and improvements that are suggested to improve its usefulness. The effort required to implement them may differ considerably and so would their importance. An effort was made in the next section to order them in order of urgency:

6.1.1 Intergrated Assessment Model

- AVEM is modeled as an aggregated "world" whereby there is no disaggregation in terms of economy and population. Thereby the model simulates based on global averages, instead of region specific situations. By taking into account multiple regions within the model, the simulation can focus more on the region-specific development of socio-economic variables, resulting in more detailed forecasts. Thereby

the transport model can rely more on the regions in terms of its calculation of transport demand.

- AVEM is based on primary energy sources, and does not distinguish end-use energy carriers thereby lacks the ability to represent the capital stocks in energy conversion explicitly. A distinction in energy usage, can result in a more realistic representation of substitution potentials, complementary infrastructure, learning and network effects.
- The accuracy of numerical integration should be checked by simulating models with different time steps and integration methods. For fast dynamics, appropriately short time steps or equilibrium solutions should be used [Fiddaman, 1997].
- Optimisation and sensitivity analysis are useful tools for discovering model flaws. An optimisation study could be performed to test the models robustness.

6.1.2 (Air) Transport Model Extension

- A detailed estimation method for (air) transport demand can help to simulate air transport demand more precisely. This helps decision-makers to formulate more effective measures to improve business performance.
- Replacement of the "one-aircraft" airline by a hybrid airline (e.g. 35% short-haul-, 25% medium haul and 40% long haul aircraft) can help to mimic the real air transport industry more accurately.
- Integration of mode transport modes can help to obtain more realistic behaviour in the transport industry.
- Adding additional dimensions to the model by dividing the world into multiple sectors (continents) will help to increase the accuracy of transport demand.
- A direct feedback loop from the endogenously modelled asset planning to air fare costs (in the transport mode selection logic) can help to skip an iteration in AVEM, which impacts the market share for trips, prior to the penalty that is added to the air fare during demand calculations due to lower asset utilisation.
- The Air Transport Model Extension focuses on the expenditures of airliners. Formulation of a full financial structure for an airliner, can help to eventually optimise the ideal conditions for airliners, by optimising an additional value function for the airliner.
- Carbon based fuels are the only energy sources used in the air transport system. This is nowadays realistic, however, aircraft in the future may be able to consume alternative fuels or even non-carbon based energy sources. This will impact the simulation results drastically, since the effect to the environment (sustainability lever) will differ.
- Aircraft aging. AVEM logic is based on one type of aircraft that is operational for the full length of the simulation. This is unrealistic in real life. The only compensation for time is made by the energy efficiency, which is determined by the energy

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system. Fuel consumption for example, stays constant. AVEM allows one to create custom aircraft, using the same simple sliders as used for scenario generation. The corresponding score (VOM) of non-existing aircraft can be evaluated. In order to provide a more realistic tool, the model should be enhanced with a system that replaces aircraft by their successor.

- The Transport Mode Selection logic can be extended by other transport modes. This work only distinguishes two transport modes, air transport and "other" transport. By adding other transport modes, one can evaluate the effects of other transport modes on air transportation. A (not jet invented) transport mode could outperform air transport on both costs, safety and time. Travelling by airplane is not the sole purpose of transportation, so if another transport mode is more effective in offering transportation services, what would be the impact to the aviation industry? Adding other transport modes to the equation is definitely worth exploring!
- An improved estimation of (aggregated) flight legs will improve the accuracy of the utilisation lever significantly. Once the IAM is split in multiple regions, one can simulate the gainable utility per region, resulting in a demand for transport kms. Based on a distribution, the efficiency of large capacity aircraft can be evaluated more precisely.
- Saturated airspace is a major concern for airlines, due to its negative effect on airline safety. A study on safety effects of airlines should be conducted and converted into the ATM/Value Operations Methodology, to provide inside in the value added by an aircraft type.

Besides the suggested improvements as listed above, future work can focus on incorporating more detailed models of the air transport industry. By enhancing the level of detail of the models within AVEM, the effect of a variation of one variable, can be validated to another variable. For example, by breaking-down the structural components of an aircraft, the effect of changing landing-gear can be validated in terms of changing air transport demand. This would for example take place based on the changing weight of the aircraft, which has an impact on the landing fees and fuel consumption, thereby impacting the airfare. Providing different conditions for which the Transport Model needs to calculate the transport demand. Detailed studies in operational structures as well as physical relations, can help to gain insight in opportunities that help to improve quality and efficiency of the industry.

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Part IV

Appendices

A Operating the Airliner Performance Evaluation Tool

The Airliner Performance Evaluation Tool is inspired on climate-economy models that are used by researchers around the world, the Value Operations Methodology is added to the system dynamics part in order to be able to assess the effects of socio-economic changes for airliner businesses, the model uses a value model. One of the key aspects of AVEM is its ease of use, the graphical user interface allows easy scenario generation. Sliders and buttons provide handles for user input.

A.1 Step 1 - Opening the application

To start the AVEM tool, open AVEM.alp in Anylogic 7.0.2 or higher and press Run (F5), see figure A.1. The Java applet will open.

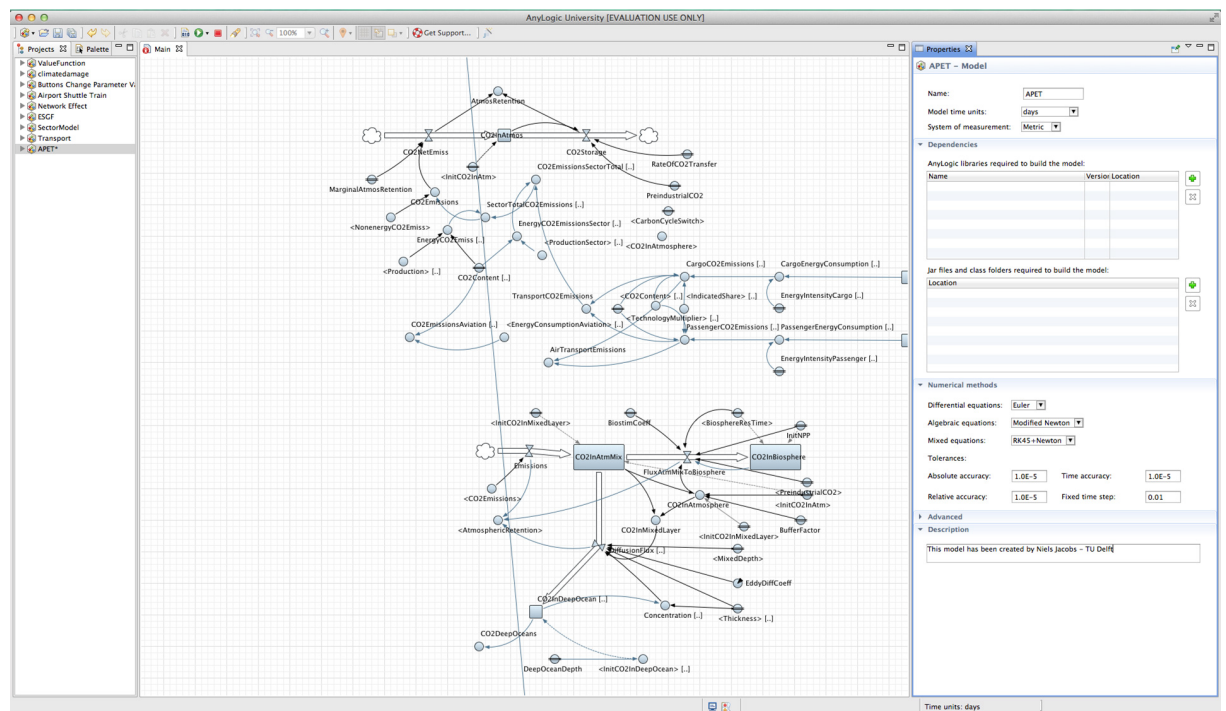


Figure A.1 – Anylogic Start Screen

A.2 Step 2 - Start AVEM

After opening the AVEM.alp file, a start screen, see figure A.2, will open. To design a scenario, click on *Run the model and switch to Main view*. The default scenario setup page will be shown.

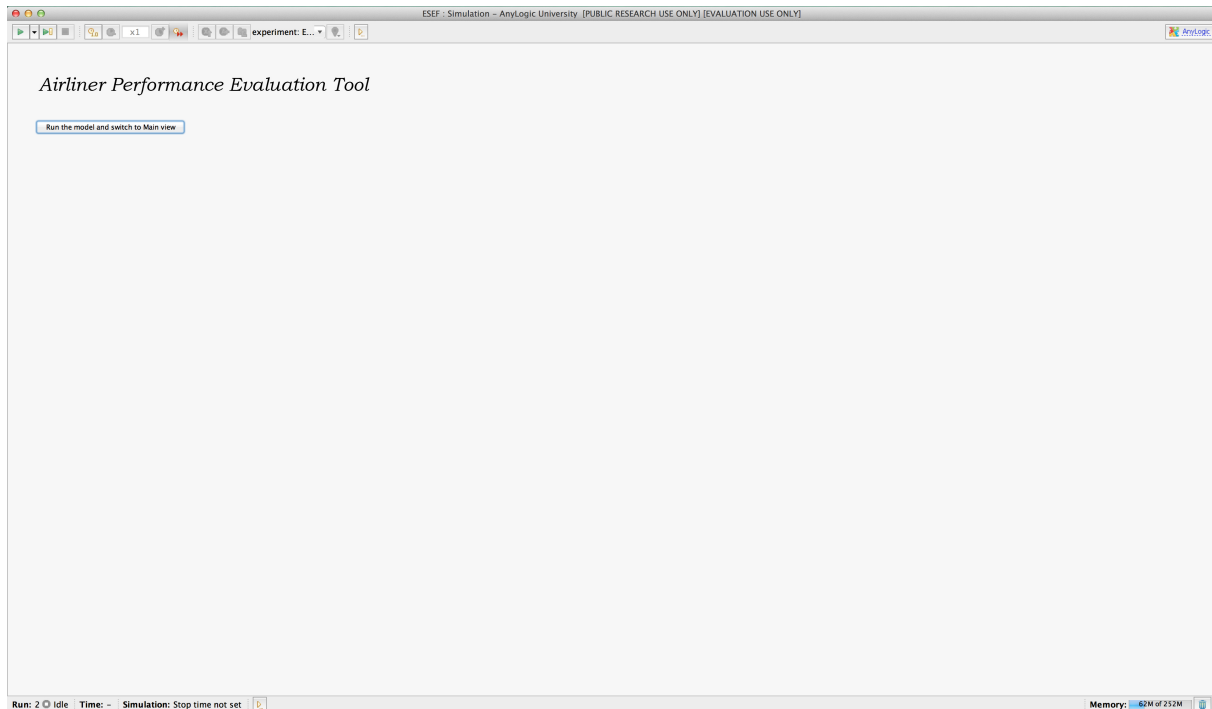


Figure A.2 – Screenshot of AVEM startscreen

A.3 Step 3 - Designing a Scenario

Once the application is running, the simulation will start with the default page, which is the scenario design page, see figure A.4. This graphical user interface provides all the handles required for designing a scenario. The exogenous variables, which are used to construct a scenario, are displayed categorically. By simple sliders, one can adjust exogenous variables, which are automatically changed in the model.

The best way to design a scenario is while the model is on pause. Otherwise the model starts running directly and any adjustment of an exogenous variable is not implemented from the beginning of the simulation, which is not desirable. Once the scenario is designed, the model could be started. Desirably, one could run the simulation from 1960 to 2150, or per time unit. To have the model running for a particular amount of time, click the small arrow, right from the run button and select the desired runtime, see figure A.3.

The scenario design page is enhanced with small plots that show the evolution of socio-economic indicators. This helps the user of the AVEM tool to check whether the scenario behaves as expected.

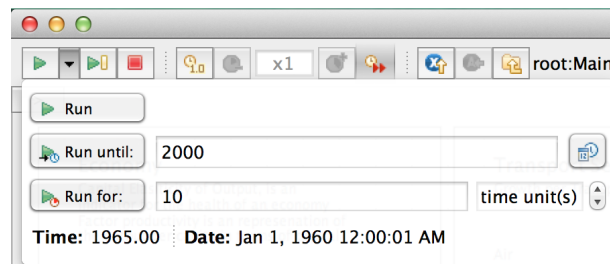


Figure A.3 – Optional runtime

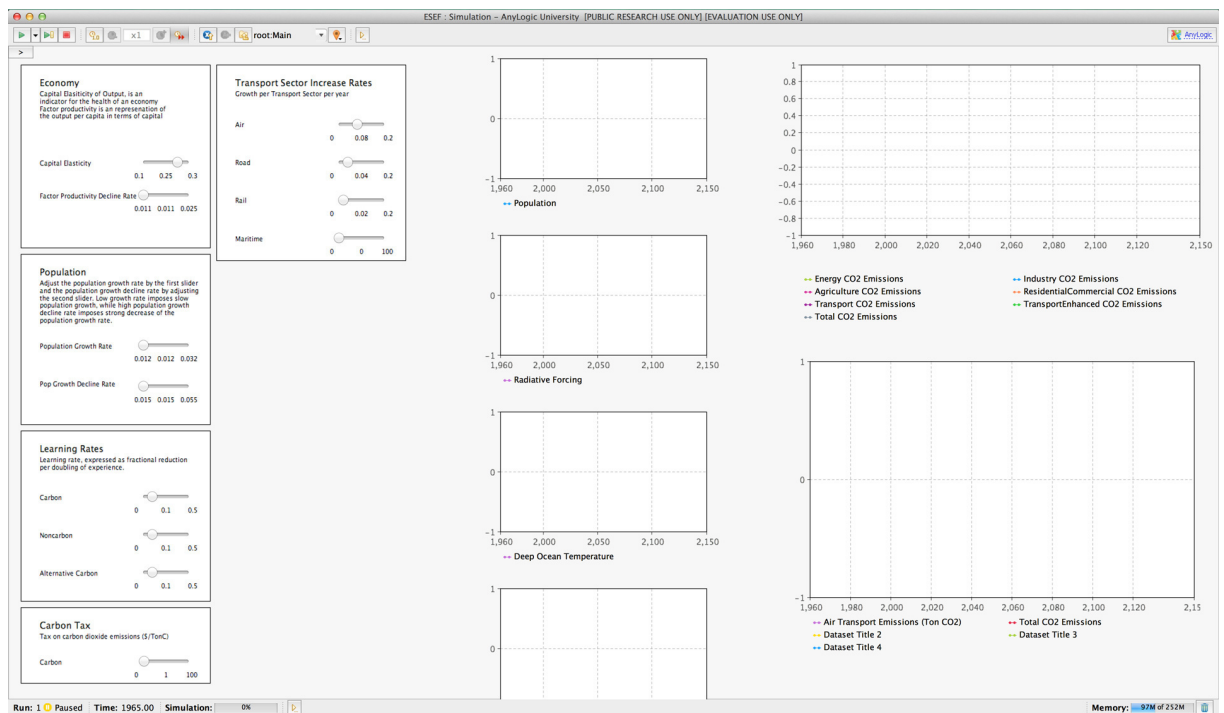


Figure A.4 – Scenario Design Screen

A.4 Step 4 - Sensitivity Analysis

To conduct a sensitivity analysis, the model offers a special designed page within the model. Based on a selection of essential exogenous variables, one can change the variables by plus or minus 10 percent. The impact on socio-economic circumstances as well as the value function, can be checked immediately. Simulation results can be exported into an .csv -file and used in an analysis tool. One can export every desired simulation output result for sensitivity analysis, this model only focuses on gross output, CO_2 emission, Radiative Forcing, Utility and Airliner Value Function. See figure A.5 for a screen cap.

OPERATING THE AIRLINER PERFORMANCE EVALUATION TOOL

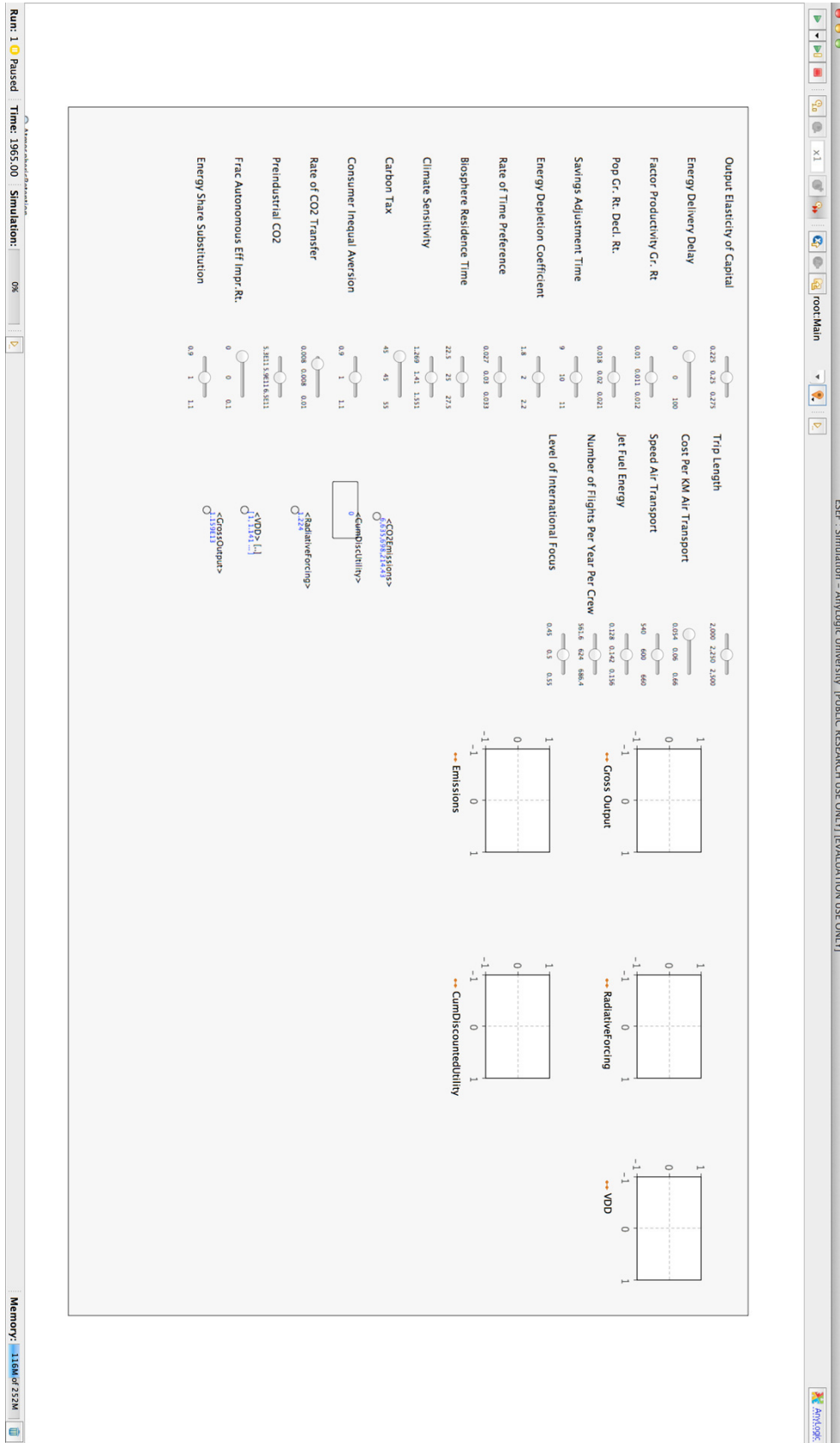


Figure A.5 – Screenshot of Sensitivity Analysis Screen

B Climate System

The intend of this chapter is to provide a comprehensive overview of one of the largest complex systems known to mankind. As the main purpose of this thesis is to approach the current view of the earth's climate system from a system dynamics perspective in the hopes of gaining new insights in the factors and causalities that cause the earth's climate system to change. This chapter provides the essential information and knowledge to understand the science assessed in this thesis.

B.1 Climate System Components

The climate system reflects the interactions between five major subsystems on global scale. The climate system involves the earth's atmosphere, the cryosphere, the hydrosphere, the earth's land surfaces and the biosphere. A schematic illustration of the climate system is provided in figure B.1.

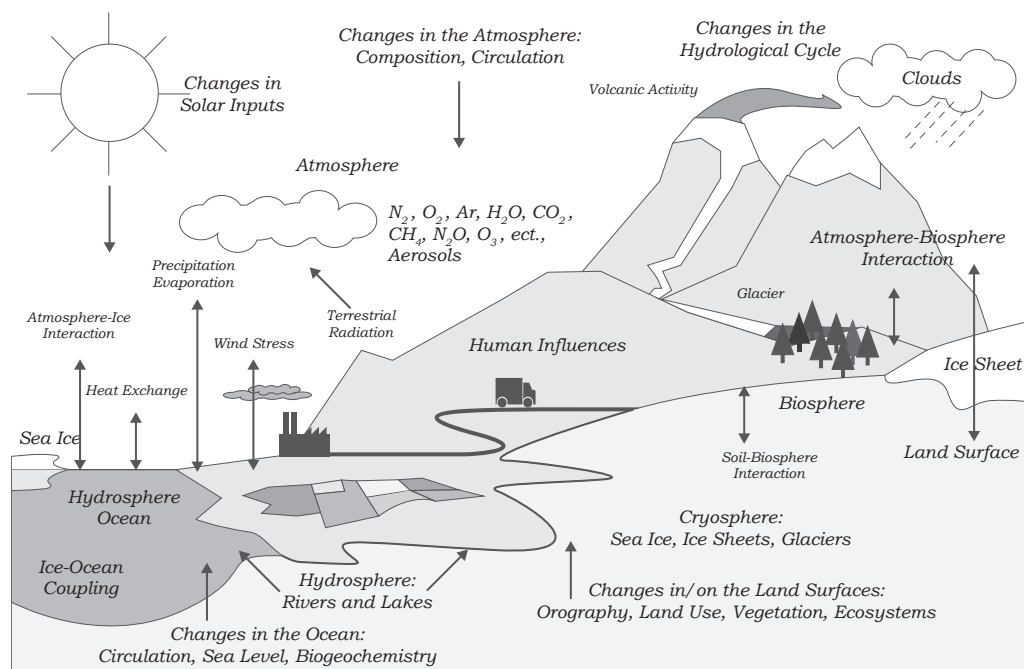


Figure B.1 – Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and the atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to the Earth as well as out to space [Kiehl and Trenberth, 1997].

B.1.1 The Atmosphere

The earth’s atmosphere is a critical component in the climate system, the atmosphere is highly unstable and can change rapidly. This instability can be explained by looking at the structure and composition of the atmosphere.

One of the characteristics of the atmosphere is the fact that the pressure and density decay exponentially over altitude. This can be seen in figure B.2.

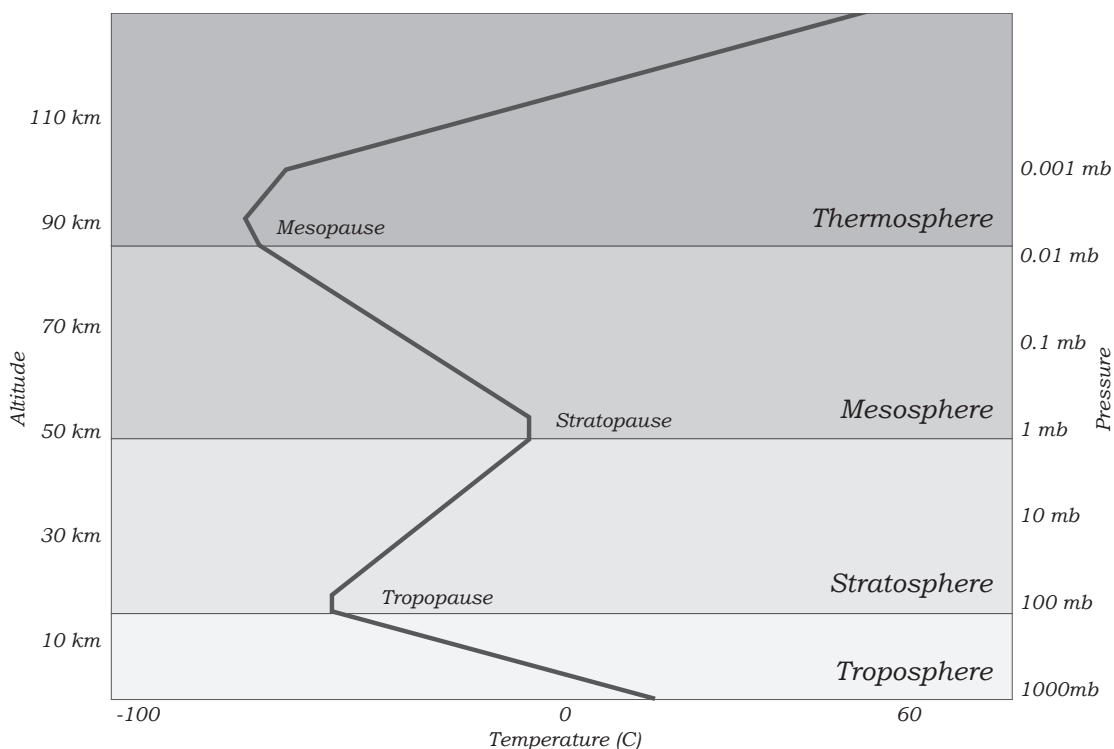


Figure B.2 – Vertical change in average global atmospheric temperature. Variations in the way temperature changes with height indicates the atmosphere is composed of a number of different layers (labeled above). These variations are due to changes in the chemical and physical characteristics of the atmosphere with altitude [Pidwirny and Jones, 2014].

The atmosphere can be divided into four major area’s, depending on the altitude, the Troposphere, the Stratosphere, the Mesosphere, and the Thermosphere.

As one can see in the figure, the temperature of the atmosphere at an altitude of 11 km reaches -50⁰ C. While the pressure almost decays to zero millibar at an altitude of 50km.

The decay in pressure and temperature can be explained by a combination of physical principles. The first principle is the ideal gas law for "free" gas, which the atmosphere consists of:

$$p = \rho RT \tag{B.1}$$

Where p is the pressure, ρ is the density of the atmosphere, $R = 287 \text{ JK}^{-1}\text{kg}^{-1}$ is the gas constant that is specific to Earth’s atmosphere, and T is the temperature.

The second principle is the force balance. Basically there are two forces acting on the atmosphere. The first one is gravity, while the second force is known as the pressure gradient force. It is the support of one part of the atmosphere acting on some other part of the atmosphere, thereby creating a balance. This balance is known as the hydrostatic balance.

Since the calculation involves only in vertical direction, the correct form of force balance is expressed by force per unit volume.

The gravity force can be expressed as in equation B.2

$$F_{gravity} = -\rho g \quad (B.2)$$

Where g is the gravitational acceleration for the earth's surface, equal to $9,81 \text{ ms}^{-2}$.

The pressure gradient force can be written in terms of a derivative:

$$F_{pgf} = \frac{dp}{dz} \quad (B.3)$$

The positive sign indicates that the atmosphere with greater density below exerts a positive, upwards, force.

In order obtain an equilibrium, the gradient force and the gravitational force should be in balance, indicating:

$$\frac{dp}{dz} = -\rho g \quad (B.4)$$

$$\frac{dp}{dz} = -\frac{p}{RT}g \quad (B.5)$$

$$\frac{dp}{p} = -\left(\frac{g}{RT}\right)dz \quad (B.6)$$

Equation B.6 is a differential equation that can be expressed as the atmospheric pressure as a function of altitude:

$$p = p_0 \exp\left[-\left(\frac{g}{RT}\right)(z - z_0)\right] \quad (B.7)$$

Where p_0 is the surface pressure and z_0 is the surface altitude. The equation stated above is known as the hypsometric equation.

The earth's atmosphere is composed out of oxygen (O_2 , 20.9% volume mixing ratio), Nitrogen (N_2 , 78.1% volume mixing ratio) and Argon (Ar , 0.93% volume mixing ratio). Due to their specific molecular characteristics, these gases do not have significant interaction with solar radiation. Beside the basis components of the atmosphere, there are trace gases present in the atmosphere. And precisely these gases do interact with the incoming solar radiation, by absorbing or emit solar radiation. The trace gases in the atmosphere can

be found in carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). However these trace gases are only responsible for 0.1% volume mixing ratio of the atmospheric composition, they are essential in the Earth's radiative balance. Besides the trace gases present in the atmosphere, water vapor is also of significant impact. However its volume mixing ratio is very variable, normally it is 1%. Greenhouse gases, including water vapor, absorb the infrared radiation emitted by the Earth and emit infrared radiation up- and downward, they tend to raise the temperature of near Earth surface [Houghton et al., 2001]. Water is the strongest greenhouse gas in the atmosphere. Due to the transitions between the phases of water in the atmosphere, water vapors release and absorb much energy.

Ozone is naturally present in the atmosphere. However it is naturally in the higher layers of the atmosphere. In the lower parts of the atmosphere (troposphere and stratosphere) ozone is a significant greenhouse gas.

Another component in the atmosphere are aerosols. This particular component consists out of solid and liquid particles that interact with the incoming and outgoing radiation.

B.1.2 The Hydrosphere

The hydrosphere embraces all the liquid surfaces, subterranean water, rivers, lakes, aquifers, oceans and seas. Since only oceans cover around 70% of the Earth's surface, the hydrosphere transports a large amount of energy, dissolve and store large quantities of carbon dioxide. The circulation in the hydrosphere is largely driven by the wind, precipitation and density contrasts caused by salinity and thermal gradients. The hydrosphere circulation is much slower than the atmospheric circulation due to the large thermal inertia of oceans [Houghton et al., 2001]. Figuratively the hydrosphere acts as a natural buffer climate change.

B.1.3 The Cryosphere

The cryosphere is different from the other parts of the climate system due to its high reflectivity, low thermal conductivity and large thermal inertia, due to the ice sheets, continental glaciers and snow fields, sea ice and permafrost. Because ice sheets contain enormous volumes of water, the cryosphere is of large influence to the sea level variations [Houghton et al., 2001].

B.1.4 The Biosphere

The biosphere is a major actor in the atmospheric composition, due to its release and absorption of greenhouse gases. Due to photosynthetic processes plants store large amounts of carbon dioxides and other greenhouse gases (however in lower significance). The impact of the biosphere can be identified in many records such as tree rings, pollen or fossils. Research conducted nowadays still uses the indicators from the biosphere to get to know past climates.

B.1.5 The Land Surface

The amount of energy received from the sun that is returned to the atmosphere is controlled by vegetation and soils at the land surface. There are multiple ways that the land surface interacts with radiation, by evaporation of water, soil moisture and indirect ways, like particles blown into the atmosphere that act as aerosols (for example Sahara sand). The geology and vegetation of the land surfaces impact the interaction with radiation to large extend.

B.2 The Earth's Energy Balance

The Earth's climate system is mainly powered by solar radiation. About half of the solar radiation is visible to the human eye and lies within the short-wave part of the electromagnetic spectrum. The other half is divided in a near-infrared part and a smaller part in the ultraviolet part of the spectrum.

On average, each square meter of the Earth's surface receives 342 Watts of solar radiation. A substantial part of this radiation is directly reflected back to space by the clouds. The remaining 235 Wm^{-2} ($342 \text{ Wm}^{-2} \times 0.69$) of solar radiation is responsible for the warming of the Earth's surface, the land and the ocean. Only a small part of this radiation is absorbed by the atmosphere itself. The Earth's surfaces release the radiation, in the form of infrared radiation, sensible heat and water vapor, back to the atmosphere. The interaction between the Earth's surface and the atmosphere result in a global near surface temperature of $14 \text{ }^\circ\text{C}$. Depending on the altitude, and corresponding atmospheric layers, the temperature will vary. Figure B.2 indicates the fluctuation of the temperature as function of the altitude and the corresponding pressure, see figure B.2.

As for all balanced systems, the inflow and outflow must be equal. This basic concept is not different for the climate system. Figure B.3 illustrates the details of this energy balance, which shows what happens with the incoming radiation and how the atmosphere emits the outgoing infrared radiation. Based on the incoming and outgoing radiation, the near earth surface temperature should be 19°C . However, the average global near surface temperature is $14 \text{ }^\circ\text{C}$, a difference of $33 \text{ }^\circ\text{C}$. This difference can be explained using the radiative properties of the atmosphere in the infrared part of the spectrum.

The atmosphere contains trace gases which absorb and emit infrared radiation. These gases trap heat within the atmosphere and emit radiation in all directions, including downward to the Earth's surface [McCarthy et al., 2001]. This mechanism is called the natural greenhouse gas. As a result of the upwards radiation from the earth's surface and caption of radiation by the trace gases in the atmosphere the temperature decreases gradually with higher altitudes. In balance with the incoming radiation, the infrared radiation that is radiated back into space from an altitude of on average $19 \text{ }^\circ\text{C}$, while the near surface temperature is on average $14 \text{ }^\circ\text{C}$ [Houghton et al., 2001].

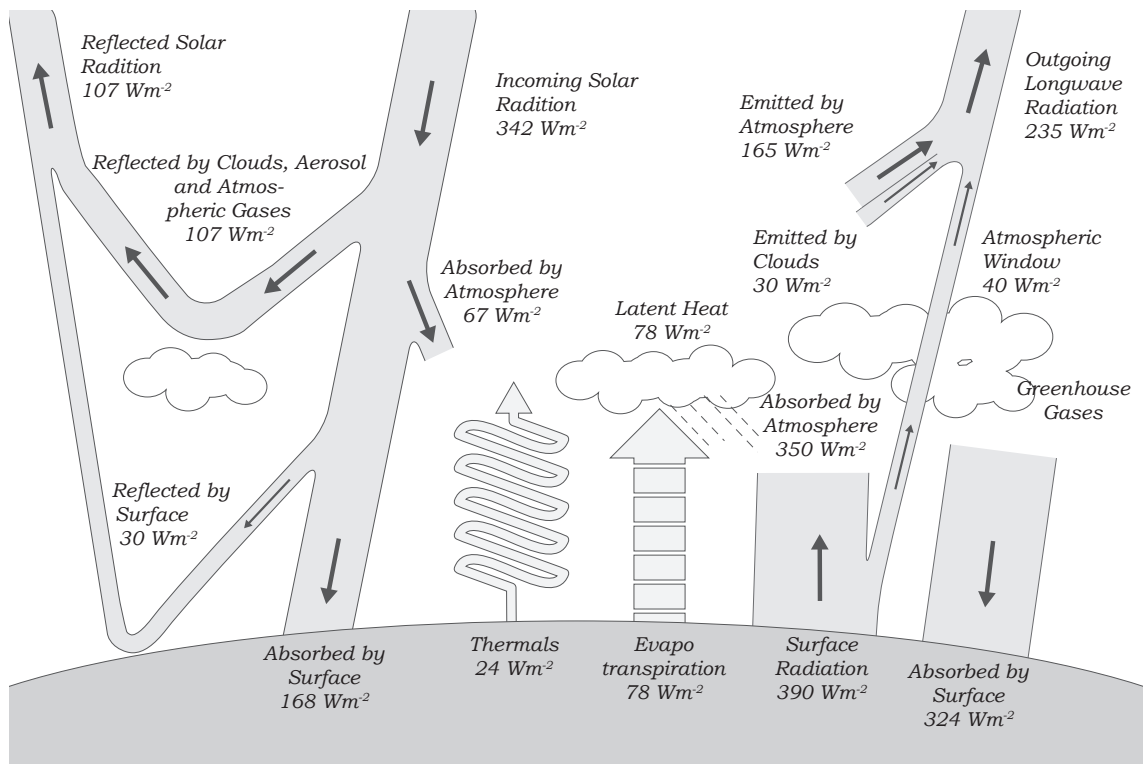


Figure B.3 – Illustration of the Earth's energy balance. [?].

B.3 Weather and Climate

Life on Earth is profoundly influenced by weather and climate. Weather and climate are to large extend responsible for the daily experience of human being and essential for food production, health and well-being [Watson and the Core Writing Team, 2001]. Due to the interactions between the components of the climate system, these components determine not only the day-to-day weather, but also the long term averages that we refer to as "climate".

"Weather" and "climate" are used interchangeably, despite their different meaning. According to NASA the difference between weather and climate is a measure of time [Staf, 2014]. Weather is the condition of the atmosphere over a short period of time, while climate is about how the atmosphere behaves over a relative long period of time [Staf, 2014].

The "weather" is the fluctuating state of the atmosphere and can be characterized as the temperature, wind, precipitation, clouds and other weather elements [Metz et al., 2001]. In practice, weather is constantly changing as a result of the rapidly developing and decaying weather systems such as mid-latitude low and high pressure systems with their associated frontal zones, showers and tropical cyclones. In contrast with the climate, weather has a very limited predictability. On larger scale, reliable predictability for weather is within a bandwidth of a couple of hours to several days. After this period, the predictability of weather is frankly senseless [Staf, 2014].

Climate, in the most broad sense, refers to "average weather". The earth's climate is normally described in terms of mean and average temperature, precipitation and wind

over a period of time. The period used for describing climate is ranging from a couple of months to millions of years. Climate can change from season to season or year to year. When statistically significant variations of the mean state of the climate are detected, typically persisting for decades or longer, one can speak of climate change.

B.4 Causes of Climate Change

Throughout the history of the Earth, the climate has warmed and cooled. Changes in climate can occur by subtle shift of the Earth's orbit, composition changes of the atmosphere or variations in incoming solar radiation. Scientists have conducted research on the climate variation of the Earth, however the earth's climate has varied over time for many centuries, they concluded that human activity has a significant impact on the variation of the climate.

An important question is: "How does this warming compare to the previous changes in the Earth's climate?", or "How can we be certain that human activities induce greenhouse gases that are causing climate warming?". In order to help gaining insight in the causes of climate change, we can divide the natural variability of climate and the human-induced variability of climate.

B.4.1 Natural Variability of Climate

Climate variations may result from radiative forcing, but can also occur from internal interactions between components of the climate system. In climate science, the distinction is made between externally and internally induced natural climate variability [Houghton et al., 2001].

Internally and externally induced climate variability

External forcings, such as the variation in solar radiation, or volcanic eruptions, can cause natural variation of the climate. Internal climate processes and feedback can also cause changes in climate system. These interactions are referred to as internal.

The response time for components of the climate system can be very different for variations in external forcing. With regard to the atmosphere, the response time of the troposphere is relatively short, in the range from days to weeks, while the response time of the stratosphere is relatively long, where it comes to equilibrium on a time-scale of typically a few months[?], citeipctar1. Different are the ocean, due to its large heat capacity, the response time of oceans are rather large, in the order of decades but can run up to centuries. Due to the heat capacity and composition of the components in the climate system, the interaction between the components can vary naturally, and therefor is never in total equilibrium.

Feedbacks and non-linearities

The response of the climate to the internal variability and the external variability is further complicated by the feedback and non-linear responses of the components. A feedback can be described as a process that affect its origin by intensifying (positive feedback) or reducing (negative feedback) the original process. Many processes in the climate system are non-linear. That means that there is no direct or simple proportional reaction between cause and effect. According to the IPCC TAR, the behaviour of the climate system is dependent on very small changes of initial conditions. The climate system can be described as chaotic, however that does not mean the climate system is unpredictable. A good example is the weather prediction. These predictions are normally not very precise and have a limited period for successful predicability of at most two weeks.

Although the climate system is highly non-linear, quasi-linear response of many models to present and predict levels of external radiative forcing suggests that the large-scale aspects of human-induced climate change may be predictable [Houghton et al., 2001].

Global and hemispheric variability

Earth has experienced climate change in the past without help of humanity. Due to evidence in tree rings or ice cores in glaciers, ocean sediments, coral reef or layers of sedimentary rocks, scientist were able to obtain information about the climate variability in the past. Based on information from ice core measurements conducted by Jouzel et al. (2007)[Jouzel et al., 2014], figure B.4 illustrates the temperature anomaly of the Earth's climate. The temperature anomaly is the difference between the long-term average temperature and the temperature that is actually occurring [NASA, 2010].

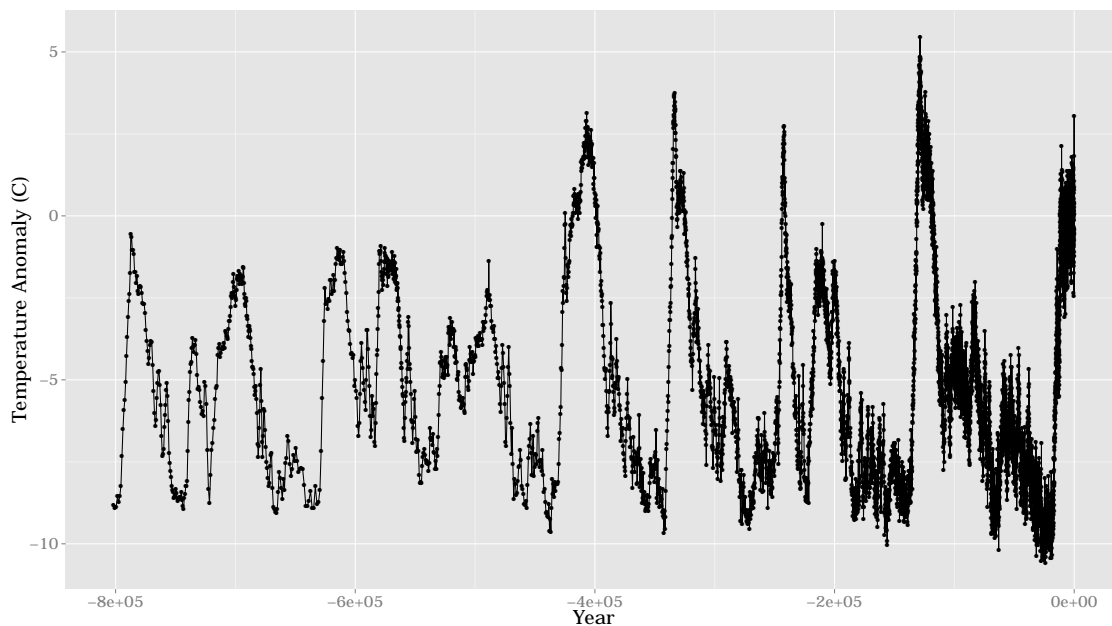


Figure B.4 – Record of the temperature anomaly for the last century [NASA, 2013].

As one can see in figure B.4 the number of measurements increased towards the current

year, as well as the natural variations in the temperature anomaly, which represent the glacial periods. The measurements of Jouzel comprise mainly the Northern hemisphere, due to the geographical position with respect to the availability of historic ice cores. Figure B.5 illustrates the stable behavior of the temperature anomaly for the last 12,000 year from now. Researchers suggest the Northern hemisphere climate of the past 1,000 years was characterized by a steady cooling, which can be observed from the smoothed line through the graph, where the temperature anomaly was slightly below 0 °C.

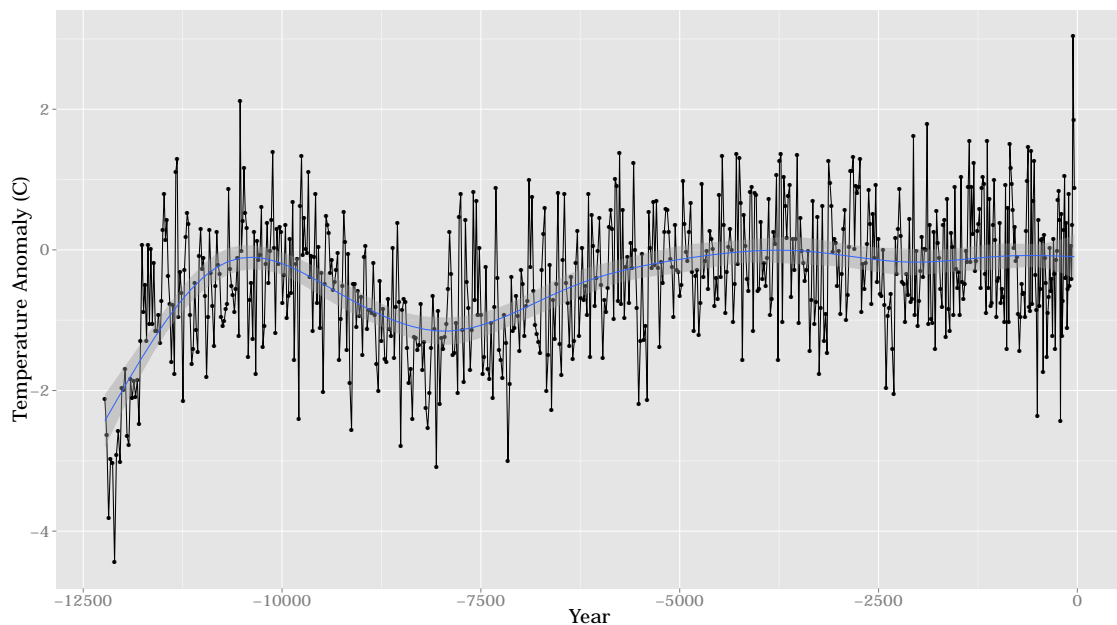


Figure B.5 – Record of carbon dioxide in glacial ice cores [?].

Despite the steady cooling of the climate in the past 1,000 years, the temperature anomaly has increased drastically in the past century. As one can observe from figure B.6 the temperature anomaly for the Northern hemisphere has increased. However there is no absolute consensus about the source for this increase in anomaly, many researchers blame human-activities as the main cause for this change [Houghton et al., 2001]. This cause will be treated in the section B.4.2

B.4.2 Human Induced Climate Variability

As long as mankind is active on the planet, human beings always have influenced their environment. For many millennia the impact of human-activities was negligible compared to the dimensions of the climate system, however since the beginning of the Industrial revolution, the impact of human-activities has begun to extend to a much larger scale [Metz et al., 2001]. Especially the fossil-fuel combustion related activities has impacted the environment drastically. Due to the production of greenhouse gases, aerosols and trace gases, the composition of the atmosphere was impacted. The emission of chlorofluorocarbons (CFCs) and other chlorine and bromine has led to depletion of the stratospheric ozone layer. While due to urbanization, forestry and agriculture, the physical properties of the Earth's surface has changed. These human-induced effects not only change the radiative forcing but also have a potential impact on the climate[Houghton et al., 2001].

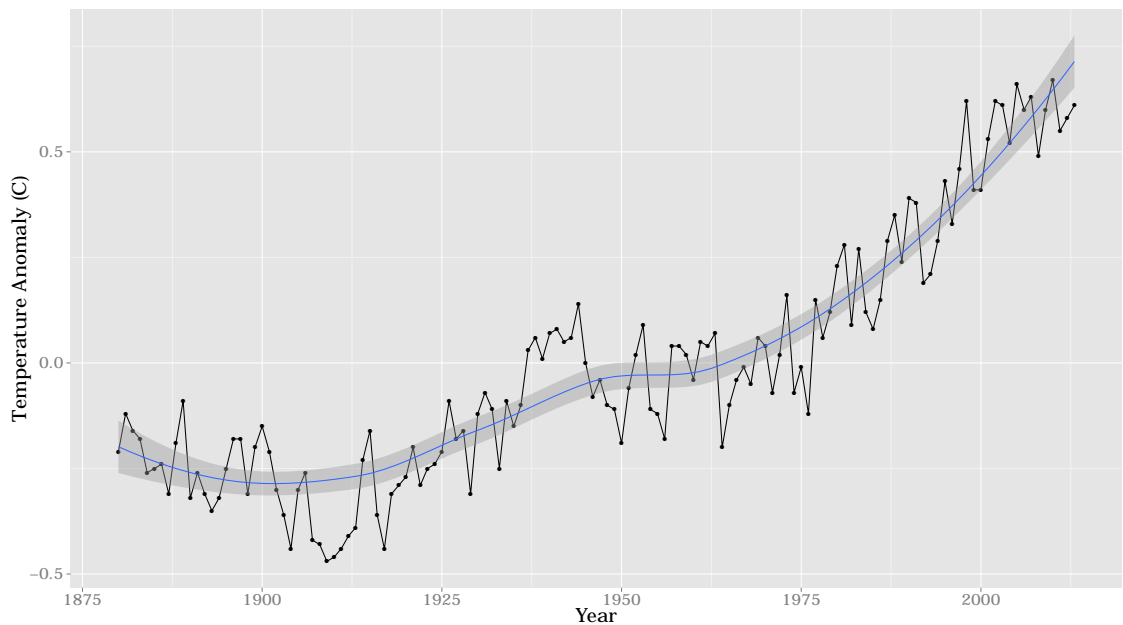


Figure B.6 – Record of the temperature anomaly for the last century [NASA, 2013]

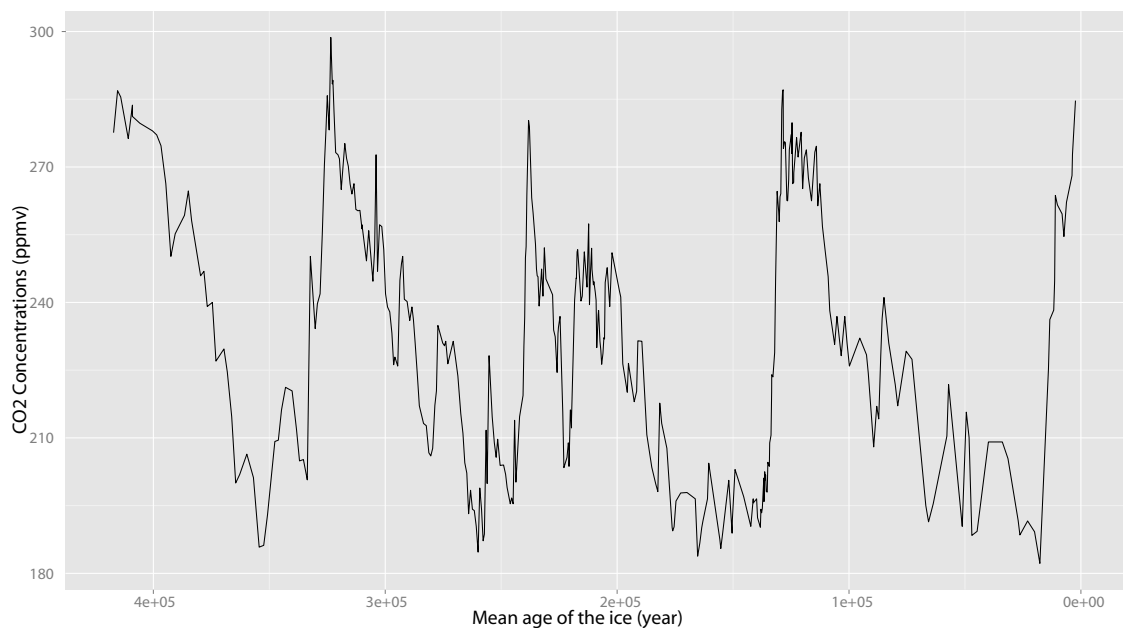


Figure B.7 – Record of the carbon dioxide concentrations over the last millenia [NASA, 2013]

For many millenia the concentrations of carbon dioxide in the atmosphere has remained relatively stable, not that there was no variation, but the concentrations of carbon dioxide showed a constant behavior on average, see (figure B.7). The carbon dioxide concentrations have never exceeded the 300 ppm boundary (on annual mean value). This has changed during the industrial revolution. The concentrations of carbon dioxide in the atmosphere has increased more than 30% since pre-industrial revolution and is still increasing at a rate of 0.4% per year. Figure B.8 illustrates the changes in atmospheric carbon dioxide concentration in the last 5 decades. As one can see, the CO_2 concentrations, ex-

pressed in ppmv, has passed the 300 ppmv level and is increasing year on year.

From the moment the industrial revolution evolves, not only the concentrations for carbon dioxide is increasing, concentrations of other natural radiatively active atmosphere components is increasing as well, due to industry, agriculture and other activities. The concentrations for nitrous gases (NO and NO_2) and carbon monoxide has also increased significantly over the last decades. Figure B.8, B.10 and B.9 indicate the vast increase of the concentration of human induced gases in the atmosphere.

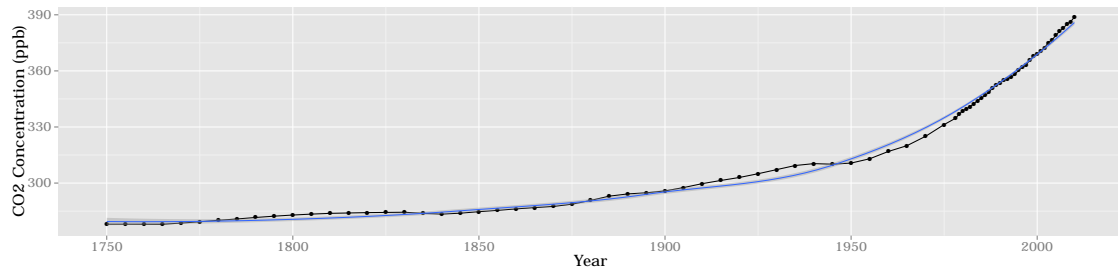


Figure B.8 – Record for global carbon dioxide concentrations in the last century. Data: European Environment Agency/ CDIAC [Agency, 2013a]

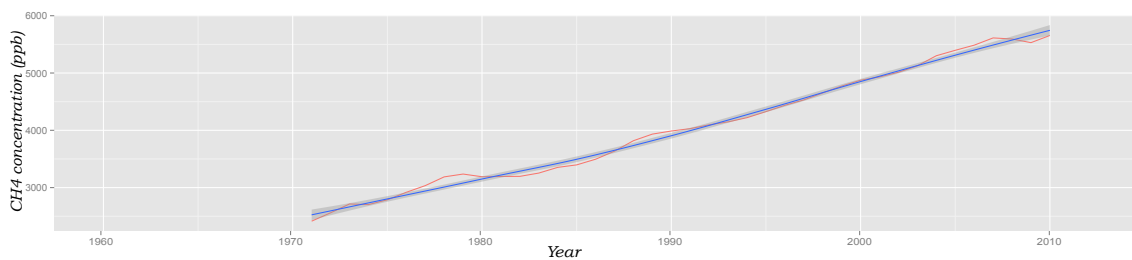


Figure B.9 – Record for global methane concentrations in the last century. Data: European Environment Agency/ CDIAC [Agency, 2013a]

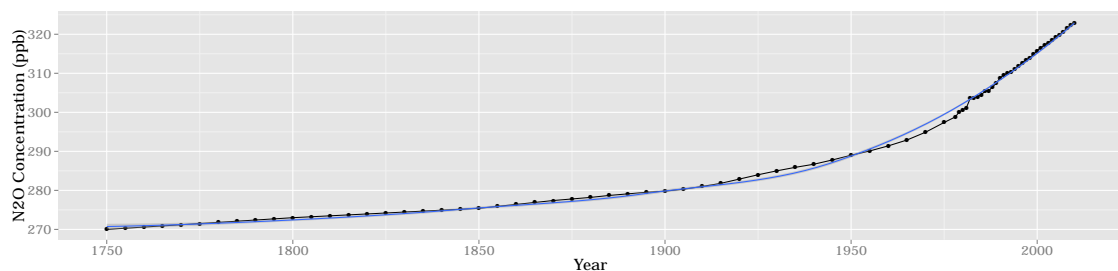


Figure B.10 – Record for global nitrous oxide concentrations in the last century. Data: European Environment Agency/CDIAC [Agency, 2013a]

Although the gases are not greenhouse gases, they play an important role in the atmospheric chemistry and have led to an increase in tropospheric ozone, by 40% since pre-industrial times [Agency, 2013a, Houghton et al., 2001]. Tropospheric ozone is a greenhouse gas and will be explained in section B.6.3. Human-activities have also introduced chlorofluorocarbons and other halogen compounds in the atmosphere, these gases are greenhouse gases, however their effects are partially compensated by their depleting ef-

fect on the tropospheric ozone layer.

Human activities also cause aerosols to exist in the atmosphere. Aerosols can exist out soot, dust, sulphates and nitrates [Grewe et al., 2007], and have a relatively short lifetime because they can be removed by rain. Their concentrations can vary for every region and season, and increase greenhouse gas concentrations regionally. They can have effect on the radiative forcing to which the climate system must act to restore balance [Houghton et al., 2001].

Enhanced Greenhouse Effect

In section B.2, the Earth's energy balance is explained. The amount of heat energy added to the atmosphere by the greenhouse effect is controlled by the concentration of greenhouse gases in the Earth's atmosphere. All of the major greenhouse gases have increased in concentration since the beginning of the industrial revolution (about 1750 A.D.). As a result of these higher concentrations, scientists predict that the greenhouse effect will be enhanced and the Earth's climate will become warmer [Crutzen and Graedel, 1993].

To give an example, if the concentration of carbon dioxide in the atmosphere is doubled, while the other concentrations remain equal, the outgoing radiative forcing would be reduced by 4 W m^{-2} . This implicates that the amount of energy that is not able to escape from the Earth's atmosphere, will result in an increase in near-surface temperature. Due to the complexity of the climate system, exact numbers for the increase in temperature cannot be calculated precisely, but will be in the range of $1.5 \text{ }^\circ\text{C}$ and $4.5 \text{ }^\circ\text{C}$ [Houghton et al., 2001].

B.5 Indicators of Climate Change

The Earth's climate system is subject to variability for millennia. However, since scientists are confident that many of the observed changes in the climate can be related to the increased concentrations in atmospheric greenhouse gases. Due to the current and future emissions, the concentration of these gases in the atmosphere will certainly increase.

In order to get track and communicate the causes and effects of climate change, it is necessary to use climate indicators. This section will elaborate on the climate indicators that are commonly used for scientific research as well as is day-to-day practices. Scientists, analysts, decision-makers and others use climate indicators to help monitor trends over time, track key factors that influence the environment and identify effects on ecosystem and society [MacCracken et al., 2012]

The climate change indicators in this section present the compelling evidence that the composition of the atmosphere and many fundamental measures of climate on global scale are changing. Measurements over time has proven the near-surface temperature is rising, the Arctic sea ice extend is decreasing, there are observed more extreme events. These observed changes have impact on humans as well as the environment. The changes in the climate system can cause fundamental disruptions to the ecosystems, affecting populations, global economy, fauna and biodiversity.

Institutions as the European Environment Agency, US Environmental Protection Agency, NASA, universities all over the world and other entities are gathering data to observe the changes in the climate system and communicate useful data to inform policies and programs based on this knowledge.

Research conducted by the EPA's office for Climate Change has provided a set of climate indicators that are chosen for a standard set of criteria that considered usefulness, objectivity, data quantity, transparency, ability to meaningfully communicate, and relevance to climate change [MacCracken et al., 2012]. The indicators are divided into five categories:

- Greenhouse Gases
- Weather and Climate
- Oceans
- Snow and Ice
- Society and Ecosystems

B.5.1 Greenhouse Gases

As mentioned in previous sections, the Earth's weather and climate is driven by solar energy. The solar energy reaching the Earth and its atmosphere is partially absorbed and partially reflected. The amount of energy that is reflected or absorbed is dependent on the amount and composition of gases in the atmosphere, referred to as greenhouse gases. These gases form figuratively a blanket around the Earth's surface, warming the Earth's temperature to a temperature higher than it without the greenhouse gases would be.

Due to human-activities the amount of greenhouse gases has increased, see figure B.8, B.9, B.10, thereby the concentrations of the gases in the atmosphere has increased. In order to quantify the effects of these gases in the atmosphere, scientists have introduced the indicator global warming potential (GWP). This indicator expresses the gas's unique ability to absorb energy combined with the length of time that the gas remains in the atmosphere [MacCracken et al., 2012]. The global warming potential of a gas is compared to the global warming potential of a equivalent mass of carbon dioxide (GWP = 1). The global warming potential is also used as a metric to relate the emission and climate impact directly.

According to many researchers and publications, number of factors influence the quantities of greenhouse gases in the atmosphere. Examples of these factors are: economic activity, population, technology, energy prices, land use, transportation, agriculture, forestry and more. In order to track the overall emissions and industry specific emissions, many countries keep records for specific sectors. Many countries started to keep track of this data from the early 60's. Thereby keeping track on the indicators for economy, environment, health, transport, climate, population, finances and other activities. This data is now represented in the World Data Bank [Ida,].

Figure B.11 shows the worldwide sectorial carbon dioxide emissions from 1960 to 2012, expressed in million metric tons of carbon dioxide. As is observable from figure B.11 the amount of emissions induced by the manufacturing, energy and heat production, and

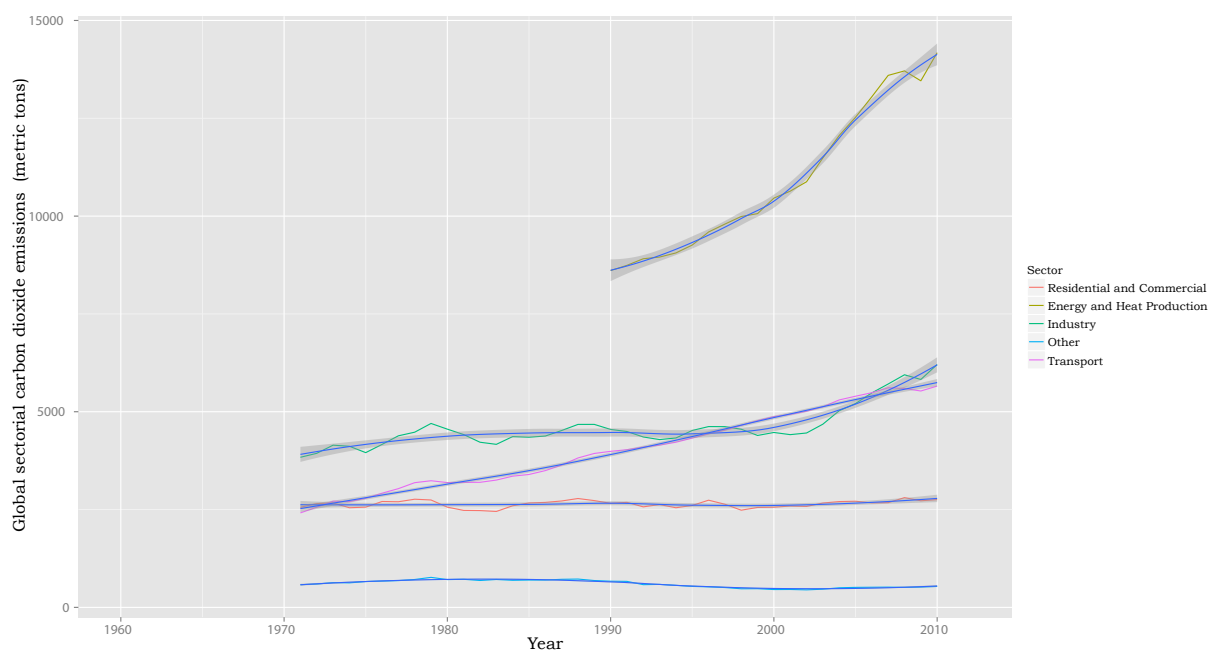


Figure B.11 – Record for global sectorial carbon dioxide emissions expressed in metric tons. Data: World Data Bank [Iida,]

transportation sector are increasing at considerable rates. The indicators for greenhouse gases focuses mainly on the emissions of carbon dioxide, methane, nitrous oxide and fluorinated gases. The measurements for these indicators is updated every month by several institutions [Staf, 2014].

Climate Forcing

When the Earth’s energy balance is altered, the average temperature on Earth will become warmer or cooler, leading to a variety of other changes in global climate. A number of natural and human-induced mechanisms are able to affect the global energy balance. Greenhouse gas concentrations in the atmosphere are a well-known examples of one of the examples. The greenhouse gases in the atmosphere can absorb or emit radiation and thereby influencing the energy balance of the Earth. Because several greenhouse gases remain in the atmosphere for decades, the impact of the emission of these gases can persist for a long time. The factors that can influence the Earth’s energy balance can be quantified in terms of "radiative climate forcing", mostly referred to as radiative forcing. Radiative forcing can be both positive as negative. Positive radiative forcing indicates a warming influence, while negative radiative forcing indicates a negative warming influence. As particular greenhouse gases have a positive impact and others have a negative impact on warming of the Earth, the difference between the positive and negative radiative forcing is driving the temperature changes.

The climate forcing indicator, measures about 20 different types of greenhouse gases. Because every type of gas has different capacity with respect to absorption or reflection of energy, radiative forcing converts the changes in greenhouse gas concentrations into a

measure of the total radiative forcing caused by each gas [Grewe et al., 2007, MacCracken et al., 2012]. Radiative forcing is calculated in Watts per meter (Wm^{-2}).

B.5.2 Weather and Climate

However weather and climate are regularly used for both each other to express the state of the atmosphere, there is a big difference between both. Weather is the state of the atmosphere at a particular time and location, while climate is the long-term average of the weather in a given place, while weather can change in minutes or hours, a change in climate is a process that takes longer periods to develop. Climate is not only expressed in average temperature, but also precipitation, the type, frequency, duration and intensity of weather events.

Temperature

As mentioned in section B.3, temperature is a fundamental measurement for describing the climate. Changes in temperature can disrupt a wide range of natural processes and human activities, especially during for example heat waves. As the concentrations of greenhouse gases are increasing steadily, the temperature of the Earth's atmosphere is rising. Since researchers predict the amount of emissions will even increase in the future, it might be expected that the temperature of the atmosphere has to increase as well. However, due to an increase in temperature, the climate change can shift towards wind patterns and ocean currents that drive the climate system in a way some might even experience cooling, while others experience more warmth. This again illustrates the complexities of the climate system [MacCracken et al., 2012].

Temperature is measured by many institutions that conduct surface measurements on global scale. In the past the measurements were land and marine-based, while since a couple of decades satellites help to gather information about the earth's surface. This evolution has helped to obtain more and more detailed information about the earth.

Many temperature indicators show anomaly as the record that compares the annual temperature values against a long-term average. Depending on the dimensions of the region, the measurements for temperature anomaly are divided in cells of a grid, averaging the data for all weather stations within each grid cell together. This method ensures that the results are not biased toward regions that happen to have many stations close together [MacCracken et al., 2012]. The global temperature anomaly for the couple of decades is shown in figure B.12. The data for this graph is obtained from the NASA GISS records [NASA, 2013].

High and Low Temperatures

High and low temperature records can always occur and are part of the natural variability in temperature. These variations can normally be assigned to the instability and interactions between the components of the climate system. However, since the climate system

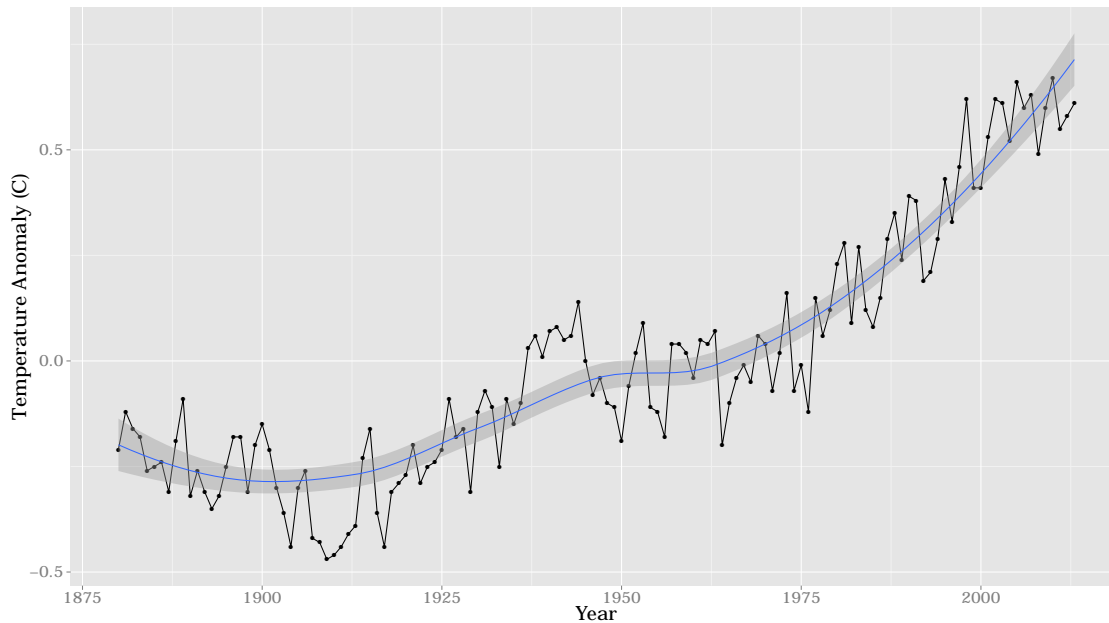


Figure B.12 – Record of the temperature anomaly for the last century [NASA, 2013]

tends to warm over the past decades, heat waves and extreme high temperatures are occurring more frequent and are most of the times more intense than they used to be. The heat index, which describes the experienced temperature, based on the actual temperature and the humidity, has shown more frequently high values [MacCracken et al., 2012]. Conversely, cold spells are expected to decrease.

In order to express the extreme variations in temperature, scientists has expressed the variations on a scale of land areas that are experiencing unusual hot or cold daily temperatures in winter or summer period.

Precipitation

Precipitation can have a wide-ranging effect on human well-being and ecosystems. Rainfall can have impact on the amount of water available for irrigation, drink water and industry. As the average earth’s surface temperature rises, more evaporation will occur [MacCracken et al., 2012]. Therefor scientists concluded that more rainfall is expected when there is more evaporation.

The amount of precipitation is measured by many weather stations across the world. Precipitation is often measured in mm, while the changes in precipitation are expressed in precipitation anomalies. Over the past decades, more precipitation is measured by the weather stations, however due to the number of weather stations in the beginning of the 20th century, measurements are somewhat less precise. Figure B.13 shows the global precipitation

Besides the normal precipitation measurements, climate research institutions keep track of the extreme precipitation events. Extreme or heavy precipitation events refer to the situation where the amount of precipitation experienced in a location is substantially

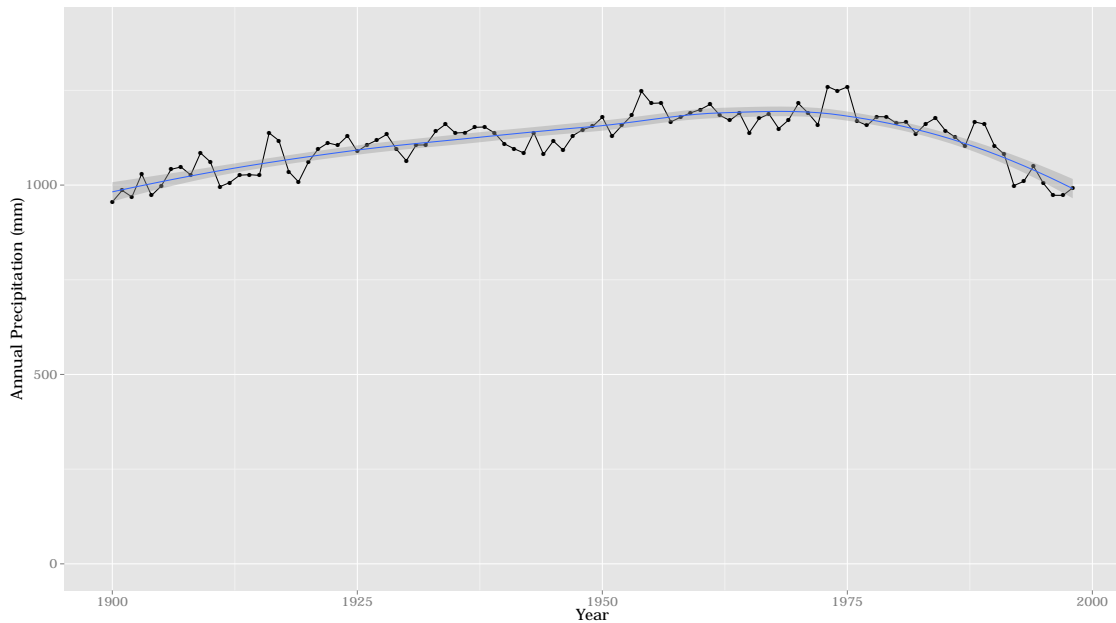


Figure B.13 – Record of the global annual precipitation. Data: MPI Echam [Bank, 2012]

exceeding the amount for normal precipitation. When the oceans and seas are warming, the amount of water evaporation will increase, when this moisture-laden air converts into a storm, it can produce more intense precipitation [MacCracken et al., 2012]. Heavy precipitation can cause damage to agricultural lands, cause floods and soil erosion.

Heavy precipitation is measured by its frequency of occurrence combined with the amount of precipitation. To quantify the heavy precipitation, scientists express this indicator by the percentage of land that experiences heavy precipitation.

Drought

Besides precipitation, the Earth's surface can also experience droughts. This is the lack of precipitation in areas that can cause serious water shortage for irrigation, drinking water or other activities.

According to researchers, the warming of the Earth's surface increases the moisture-laden air quantities, while it dries out land surfaces. This change in climate, can cause longer and more frequent droughts for particular areas that are located off the storm track.

Droughts are commonly recorded by the Palmer Drought Severity Index, and is calculated by the temperature and precipitation. An index value of zero represents average moisture conditions for a given location, based on many years of observation. Positive values mean wetter conditions than normal, while negative index values indicate dryer conditions [MacCracken et al., 2012]. Other ways of observing droughts is to measure the precipitation, temperature, soil moisture, stream flow and vegetation health.

Cyclone Activity

Cyclones are well-known examples of extreme weather events. There are two types of cyclones, tropical and extratropical. Tropical cyclones get their energy from warm tropical oceans, while extratropical cyclones get their energy from the jet stream and from temperature differences between cold, dry air masses from higher latitudes and warm, moist air masses from lower latitudes [MacCracken et al., 2012].

Sea and ocean temperature increase is expected to induce more cyclones on long term. According to the Global Climate Change Research Program, it is very likely the increased levels of greenhouse gases have contributed to an increase of sea surface temperature increases, thereby forming cyclones.

For more than 200 years, records of cyclones have been collected. The number of cyclones is closely monitored by institutions and is measured from numerous weather stations across the world, both on land and oceans. For a couple of decades, cyclones are monitored by satellites as well. The cyclone activity is expressed using indices as the Cyclone Energy Index and the Power Dissipation Index, by monitoring the frequency, strength and duration of cyclones based on wind speed measurements.

B.5.3 Oceans

Oceans are an important component in the climate system. The oceans and atmosphere continuously interact, physically and chemically, thereby exchanging energy, gases and particles. Oceans influence the climate both regionally and globally.

Almost 70% of the planet's surface is covered by water, due to its enormous mass, the oceans have a huge energy capacity. Oceans are part of the Earth's climate cycle and store large amounts of carbon dioxides and other emissions.

Greenhouse gases trap the energy from the sun, due to the large heat capacity of the oceans, they absorb more heat, resulting in an increase in temperature of the oceans and higher sea levels. As stated above, oceans are part of the carbon cycle and absorb gases, carbon dioxide and other compounds. Thereby the oceans are helping to minimize the amount of greenhouse gases and limit the climate change induced by these gases. However, due to the absorption of carbon dioxide, the oceans' chemistry composition is changing and are becoming more acidic.

As explained in previous section, the rise of sea and ocean temperatures can induce extra cyclones. In less extreme situations, the increase in temperature can cause more moisturized air masses that change the typical precipitation behavior. The impact of acidic oceans can also have far reaching causes, it can reduce the availability of minerals and make it harder for organisms, such as coral and shellfish to build skeletons. The effects of changes in the oceans have substantial effects on the biodiversity of ocean ecosystems [MacCracken et al., 2012].

Ocean Heat

Solar radiation and reflected heat are absorbed partially by the oceans. The absorbed solar radiation and heat is initially absorbed by the upper surfaces of the oceans and transported towards lower layers of the ocean over time. The oceans also transport heat by the ocean currents. Due to the high heat capacity of water, oceans warm much slower compared to air in the atmosphere.

In order to express the total amount of heat stored in the oceans, scientists refer to ocean heat content. The measurement of water temperature reflects the amount of heat in the water at a particular time and location [MacCracken et al., 2012]. Based on research on the ocean heat content, it is shown that the additional energy due to the trapping of energy by greenhouse gases is currently absorbed by the oceans for 80% to 90%.

Water has the characteristic of expanding slightly when it warms, an increase in ocean temperature will therefore result in an increase in the volume of water in the ocean. This is one of the explanations for the rise in ocean and sea levels.

Sea Surface Temperature

One of the most important attributes of the ocean's physical conditions is the sea surface temperature. The temperature of the sea surface varies with latitude. The warmest sea surfaces are near the equator, while the coldest sea surfaces are located in the Arctic and Antarctic regions.

On short term, variations in the surface temperatures of seas can alter ecosystems, thereby threaten sensitive ocean life or alter migration and breeding patterns. On long term, variations in the sea surface temperature can impact the currents and circulation patterns. This can change the nutrition supply and can lead for example to declines in fish population, which in its turn can affect the lives of thousands of people depending on fishery.

Not only the effects of sea surface temperature increases affect the marine ecosystems, the changes in temperature can also impact the atmosphere, since the atmosphere and the oceans interact closely. Research showed the amount of water vapors over the oceans increased by about 5% over the past century. This effect can induce the cyclone activity or induce additional precipitation.

Over the past centuries one is measuring the temperature of surface water, however since the existence of new techniques the data has become more reliable. Satellite technology has positive contribution on the observational capabilities for sea surface temperatures.

Sea Level

One of the favorite indicators for climate scepticists is the sea level. As the Earth warms, the sea level is rising. Two main explanations can be made for this relation: Changes in the volume of water and ice on land can increase or decrease the volume of water in the ocean; and the fact water expands when it warms. Since this effect is cumulative over the entire depth of the ocean, this effect is a major contributor.

The changing level of the sea can affect many human activities all over the world, especially low-lying lands. Holland is for example subject to the threats of a rising sea level. It can cause coastal flooding and erosion, with all causes reserved. Land areas can sink into the ocean or wetlands can be changed into open waters.

Scientists use two indicators for to express the sea level rise. The relative sea level, where the measurements for the sea level is compared to the land area. In contrast, absolute sea level change refers to the height of the ocean surface above the center of the earth, without regard to whether nearby land is rising or falling [MacCracken et al., 2012].

Ocean Acidity

The oceans play an important role in the carbon cycle of the Earth. The surface waters of the oceans absorb heat and gases. Around 80%-90% of the carbon dioxide is absorbed by the mixed layer of the oceans. Over a long time period, the absorbed carbon dioxide and other gases and particles, are transported to the lower layers of the ocean. Due to the slow mixing time of the layers, it takes hundreds to thousands years to establish a balance in the absorption of carbon dioxide and other greenhouse gases by the oceans. Over the past 250 years, oceans have absorbed approximately 40 percent of the carbon dioxide produced by human activities [MacCracken et al., 2012].

However, the oceans ability to uptake of carbon dioxide, preventing the atmosphere to warm even harder, the oceans are affected by the uptake of carbon dioxide and have an impact on marine life. Carbon dioxide will react with the sea water to produce carbonic acid. This will result in an increase of the pH levels in the oceans. The increase of sea level pH values, reduced the ability of minerals, plankton and other organisms to survive.

The pH trends in the atmosphere are monitored and modeled. Based on measurements and simulations, the relation between carbon dioxide dissolved in the oceans and the declined pH-values in the ocean can be assumed strongly related.

The pH-scale, the scale that is used for acidic measurements has 14 levels. Pure water has a pH of about 7 and is considered neutral. Matter with a pH-index lower than 7 is considered acidic, while higher values are considered basic or alkaline. In normal situations the average pH-level of the oceans, however is depending on the location of the ocean, is around 8.1 with a deviation of 0.05 [MacCracken et al., 2012]. Figure B.14 illustrates the pH-scale and the position of acid rain, normal precipitation and normal range of stream compared to other substances on the pH-scale.

B.5.4 Snow and Ice

One of the components of the climate system is the cryosphere. This component consists of land and sea ice, glaciers, permafrost and ice caps. The cryosphere is an important component of the climate system, due to the reflectivity of snow and ice. The incoming sunlight is directly reflected back into space by snow and ice. Thereby the sunlight is not absorbed by the Earth's surface and has a positive effect on the cooling of the atmosphere. On the other hand the presence of snow and ice affects the heating and cooling of the Earth's surface.

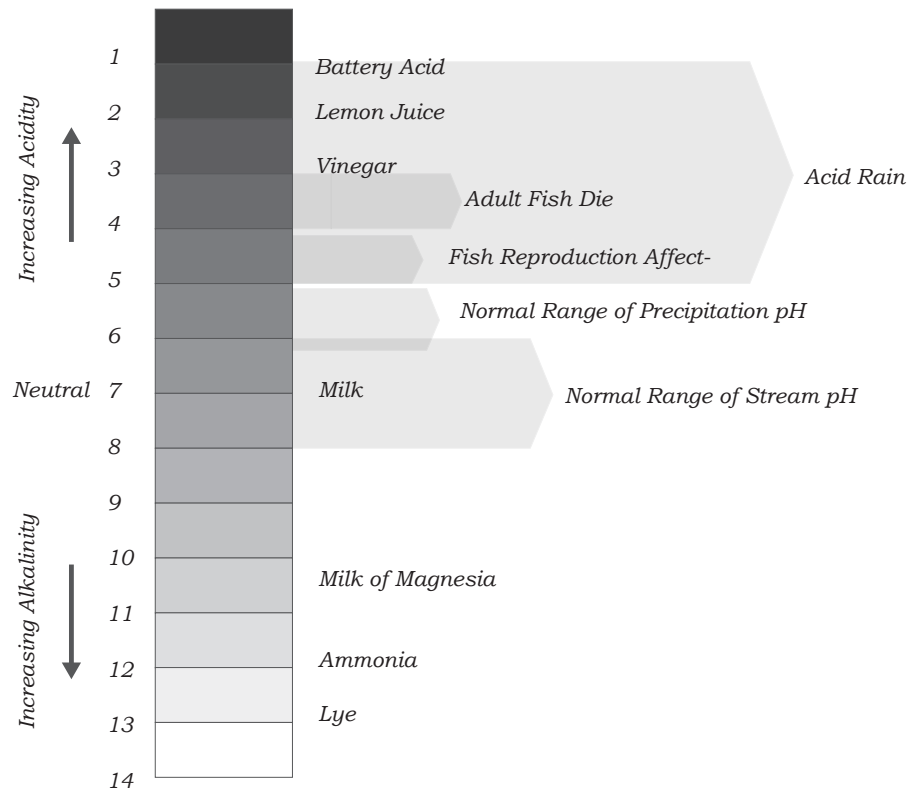


Figure B.14 – pH scale

Due to the circumstances snow and ice exist on the planet, mostly around the melting point, small variations in temperature can result in a change from solid state to liquid state for snow and ice.

Arctic Sea Ice

One of the largest masses of ice can be found in the arctic sea. In the winter months ice masses cover nearly the whole Arctic sea. In mid-September, the ice masses have reached its minimum thickness, and in the winter period the ice masses extend.

The increase in air temperature and ocean temperature causes ice masses to melt and therefor Arctic Sea Ice is an important climate change indicator.

The age of ice is an important indicator of the Arctic ice condition, since old ice is generally thicker and stronger than young ice. The loss of old ice indicates the arctic is losing ice faster than it is accumulating it.

The effect of climate change on the Arctic ice masses is twofold. On one hand, the reduction in ice masses impact directly the lives of many animals and the ecosystem. Since many wales, ice bears, seals and other animals rely on the ice masses as it is their area for hunting, breeding and migration. On the other hand the diminishing sea ice can also present commercial opportunities. The reduced sea ice opens shipping lanes and increases access to the natural resources in the Arctic region [MacCracken et al., 2012].

Arctic sea ice is normally expressed in surface area, square miles or square kilometers. Sea ice extend is defined as the area of ocean where at least 15 percent of the surface is frozen.

Glaciers

Glaciers are often under public interest. As the climate changes, the size of the glaciers is decreasing. Glaciers are large masses of ice, flowing comparable to a river but at a much lower rate. Glaciers are balanced by snowfall. The accumulation of snow is balancing the melting of the glacier. If the accumulation of snow is equal to the amount of ice melted, the glacier is in balance. Glaciers provide drinking communities and ecosystems with a reliable source of streamflow and drinking water. Glaciers are important indicators of climate change because physical changes in glaciers provide visible evidence of changes in temperature and precipitation [MacCracken et al., 2012].

Scientists collect detailed measurements to determine glacier mass balance, which is the net gain or loss of snow and ice over the course of the year. Negative values indicate a loss of mass, while positive values indicate a gain in mass. In some situations it can be useful to express the gain or loss in ice mass in equivalent amount of liquid water.

Snowfall

Warmer temperatures can cause more water to evaporate from the land and oceans, which leads to larger storms and more precipitation. In general, the warmer temperatures cause more precipitation in the form of rain than snow. But there are exceptions, when lakes are not frozen, there is more water to evaporate that can result in snow.

Many people and ecosystems are dependent on the amount of snow, whether it is for drinking water or recreation, while plants and animals depend on snow and snowmelt for survival. Changes in the amount of snowfall are not without consequences.

The indicator snowfall is measured in comparison to rainfall. The percentage of snowfall on the total amount of precipitation is used to express the amount of snowfall.

Snow Cover

Besides snowfall, the snow cover is also an important indicator. The snow cover, as the ice cover does as well, increases the albedo, the reflectivity of the Earth's surface. This causes more sunlight being reflected back into space thereby minimizing the amount of energy absorbed by the Earth's surface and the atmosphere. The snow cover is measured as the amount of land covered by snow. Thereby it is strongly impacted by the temperature and precipitation. As the temperature and precipitation patterns change, the overall area covered by snow can be affected.

B.5.5 Society and Ecosystems

The changes in temperature, precipitation, snow cover, ice masses, sea level and in all the indicators described in previous sections can present a wide range of challenges to human well-being, the economy and ecosystems. For society, human health effects from increases in temperature are likely to include increases in heat-related illnesses and deaths, especially in urban areas [MacCracken et al., 2012]. The changes in sea level, precipitation and the patterns of streamflow can damage the infrastructure and property, thereby demolishing roads, bridges and utilities.

Besides the effect of climate change to human beings, the changes in climate will affect ecosystems. Animal behavior, such as nestling, breeding and migration patterns can will be influenced. Since human-beings are reliable on the ecosystem for food, drinking water and much more services, it is important that the source for all these services cannot threaten human well-being. While species have adapted to environmental change for millions of years, the climate changes being experienced now could require adaption on larger and faster scales than current species have successfully achieved in the past. Thereby there is a risk of extinction of some species.

The more intense the climate changes, the more severe the effects of these changes can influence the ecosystems. The extent to which climate change will affect different ecosystems, regions and sectors of society will depend not only on the sensitivity of those systems to change but also on their ability to adapt to cope with climate change [MacCracken et al., 2012].

Streamflow

Streamflow is a measure of the amount of water carried by rivers and streams. It represents a critical resource for people and the environment. Since changes in streamflow can immediately affect ecosystems, the streamflow is closely measured. Streamflow can influence the amount of water available for drinking water, irrigation or energy production. Thereby many animals and plants depend on streamflow for habitat and survival.

Streamflow varies per season. In the spring, the streamflow of rivers on the Northern hemisphere experience the highest sustained flow, due to the melting water from the mountain ice masses and glaciers. In the winter, the streamflow is in most situations less sustained. Streamflows can cause erosion and damaging flows. In many countries the peak flow in streamflow is balanced by sluices and reservoirs. If the streamflow will reach high sustained flow, the water is led to the reservoirs to balance the increase in water level to prevent floods to happen.

Streamflow is measured in many countries by stream gauges. These gauges are placed in streams with no human interference, since the measurements otherwise will be influenced by human interaction (for example by dams and sluices).

Emissions

B.6 Greenhouse Gases

Many chemical compounds present in Earth's atmosphere behave as 'greenhouse gases'. There are gases which allow direct sunlight (with relative shortwave energy) to reach the Earth's surface unimpeded. As the shortwave energy heats the surface, longer-wave (infrared) energy is reradiated to the atmosphere. Greenhouse gases absorb this energy, thereby allowing less heat to escape back to space and trapping it in the lower atmosphere [Center, 2013]. Many greenhouse gases occur naturally in the atmosphere. Well-known components are carbon dioxide, methane, water vapor and nitrous oxides. Human-induced "greenhouse gases" include also the chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), sulfur hexafluoride (SF_6) and perfluorocarbons (PFCs).

All of the effects of the greenhouse gases in the atmosphere depend on three main factors [Agency, 2013b]:

- Concentration or abundance. This is the amount of particular gas in the air. Larger emissions of greenhouse gases lead to higher concentrations in the atmosphere. Greenhouse gases are measured in particles per million, parts per billion or parts per trillion. To provide any reference, one part per million is equivalent to one drop of water diluted into 13 gallons of liquid.
- Life time of emissions. Each gas can remain in the atmosphere for a different amount of time. This can range from a few months to thousands of years. If a gas has a very long lifetime, the concentrations of the gas in the atmosphere will become mixed with other gases. This process distributes the concentration of gases around the world.
- Impact on global temperatures. Some gases are more effective than others at making the planet warmer and "thickening" the blanket around the Earth.

For each greenhouse gas, a Global Warming Potential (GWP) has been calculated to reflect how long it remains in the atmosphere, on average, and how strongly it absorbs energy. Gases with a higher GWP absorb more energy, per pound, than gases with a lower GWP, and thus contribute more to warming Earth [Agency, 2013b].

In the next sections one can find an overview of the emissions that influence the chemical and physical characteristics of the atmosphere and clouds.

B.6.1 Carbon dioxide (CO_2)

Carbon dioxide is one of the most significant components of greenhouse gases. In a lot of combustion processes hydro carbonates will react with oxygen into carbon dioxide (CO_2) and water (H_2O). To illustrate the reaction size of hydro carbonates,

one kilogram of burned kerosine will result in 3.15 kilogram (CO_2). Carbon dioxide will be absorbed in the atmosphere around the spectral range of $15\ \mu\text{m}$, the terrestrial spectrum, that influences the solar radiation and will heat up the atmosphere.

Important factor of the influence of (CO_2) emissions in the atmosphere is the lifespan of gases in the atmosphere. Merely all of the carbon dioxides in the atmosphere will be noticeable to a maximum of 80 years [Hasselmann et al., 1997]. An important sink of carbon dioxides is the ocean, that will distribute the (CO_2) concentrations evenly over the atmosphere. For this reason the climate effects of (CO_2) are not dependent on the kind of emission, but more importantly the strength of the overall emissions.

However some industries emit relatively low amounts of carbon dioxides every year, the summation of the emissions emitted over 80 years result in undeniable contribution. Aviation industry is responsible for 2% of the total emissions of (CO_2) and responsible for a radiation supply of $28\ \text{mW}/\text{m}^2$ [Lee et al., 2009]. The reliability of this number is supported by scientific research on this topic, that is defined by the Level of Scientific Understanding (LOSU) as reliable. This research has also provided insights that state (CO_2) emissions do not have a strong impact on conversion or degradative processes. An interference of (CO_2) can cause a spectral absorption change in the atmosphere, what will influence the calculation of (CO_2) concentrations since the new and existing concentrations of (CO_2) are required over a longer period of time.

B.6.2 Water vapor (H_2O)

As for carbon dioxide, water vapor absorbs radiation as well. This is happening in the terrestrial spectral range from $5\text{-}8\ \mu\text{m}$. Water vapor is for $2/3$ a natural greenhouse gas, while the other part is human-induced. The lifetime of water vapor is related to its height in the atmosphere. In the lower Troposphere it's lifetime is just a couple of hours, while the water vapors in the Stratosphere can exist for more than six months [Grewe et al., 2007]. Additionally the concentrations of water vapor will decrease over an increase in height.

Besides carbon dioxide, water vapors are direct result of the combustion of hydro carbon fuels. One kilogram of burned kerosine results in 1.26 kilogram of water vapor. The impact of water vapors to the atmosphere is highly dependent on the concentrations in the atmosphere, temperature and the height of emission. In the lower parts of the troposphere the impact of water vapor is less significant. Research has estimated the radiation of water vapor to be $2.8\ \text{mW}/\text{m}^2$. However the impact of water vapor in the atmosphere is less than the impact of carbon dioxide, it cannot be denied. Due to the high natural variability of water vapors in the atmosphere, the climate impact can only be modeled with high uncertainty. Future research on the effects of water vapor are therefor unbearable.

B.6.3 Nitrogen Oxides (NO_x)

NO_x is the name for nitrogen oxides NO and NO₂ and is formed during burning of fuels. In the combustion chamber N₂ and O₂ oxide into NO. Due to chemical reactions in the atmosphere volumes of NO are converted into NO₂ and form a balance between NO and NO₂. The amount of NO created during combustion is dependent on the pressure, temperature and design of the particular combustion. Due to the low concentrations of NO in the atmosphere, its impact is not significant. However its indirect impact is undeniable. NO is influencing the formation of Ozone and Methane in the atmosphere. NO has a positive short-term impact on ozone, while the long-term influence of NO is causing a change in concentrations of methane which has a negative effect on ozone.

Photochemical

In figure B.15 a representation of the reaction and formation of ozone is provided. NO_x emissions in the upper parts of the troposphere and the lower parts of the stratosphere force the balance of HO_x to shift in the direction of OH. The OH molecules activates the oxidation of CO and CH₄ resulting in a NO catalysed formation of ozone [Fishman et al., 1979, Crutzen and Graedel, 1993].

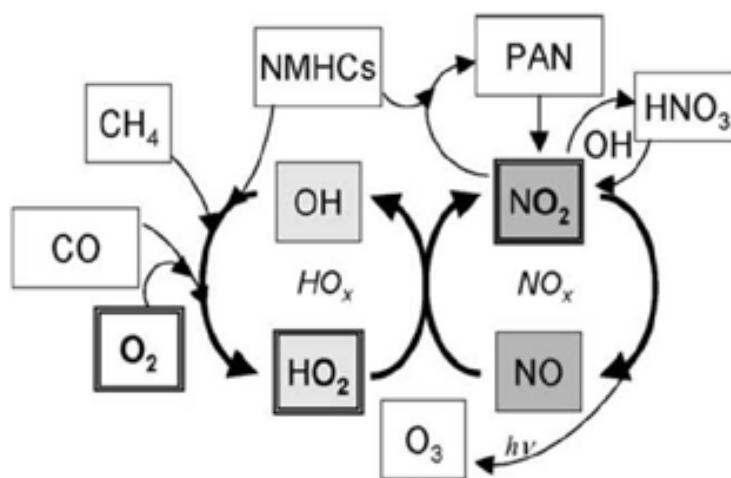


Figure B.15 – Schematic representation of ozone chemics

Ozone(O₃)

The impact of ozone on the environment can be twofold, since ozone absorbs in the terrestrial as well as in the solar spectral ranges. Although the absorption rate in the troposphere in terrestrial range is significantly higher than in the solar range [Fishman et al., 1979, Crutzen and Graedel, 1993]. Forcing ozone to be a greenhouse gases causing warming of the atmosphere. A lifespan of several weeks

in the upper parts of the troposphere cause the ozone to get distributed homogeneous in the atmosphere.

The radiation impact of ozone was estimated to be $26\text{mW}/\text{m}^2$ [Lee et al., 2009]. This number is subject to some uncertainties since the reactive characteristics of OH and NO_x are rough estimations and need to be investigated more closely. Another problem is the inaccurate determination of the emission index, making the total amount of emitted NO_x hard to determine.

Methane (CH_4)

Methane is an important greenhouse gas and mainly absorbs radiation in the terrestrial spectral range (7-8 μm). NO_x emissions raise the concentrations of OH in the atmosphere, which in their turn react together with CO_2 into methane. The warming effect of OH and NO_x is cancelled out by reaction and formation of CH_4 , in fact causing the atmosphere to cool down. The atmospheric lifetime of CH_4 is estimated to be 8-9 years. Due to the long lifetime of CH_4 , the gas is able to get equally distributed over the atmosphere. Thereby is the radiative impact on CH_4 less dependent on the height of the emission than ozone.

As the ozone production and the formation of methane is correlated to OH, the estimation of the net effect of NO_x is rather difficult to predict. Existing climate models usually calculate a large change in ozone while they find a large change in concentrations of methane and vice versa. The relation $\text{RF}(\text{O}_3)/\text{RF}(\text{CH}_4)$ indicates clearly a low uncertainty if both gases are separated. Therefore the estimations of combined NO_x emissions are better to predict than for each component separately [Lee et al., 2009].

B.6.4 Contrails

Contrails are thin cirrus clouds, which reflect solar radiation and trap outgoing longwave radiation. Research has shown that the latter effect will dominate for thin cirrus, resulting in a net positive RF value for contrails. The impact of contrails to the atmosphere is depending on the time as well as the season. Contrails are not only influenced by the coverage over regions in the atmosphere, but are also influenced by the zenith angle and optical properties of the sun.

The persistence of contrail cover has been calculated globally from meteorological data or by using modified cirrus cloud parametrization in a Global Circulation Model (GCM). Unfortunately contrail cover calculations are rather uncertain since the supersaturated regions in the atmosphere are poorly known. The associated contrail RF follows from determining an optical depth for the computed contrail cover. The current best estimate for the RF of persistent contrails is $10\text{mW}/\text{m}^2$ [Sausen et al., 1998]. There is however an uncertainty range estimated to be factor 3.

Linear contrails

Linear contrails are young contrails that are still not deformed into a homogeneous cover, yet they are to be observed by satellites as linear stripes. Linear contrails are induced by air traffic. When the warm and humid exhaust gases are mixed with relatively cold and dry air, icing will occur. Research conducted on linear contrails has pointed out that the coverage of linear contrails over Europe is estimated to be around 0.72% [Meyer et al., 2002]. Globally this coverage is slightly lower and will range between 0.06% and 0.09% in 1992 and between 0.22% and 0.49% in 2050 [Minnis et al., 1999, Marquart et al., 2003]. The radiative forcing of linear contrails has been assumed to be between 3.5 and 20mW/m² in 1992 and 14.8 and 122 mW/m² in 2050. The climate effect of linear contrails is strongly depending on their longitude and latitude and is especially strong in the tropopause [Fichter, 2009].

Contrail cirrus

Besides the linear contrails air traffic can also induce contrail cirrus. These cirrus will exist for a long time and will also embody linear contrails that are transformed into cirrus over time. Due to the resemblance between both types of contrails, it is hard to determine the type source of the cirrus, for data analysis as well as for modeling climate impact of contrails. Due to the high uncertainty, IPCC and Lee, et al. publish only estimates, rather than best estimate for radiative forcing. The most recent research conducted on contrails has calculated a radiative forcing for contrails of 37.5 mW/m² [Kärcher et al., 2007], almost 9 times higher compared to the RF of linear contrails.

B.6.5 Aerosols

Aerosols are a rest products of combustion, influencing the energy balance of the atmosphere in two ways. On one hand by reflection of solar radiation and on the other hand by absorption of solar radiation. Sulphate is formed in the cloud tops, by oxidation of SO₂ with OH and condensation of existing particles. The sulphate particles reflect the solar radiation partially, thereby being responsible for a cooling effect on the atmosphere. Sulphate is also absorbing longwave radiation, but the warming effect of sulphate in the atmosphere is smaller than the cooling effect, resulting in a net cooling effect of sulphate. The radiative forcing of sulphate is determined to be -4.8mW/m² [Lee et al., 2009].

Soot is a product of inefficient combustion. In contradiction to sulphate, soot is responsible for a positive radiative forcing effect on the atmosphere of 3.4 mW/m² if emitted in the tropopause, while a negative effect is found if emitted in the stratosphere.

Besides the direct effects aerosols are known for, aerosols can also affect the atmosphere indirect. Soot and sulphate can influence the formation of clouds, thereby changing its natural optical properties. A larger number of iced particles within a cloud, result in less cloud drops. Thereby increasing the albedo of clouds while

having a comparable moisture [Twomey, 1977]. At the same time having a longer lifetime of clouds, while the clouds will burst less easily.

B.7 Sources of Emissions

Greenhouse gases trap heat and make the planet warmer. Human activities are responsible for almost all of the increase in greenhouse gas concentrations in the atmosphere over the last 150 years. One of the largest source of the increase in greenhouse gases is from burning fossil fuels for electricity, heat and transportation. In the next sections, the major sectors that form a source of greenhouse gas emissions are listed and explained.

B.7.1 Electricity

The electricity sector involves the generation, transmission and distribution of electricity. The electricity sector produces enormous amount of carbon dioxide, smaller amounts of methane and nitrous oxide. These emissions are produced by the combustion of fossil fuels, such as coal, oil and natural gas, to produce electricity.

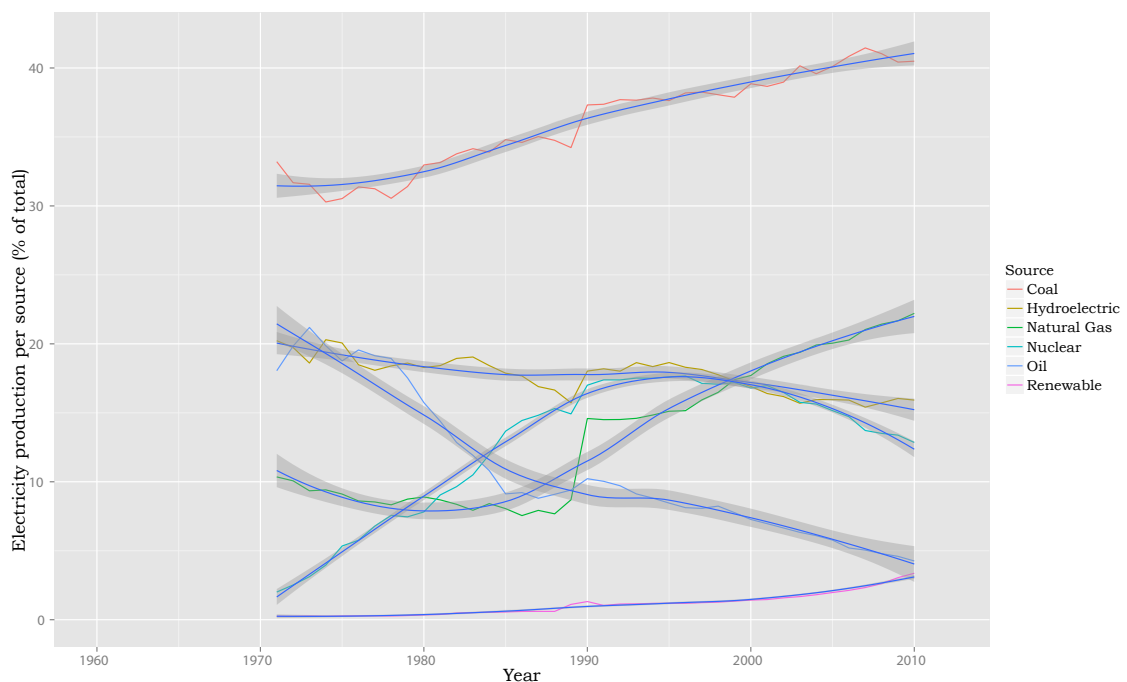


Figure B.16 – Sources for electricity production, per source globally

Figure B.16 and figure B.18 show the share of each of the six sources for energy production on respectively global scale and in the euro zone. As one can see, there are differences in the distribution of the sources. In the euro-zone, the share of coal combustion for energy production is decreased drastically since the 1960's, while

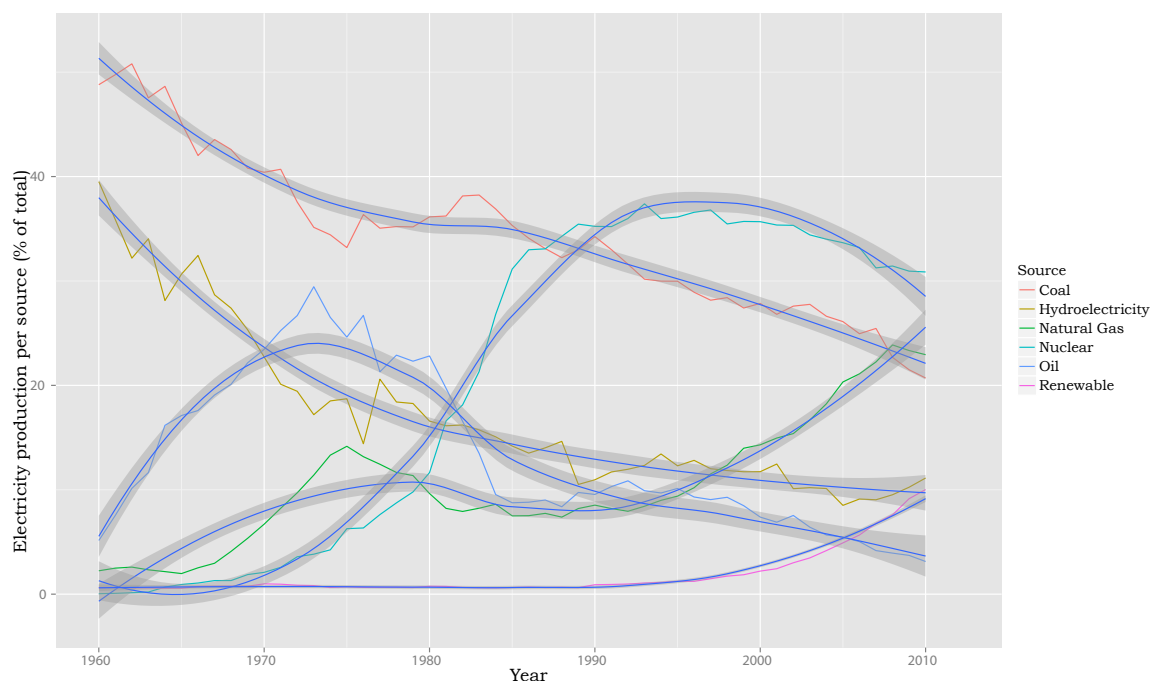


Figure B.17 – Sources for electricity production, per source in Euro-zone

the share of coal combustion on global scale still increases every year. Another observation can be made for nuclear electricity production, after the Tsjernobyl disaster in 1986, the growth in share of nuclear electricity production has stopped immediately. Despite nuclear power is a carbon dioxide friendly electricity production method, its share is decreasing every year on global scale. Renewable energy production and the use of natural gas for energy production is increasing steadily, both on European and global scale.

Electricity is consumed by other sectors. Homes, businesses, industries and other sectors. Therefore it is possible to attribute the greenhouse gas emissions from electricity production to the sectors that use the electricity [MacCracken et al., 2012]. By looking at the energy consumption per end-use sector, can help to increase understand the energy demand across sectors and changes in energy use over time.

B.7.2 Transportation

The transportation sector included the movement of people and goods by cars, trucks, trains, ships, airplanes and other vehicles. The majority of the greenhouse gas emissions of the transportation sector resulting from the combustion of fossil fuels, such as gasoline, diesel and kerosine. The largest source for the greenhouse gas emission of the transportation sector include passenger cars, light-duty trucks. These sources account for almost half of the emissions of the sector. The remainder of the greenhouse gas emissions come from freight trucks, airplanes, ships and boats, trains and pipelines and lubricants.



Figure B.18 – CO_2 emission from energy and heat production on global scale, expressed in million metric tons

The transportation sector is mainly producing carbon dioxides. However, due to the chemical composition of fossil fuels, there are small amounts of methane and nitrous oxide produces by the sector. The emitted hydrofluorocarbons (HFCs) are the result of the mobile air conditioners used in transportation modes.

The transportation sector is the second largest source of greenhouse gas emissions world wide. Over the past decades the total amount of produced greenhouse gases by the sector is increasing and can be related to the increase of population growth, economic growth, urban sprawl and low fuel prices over a long period.

B.7.3 Industry

The industry sector produces goods and materials that we use every day. The greenhouse gases emitted by the production of these goods can be split up in two categories: direct emissions, that are produced at the facility and indirect emissions that occur off site, but are associated with the facility's use of energy.

Direct missions are produced by burning fuel for power or heat, through chemical reactions, from leaks from industrial processes or equipment. Most direct emissions come from the combustion of fossil fuels for energy.

Indirect missions are produced by burning fossil fuel at power plants to make electricity. Referred to as end-use sector in precious section. The indirect emissions result from the electricity needed to power machinery and industrial buildings.

In 2012, the direct industry greenhouse gas emissions accounted for approximately

20% of the global greenhouse gas emissions, making the industry sector the third largest contributor to greenhouse gas emissions. As one can see, the global sectorial carbon dioxide emissions from the industry sector are increasing rapidly, while the industry sector emissions in Europe and the United States of America are decreasing. This is clearly the result of the increase in demand for goods and materials in the rising markets of South-America, China and East-Asia.

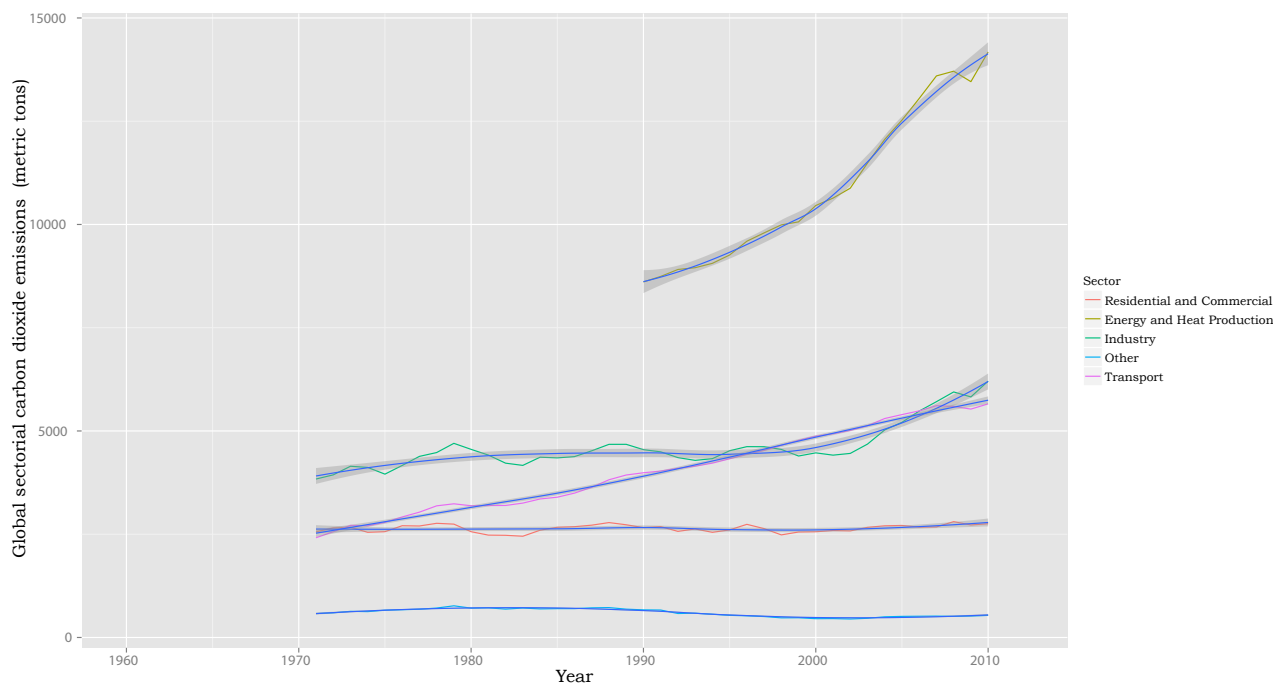


Figure B.19 – Global CO₂ emission per sector, expressed in million metric tons

B.7.4 Commercial & Residential

The commercial and residential sector includes all homes and commercial businesses (excluding agricultural and industrial activities). The majority of the greenhouse gases from this sector come from fossil fuel combustion for heating and cooking, management of waste and wastewater. And as for the industrial sector, the indirect emissions, resulting from electricity consumed by homes and businesses.

Commercial and residential activities contribute to emissions in various ways [Agency, 2013c]:

- Combustion of natural gas and petroleum products for heating and cooking needs emits carbon dioxide and nitrous oxide. Emissions from natural gas consumption represents about 77% of the direct fossil fuel carbon dioxide emissions from the residential and commercial sector. Coal combustion has a minority share in the emissions.
- Organic waste sent to landfills emits methane.
- Wastewater treatment plants emit methane and nitrous oxide.

- Fluorinated gases used in air conditioning and refrigerator systems can be released during servicing or from leaking equipment.

B.7.5 Agriculture

The agricultural sector includes the cultivation of crops and livestock for food. The sector contributes to the emission of greenhouse gases in a variety of ways [Agency, 2011]:

- Various management practices for agricultural soils can lead to production and emission of nitrous oxide. The large number of different activities that can contribute to nitrous oxide emissions from agricultural lands range from fertiliser application to methods of irrigation and tillage. Management of agricultural soils account for about half of the emissions from the agriculture sector.
- Livestock produce methane as part of their digestion. This process is called fermentation and it represent almost one third of the emissions from the agriculture sector.
- The way in which manure from livestock is managed also contributes to methane and nitrous oxide emissions. Manure storage methods and the amount of exposure to oxygen and moisture can affect how these greenhouse gases are produced. Manure management accounts for about 15% of the total greenhouse gas emissions from the agriculture sector.
- Smaller sources of emissions include rice cultivation, which produced methane, and burning crop residues that produce methane and nitrous oxide.

B.7.6 Land Use & Forestry

Plants absorb carbon dioxide from the atmosphere as they grow, and they store some of the carbon throughout their lifetime. Soils can also absorb carbon dioxide, depending on how the soil is managed. This storage of carbon in plants and soils is called biological carbon sequestration. Because biological sequestration takes carbon dioxide out the atmosphere, it is also called a greenhouse gas sink.

As the type of land changes, emission of carbon dioxide or sequestration can occur. If a cropland or forestland is converted into a grassland, changes in the emission or sequestration will occur.

Agricultural land in figure B.20 refers to the share of land area that is arable, under permanent crops, and under permanent pastures. Arable land includes land defined by the FAO as land under temporary crops (double-cropped areas are counted once), temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded. Land under permanent crops is land cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as cocoa, coffee, and rubber. This category includes land under flowering shrubs,

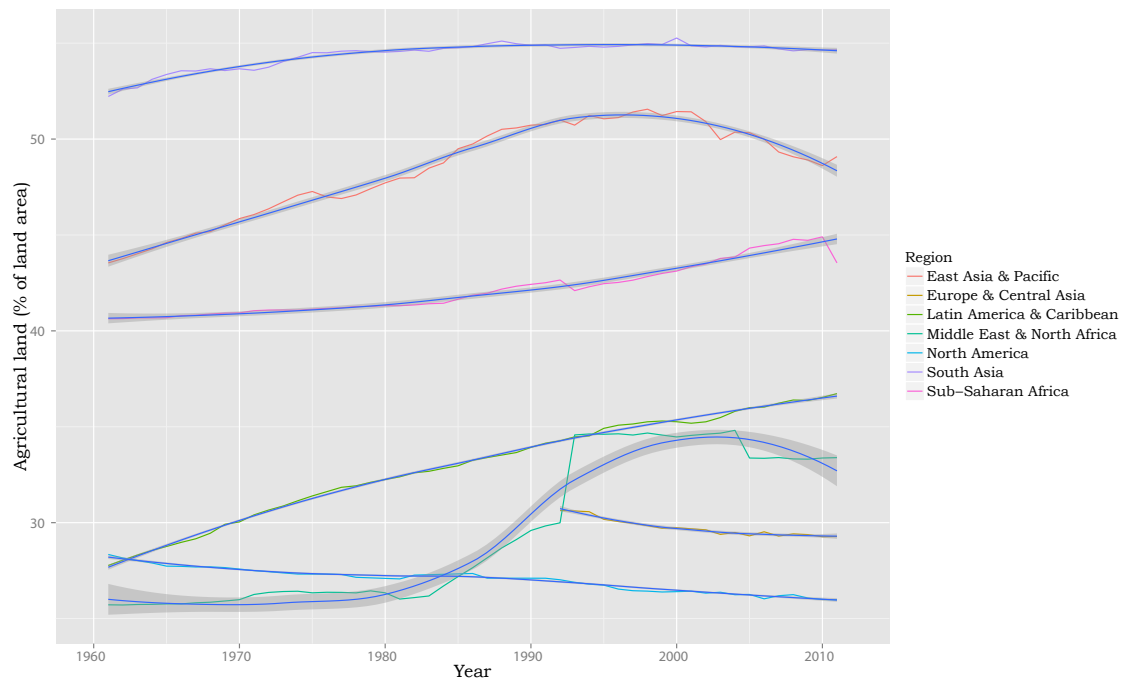


Figure B.20 – Agricultural land in percentage of total land, data source: World Databank [Ida,]

fruit trees, nut trees, and vines, but excludes land under trees grown for wood or timber. Permanent pasture is land used for five or more years for forage, including natural and cultivated crops.