A comparative analysis of behavioural dynamics to support the formulation of strategies that foster sustainable development in renewable and non-renewable resource systems

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AIT – Asian Institute of Technology (School of Environment, Resource & Development)

CITEP – Fish Technology Research Centre

CLD – Causal Loop Diagram

CMEPSP – The Commission of the Measurement of Economic Performance and Social Progress

GHG – Green House Gases

FTE – Full Time Employee

IFFO – The Marine Ingredients Organisation

INTI – National Institute of Industrial Technology

ITQ – Individual Tradable Quota

IAI – International Aluminium Institute

kWh – kilo Watt hour

MSC – Marine Stewardship Council

SFD – Stock and Flow Diagram

STECF – Scientific, Technical and Economic Committee for Fisheries

I. Preface

My motivation for writing such an extended thesis was that I wanted to challenge myself in several ways. While working with Andrea Bassi, who has a lot of practical experience with the application of system dynamics in the field of sustainable development, I saw the chance to work with somebody who can guide me in developing the necessary skills for a career in the field of system dynamics consulting. In Lisbon, I have been working on a paper where we applied system dynamics to collaborative consumption practices, and tried to identify ways to close the loops in order to reduce primarily waste, but also consumption in general and therewith resource exploitation. Next to this interest, I wanted to progress on building system dynamics models that can serve as a platform for scenario analysis and provide useful insights for the formulation of strategies that foster sustainable development.

The purpose of this study is to explore the feedback structure of the supply chains of a renewable and a non-renewable sector, in order to better investigate the feedback loops that govern their behaviour, and are also responsible for inefficiencies. While doing so, I want to identify leverage points for sustainable development in the systems, and to simulate the effects of different scenarios in order to evaluate their outcomes in terms of economic, environmental and social indicators.

Next to identifying the feedback loops that drive the behaviour of the two systems, two additional objectives are the internalization of externalities in terms of natural capital valuation, and an overall structural comparison according to the way how the supply chain exploit the respective resource. The aim is not only to look at operational efficiency, but also take environmental and social aspects into account to conduct an integrated analysis. Sustainability science adds a little explored feature in other models feature to the model, the structural comparison of the two resource types will add to the understanding of key sector dynamics.

Sustainability science allows for a holistic analysis of economic activities, especially those causing negative environmental impacts, and thereby enriches the information provided to key decision makers. An example in the context of this study would be how by-catch affects the reproduction rate of fish what in turn affects its regeneration rate and has the potential to undermine future profits. Through a structural comparison in terms of feedback loops and their respective function in the systems, I want to evaluate whether, and if so what the respective similarities and differences of renewable and non-renewable resource systems are. Even though these insights are merely suitable for generalization, they provide a starting point for future analysis of the strategies that can be implemented to improve the sustainability of resource use. In addition, this analysis will reveal whether the structures underlying the fishery and the aluminium sector are comparable. If so, these insights could be used to support the formulation of green economy strategies across several sectors, serving as key methodology for integration and furthering progress on sustainability science.

Therefore I hope to open a discussion about underlying feedback structures in renewable and non-renewable resource supply chains that aims at enhancing the understanding of the archetypes that underlie certain supply chains. According to my perception, there are renewable resources where consumption takes place in a linear fashion, and non-renewable resource systems in which consumption of the resource takes place in a circular way and vice versa. Evaluating the general supply chain dynamics, in combination with the underlying feedbacks and driving factors, has the potential to enrich our understanding of resource consumption and drivers in general, and to enable us to develop strategies that foster long term sustainable development without the erosion of the natural capital we have.

1. Introduction

The recent COP21 conference in Paris was a landmark for the international sustainable development. In 2015, 195 nations signed the COP21 agreement, indicating that the international recognition of sustainability has reached a new all-time high (UNFCCC, 2015). With the recognition of sustainability, questions about the "How to achieve the desired state?" naturally follow. A couple of years back, a working group of the UNEP determined and assessed key sectors of humanities' economic activities in terms of their performance and their potential for sustainable development, and published the results in their report "Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication" (2011).

According to the UNEP (2011), the largest potential for indentifying high leverage strategies can be realized in the key sectors of our industry. Furthermore, it has been recognized that overarching strategies (cf. Dietz et al., 2003) will be needed to capitalize on this potential and achieve long-term benefits (e.g. Dietz et al., 2003; Sterner & Svedäng, 2005; Stouten et al., 2008). Economic viability of the sectors, a crucial aspect for the industries' allegiance during the implementation phase, is often overlooked or under-prioritized in the process of making the industry more sustainable (Sterner & Svedäng, 2005; Ward et al., 2012). This indicates that for policies to be successful, overarching strategies need to be developed that foster sustainable behaviour, while enabling the industry to be more profitable than it would be with actual business practices. In order to develop such strategies it is necessary to understand the feedback loops that are governing the dynamics of the current business practices within the different sectors, and therewith are also responsible for side effects that business interactions have on society and environment, also called externalities (FAO, 2002)[1]. "Environmental issues usually involve negative externalities, however, including air and water pollution, waste disposal, degradation of ecosystems, depletion of natural resources, and adverse impacts on human health."[2] The effects of negative externalities on the business environment are likely to affect future business activities and have the potential to undermine future profitability. This hampers key sectors from being more profitable in the long run, since they are eroding their own resource base.

The emergence of the green economy concept has led several countries to re-assess their national planning processes. This has broadened the scope of sectoral planning to consider simultaneously the social, economic and environmental outcomes of actions, but the integration of planning across sectors is still lacking. One of the main reasons for this is the perception that very different drivers are responsible for the performance of each sector. For instance, technology-driven solutions are envisaged for efficiency-based sectors (e.g. manufacturing), while conservation is primarily proposed for resource-based sectors (e.g. forestry). In reality, there are many more similarities across sectors that decision makers recognize. We take the global fishery and aluminum sector as examples. Both are dependent on natural resources, one of which is renewable (fish) and one that is not (bauxite). Both sectors are characterized a long supply chain, and both have a series of impacts on the economy (through production and value addition), society (through employment and the provision of food and materials for housing and infrastructure), and the environment (through the use of energy and emissions as well as influencing ecosystem services). Most importantly, both sectors have developed strategies to improve their sustainability: aquaculture and recycling. We argue that there are several similarities in these sectors, and that green economy planning can therefore be seen as a unifying platform for improving planning for sustainability.

The aim is to gain insight into the dynamics that are driving the behaviour of the systems and therefore are responsible for some of the long term negative consequences for business and environment alike.

1 http://www.fao.org/docrep/005/y4256e/y4256e04.htm#fn11
2 Sage knowledge - http://sk.sagepub.com.ru.idm.oclc.org/reference/environment/n389.xml

Based on these insights it is possible to test different strategies that affect detrimental feedback loops, and to determine whether they would meet public (sustainable development), private (profitability), and social (livelihoods) goals alike. This research contributes to the SD literature about the design of resource specific strategies, and by developing models that integrates economic, environmental and social aspects by applying the sustainability science approach. Furthermore, the knowledge obtained during this project will contribute to informing high level decision makers about the expected amount of leverage that certain strategies could have. The models can then be used as blueprints for models that are adapted for local circumstances and serve both, designing sector specific strategies, and educating key decision makers about the dynamics of the specific sectors and the implications that certain actions might have.

Research questions

In order to establish a baseline one must evaluate how the externalities in the business as usual (BAU) scenario affect the profitability of the sector. The first research question of this thesis is:

1) *To what extent do the externalities of the BAU scenario harm the profitability of the chosen sectors?*

Identifying sector specific externalities will help to guide the determination or development of policy instruments aiming at reducing or internalising these externalities. Subsequently it can be determined which areas of the sectors are vulnerable to sustainability. The second research question is:

2) *In which areas of the chosen sectors could a transition towards sustainable development pose a threat to (future) profitability?*

Answering the first research question will provide information about the dynamics of the BAU scenario. Answering the second question provides indications as to what the sensitive areas in the respective sectors are, and will help to develop policy instruments that foster sustainable development while accounting for the industries' long-term profitability. In order to answer the main research questions, the following sub-questions must be addressed for the two sectors respectively:

Fisheries

- *What are the main feedback loops that underlie the dynamics in the fisheries sector?*
- *What would be the effect of implementing the proposed solutions mentioned in the Green Economy Report (2011) on the profitability of fisheries?*
- *Which policy instruments would help to improve the problem of the global commons (in case of a global approach)?*

Aluminium

- *What are the main feedback loops that underlie the dynamics in the Aluminium sector?*
- *What insights does the analysis of the dynamics of the sector produce regarding leverage points for the improvement of the profitability of the sector?*
- *Which policy instruments could help to make the Aluminium industry more profitable in the long run, while reducing its externalities?*

2. Literature review

2.1 Sustainability science

Sustainability science is recognizing the complexity of the interaction between humanity and environment, and calls for transdisciplinary research to find creative solutions to existing and emerging sustainability challenges (Jerneck et al., 2011). The aim is to establish an interdisciplinary research agenda that acknowledges that problems of sustainability cannot be understood and/or solved by studying them from one specific perspective, and thereby foster collaboration between different disciplines.

With all the rising pressures on the environment and the resulting consequences as climate change due to GHG emissions or overexploitation of fish stocks, the concept of sustainability has moved into the spotlight of the scientific community over the last three decades (Goodland, 1995; Jerneck et al., 2011; Sterman 2012). Humanity is exploiting the planets' resources at a rate which is often exceeding the capacity of ecosystems to regenerate, while at the same time emitting greenhouse gases and other toxic substances in the environment (e.g. Dietz et al., 2003, Sterman, 2012). According to Sterman (2012), solutions that originate from the current sustainability paradigm are often fighting symptoms, but not the root of the problem, due to erroneous mental models of the systems that we try to change. Moxnes (2000) found that misperceptions of feedback and delays cause mismanagement in renewable resource systems, which indicates that mismanagement is not solely caused by the 'commons problem', but by the mental models that drive the decision making process.

Sustainability science is integrating different viewpoints, from academia, practitioners and policy makers, and spans several disciplines and fields, theoretical as practical, in order to gain the knowledge to develop insights about the system under evaluation (Bettencourt & Kaur, 2011). According to Martens (2006, p. 38), "[t]he central elements of sustainability science are

i) inter- and intra-disciplinary research
ii) co-production of knowledge
iii) co-evolution of a complex system and its environment
iv) learning through doing, and doing through learning, and
v) system innovation instead of system optimization"

Following this line it becomes clear that sustainability science is a field that spans many different activities, and not only focuses on the integration of different parties in the knowledge creation process, but also on the usability and the transfer of that knowledge.

Furthermore, recent literature stresses that GDP is not representative to measure the well-being of a country and asks new measures for well-being are needed (e.g. Costanza et al., 2009; Stiglitz et al., 2010). Costanza et al. (2009) stress that the GDP was never designed to measure the well-being of society, even though it is frequently used to do so. Well-being should be measured by a construct that is taking into account to which extent social goals are met. The Stiglitz report (2010) was written by the CMEPSP on the evaluation of the GDP's limitations as a measure for well-being, and the assessment of alternative measurement tools. It advocates the application of a multidimensional definition to capture the meaning of well-being, and an integrated approach of measurement.

In the scope of this thesis sustainability science will be used as a lens to examine supply chains and to evaluate their respective externalities. Even though this research does not include scientists from different disciplines, different perspectives on sustainability (economic, environmental, and social) are used to conduct a holistic analysis.

2.2 The fisheries sector

The fisheries sector has been chosen as the renewable resource sector for analysis. Fish is an essential part of the human nutrition, and in 2013 fish consumption accounted for about 13% of the world populations' animal protein intake.[3] The global fisheries sector can be separated into capture fisheries, on- and off-shore, and aquaculture. Nowadays, with the food fish supply outpacing population growth, the global fish consumption per capita has been increasing steadily from an average of 9.9kg in 1960 to an average of 19.2kg in 2012 (FAO, 2014). The increase in fish supply is mainly caused by a growth in aquaculture, while the supply from capture fisheries is stagnating at around 95 million tons. Figure 1 shows the total global fish supply and the respective contributions from fisheries and aquaculture. Almost 30% of today's supply is produced by aquaculture.

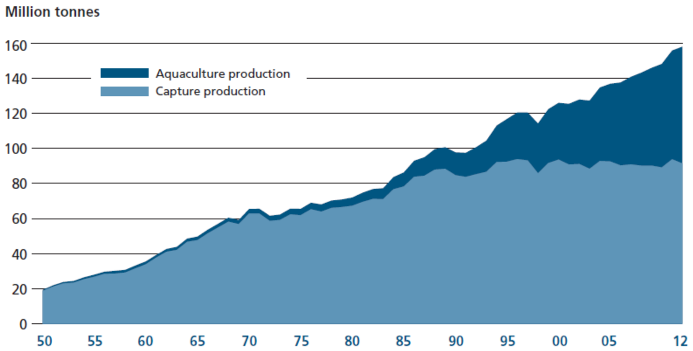

Figure 1: World capture fisheries and aquaculture production (FAO, 2014)

But the increase in supply has not come without cost. The fact that the fish is an open access resource, and that fish from the sea has always been abundant led to a situation of overcapacity (UNEP, 2011). The existing capture fishery capacity is higher than required to fish at the maximum sustainable yield, which puts an immense pressure on the fish stocks. In addition to overcapacity, other issues that arise with fishing practices, like by-catch (Hall et al., 2000; Gilman et al., 2006; Carruthers & Neis, 2011; Ward et al., 2012), high grading (Ward et al., 2012), and unreported and illegal fishing practices (e.g. OECD, 2004) increase the pressure even more. Figure 2 is showing the actual state of all fish stocks that have been assessed and classified by the FAO (Froese et al., 2012).

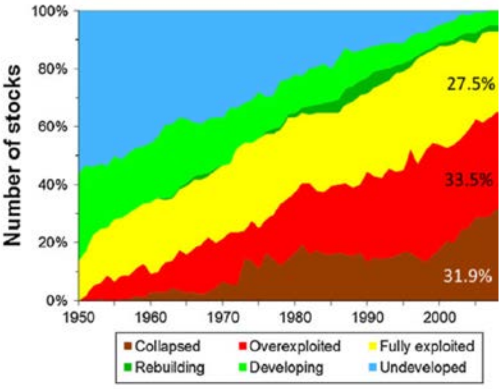

Figure 2: Evaluation of the state of commercial fish stock (Froese et al., 2012)

Practical examples, like the Canadian cod, and research into fisheries are creating awareness of the fact that overfishing has long lasting negative consequences from which it may take years to recover

[3] https://www.msc.org/healthy-oceans/the-oceans-today/fish-as-food

from (UNEP, 2011). Due to their global significance to the employment market, reducing the capacity of capture fisheries would directly threaten the livelihoods of those employed in this sector. In addition, capital and maintenance costs create economic pressures for using the capacity and cause a lock-in effect that increases the difficulty to reduce capacity utilization.

With the raising awareness of the dangers of overexploiting fish stocks more regulatory actions have been taken over the last 30 years. On an aggregate level, the total allowable catch (TAC) is the a commonly implemented measure to regulate fisheries. “The total allowable catch is a catch limit set for a particular fishery, generally for a year or a fishing season.” (OECD, 2001[4]). According to the evaluation of policy instruments Sterner and Svedäng (2005), policy instruments can be classified into top-down and bottom-up categories. Top- down policy instruments that are implemented by institutions include taxes, subsidies, quotas, licenses and catch restrictions (Sterner & Svedäng, 2005; Stouten et al. 2011). Bottom-up policy instruments are measures taken by the fishermen for common property resource management. These measures include labelling, marine reserves, and fishing moratoria, whereby moratoria are also implemented by the government (Sterner & Svedäng, 2005). Other successful examples of implemented policies can be found in the UNEP (2011) report, in chapter four.

2.2.1 System Dynamics and fisheries

There are several applications of system dynamics in the fisheries sector, most of them focusing on a specific aspect of fisheries. The reviewed papers were used to inform the modelling process at different stages. Starting with the model built by Davidsen (1991) who shows that growth and death rates of a fish stock are related to the carrying capacity of the environment. Furthermore he provides a dynamical hypothesis why harvest policies can fail by choosing the wrong yield for harvesting. Erling Moxnes applied system dynamics to the fisheries sector as renewable resource to explain the tragedy of the commons and proposes policies for sustainable development (2000). In addition he applies system dynamics in an experimental context to analyse different policy instruments, as for example ITQs (2012). The reported results of the UNEP report “*Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication*” (2011) are based on system dynamics simulation models and were used for informing policy analysis and provide information that can serve as input for future policy design.

System dynamics has been applied to examine specific cases. An evaluation of the economic effects of changes in three different restrictive policy instruments was conducted by Stouten et al. (2008), who built a system dynamics model on the Belgian fishing fleet. Changes in three policy instruments were tested and their effects on future fleet performance and dynamics were evaluated. Bueno and Basurto (2009) investigated the interaction between fleet size and population size of a shellfish species in the Gulf of California by means of system dynamics. A two-stock population model of the shellfish species was built and effects of fleet size and harvest rate on the fish stock dynamics were evaluated with the aim to maintain the resilience of artisanal fisheries.

System dynamics was also used to develop educational management games. One application of system dynamics to the fisheries sector is the Fish Banks model, or “Fish Banks Ltd. Game”[5], developed by Dennis Meadows. The Fish Banks model is used for educating students and professional about renewable resource management. It is calculating the interactions between vessels and fish stock in the background, and players learn about the feedback effects of their actions, short- and long-term. Therewith, the fish banks model can also be used to gain insights about in the fisheries sector and to develop policy instruments on a macro level (e.g. Ruiz-Pérez et al., 2011).

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4 https://stats.oecd.org/glossary/detail.asp?ID=2713
5 http://www.systemdynamics.org/products/fish-bank/

2.3 The global Aluminium industry

The aluminium sector was chosen as the non-renewable resource sector for analysis. Throughout the last 40 years, the aluminium industry has undergone some important changes, of which the most important are a geographical relocation of bauxite, alumina and aluminium production centres and a compression of demand for primary production through the rise of aluminium recycling. Even though threatened by several substitutes, the demand for aluminium has been growing at an average of 3% per year between 1975 and 2010 (Nappi, 2013).

Aluminium can be used for many different purposes due to its many beneficial properties. Aluminium is a light weight, high tensile metal with a high corrosion resistance and exceptional unit strengths, which makes it feasible for many different industrial sectors (Das & Yin, 2007). One of its most beneficial properties is that it can be recycled without any loss of quality, and at only 5% of the energy which would be needed to produce primary aluminium (IAI, 2009). From a recycling point of view, its areas of application can be seen as a bank account in which aluminium is stored, and then released once it is at the end of the applications' life time. Due to its recyclability around 70% of the aluminium that has been produced since the late 19th century is still in use (IAI, 2009). Figure 3 shows the main sectors in which aluminium is used and the respective amount of aluminium stored in them.

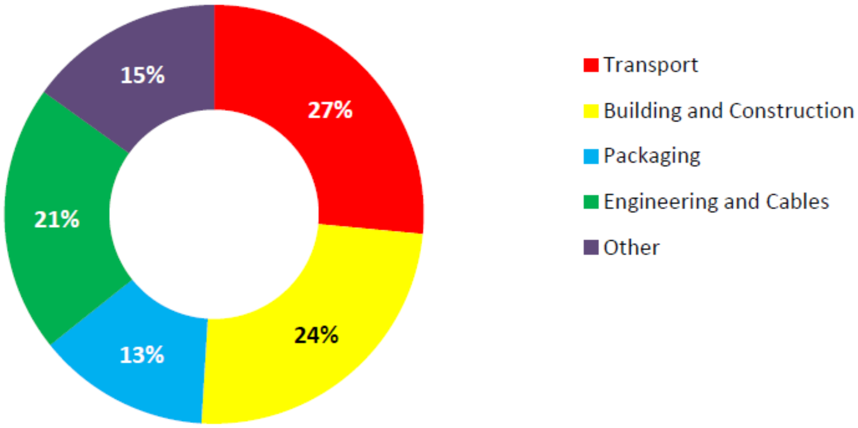


Figure 3: Global end-use markets for finished aluminium products in 2007 (IAI, 2009)

Accounting for roughly 3% of the global electricity consumption, primary aluminium is in the group of top 10 industries in terms of energy consumption (UNEP, 2008; GEA, 2012) and therefore a major contributor to the anthropogenic CO2 emissions. The decline of real prices for metal and the rise in energy prices through the last decade have increased the competitiveness within the industry (Nappi, 2013). Even though the price for energy is subsidized, the rise in energy prices and a possible implementation of carbon taxing are threatening the viability of the industry by increasing the costs for the production of primary aluminium.

The primary aluminium production rate is depending on the cost curve of aluminium smelters and the sales price for aluminium at the LME. The cost curve, a concept developed in the late 1970s, is representing business costs per ton of primary aluminium produced for all aluminium smelters and can, according to Nappi (2013, p. 14) be used to

- calculate the global weighted operating costs for all aluminium smelters
- identify the share of the industry which is producing with a loss
- benchmark within the industry

- access the viability of the industry

Figure 4 shows an example of the operating cost curve for the year 2010. The horizontal axis shows the total global output quantity and the vertical axis the costs at which the respective quantities can be produced.

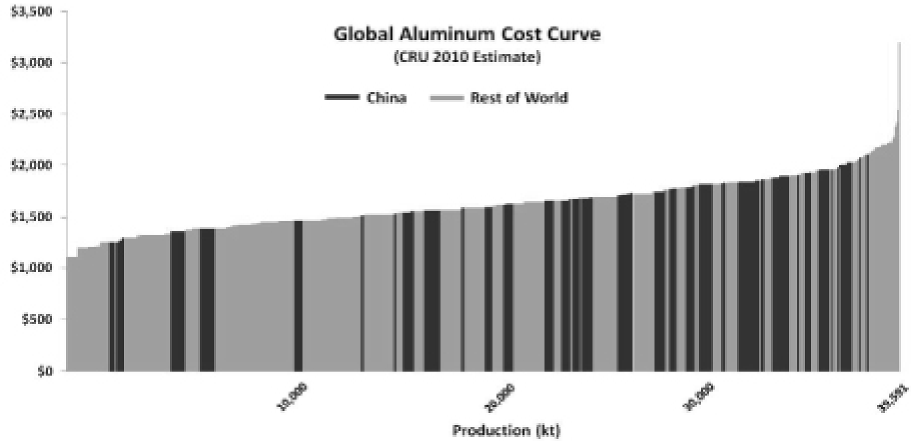


Figure 4: Example Aluminium cost curve 2010 (Source: CRU as of February 19, 2010)[6]

Next to the economical performance, the environmental performance of the aluminium industry is considered in this thesis. Being one of the most energy intensive industries, the primary aluminium industry is a big contributor of both, direct and indirect CO_2 emissions (cf. World Bank, 1998). Direct emissions are CO_2 emissions and CO_2 equivalent (CO_2e) emissions that are directly related to the physical aluminium production process, whereby indirect CO_2 emissions consider CO_2 emissions of energy consumption and transportation. Due to technological improvements, and motivated by sustainability considerations, the aluminium industry was able to improve its environmental footprint throughout the last decades. The global average energy intensity per ton of aluminium was reduced by approximately 15% between 1980 and 2010, from around 17,000 kWh per ton to approximately 14,300 kWh per ton[7], as displayed in Figure 5. The emissions of perfluorocarbon (PFC) gases, which count as direct CO_2e emissions, were reduced by 70% between 1990 and 2010, through improved cell management and a change in the utilized technology (IAI, 2013).

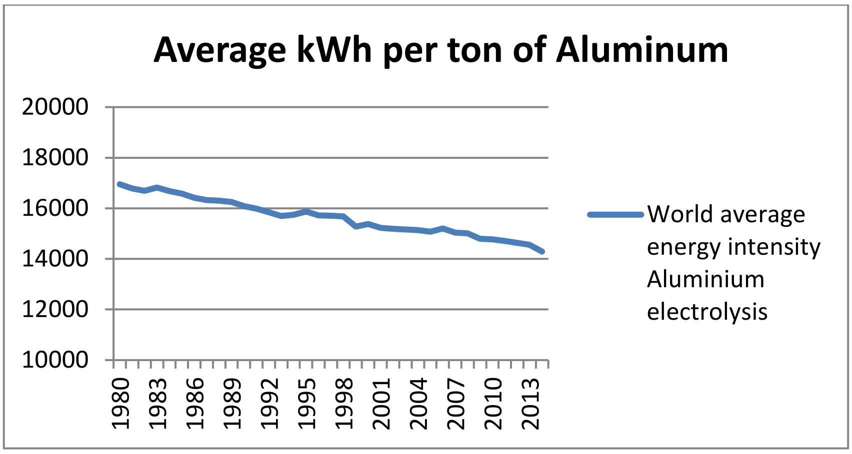


Figure 5: Global average energy intensity of Aluminium electrolysis (IAI, 2016)

6 https://www.sec.gov/Archives/edgar/data/1422105/000119312510113944/ds1a.htm
7 http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/

However, because of the decreasing yield of Bauxit ore, recent improvements in energy efficiency only have a compensating effect so that environmental performance stays the same (Nappi, 2013). Research into inert anodes for primary Aluminium is ongoing, and further efficiency gains in terms of electricity consumption and emissions can be expected (Kvande & Haupin, 2001).

2.3.1 System dynamics and Aluminium

A system dynamics model on the world metal consumption was available, focussing on production and consumption of metals “[...] in relation to impacts such as ore-grade decline, capital and energy requirements and waste flows.” (Van Vuuren et al., 1999, p. 239). The model was developed to for the exploration of sustainability issues and informing decision makers about the uncertainty governing the metal industry as a whole.

System dynamics has also directly been applied to the aluminium sector to investigate possible effects that carbon policies could have on the aluminium sector (Yudken & Bassi, 2009). They concluded that the introduction of a climate policy would have a significant impact on the aluminium industry, whereby the primary production sector is more affected by these measures than the secondary production sector. A big share of the projected impacts would be caused by increasing energy costs in case of the implementation of a CO2 climate policy.

In an updated version of their report (Yudken & Bassi, 2010) they evaluate the effectiveness of output-based allowance rebate measures on the operating surplus of energy intensive industries. They state that rebates dampen the effect of emission payments on the primary aluminium sector, but that additional efficiency gains are required to mitigate their effect. Furthermore they point out the oxidation of carbon emissions during the electrolysis process as critical when it comes to the emission of greenhouse gases (Yudken & Bassi, 2010, p. 5). From a legal point of view, the secondary industry is regarded as not eligible for allowance rebates, though full payments for emissions would reduce the operating surplus considerably.

The International Aluminium Institute has built a “Global Mass Flow Model – 2013”, an Excel sheet using iterative calculations to determine stock and flow values[8]. The model contains the main sectors mentioned in the IAI’s report (2009) together with historical (reported) data and calculated future values for several variables such as primary production, recycling and demand. The data from the IAI model was used as reference mode for the Aluminium stock and flow model in this thesis.

[8] http://www.world-aluminium.org/publications/

3. Understanding the fishery and aluminium sector

In this section an overview over the processes that take place in the fisheries and aluminium sector will be provided. The processes will be described in more detail, than they are represented on the same level of aggregation in the simulation model. Some aspects are mentioned but not included in the model due to a lack of data or because they are outside the scope of analysis for this thesis.

3.1 Fisheries

From a global point of view, fish for human consumption can have two different origins: capture fisheries or aquaculture. In this model the capture fisheries sector does not discriminate between on- or offshore fishing, and refer to wild fish caught by humans for the purpose of consumption. In aquaculture, fish is 'produced' in fish tanks, small lakes or big cages.

Once fish has been captured, or harvested, it is transported to processing plants. The FAO (2014) distinguishes between fish used for food purposes, and fish used for non-food purposes. Fish used for food purposes is shipped to fish processing plants. Here fish is processed into different fish products, from fish used for canning, curled produce, frozen fish fillets, or fish for fresh consumption (FAO, 2008). According to the UNEP's "Cleaner Production Assessment in Fish Processing" report fish processing for human consumption involves typically, but not exclusively, de-icing, washing, grading, de-heading, cutting tails, gutting filleting, and skinning (UNEP, 2000, pp.9-11). Depending on the type of product, only a certain fraction of the original biomass can be used. In tuna canning for example, the average yield is approximately 45.5% (AIT, 2007), meaning that 1 ton of frozen tuna (whole fish) equals 445kg boiled tuna meat to be canned. According to the UNEP (2000), the average processing yield for white fish is between 40-50% and for oily fish between 46-54%, assuming an average fish processing technology.

Fish used for non-food purposes is typically reduced to fishmeal and fish oil (UNEP, 2000), also referred to as secondary processing. Both products are also referred to as marine ingredients, which are defined by the IFFO as "*nutritious products used mainly for human consumption or animal feed and are derived from marine organisms such as fish, krill, shellfish and algae.*"[9]. On average, the reduction of 1 ton of fish yields 216kg (~22%) of fish meal, and 34kg (~3.4%) of fish oil (UNEP, 2000).

According to the IFFO, fish mean and fish oil production has been relatively static throughout the last two decades. Approximately 30% of the global fish meal and 70% of fish oil supply are used as fish feed in the aquaculture sector (Kaliba et al., 2010). These numbers have been relatively constant, despite a strong growth in aquaculture fish production. According to Tacon and Metian (2008) the use of fish oil and fish meal in feed compounds for aquaculture has been declining between 1995 and 2006 for almost all farmed species, and is likely to decline further in the future.

The finished goods are then distributed via the wholesale and the retail markets, driven by the demand for fish and fish products. Costs and income are depending on the former supply chain partners, or the operational costs for fisheries and aquaculture. The operations of fish processing and trade have different yields for the respective elements of the supply chain, typically low yields at the producer site that are increasing towards the retail end of the supply chain (De Silva, 2011).

[9] http://www.iffo.net/what-are-marine-ingredients

3.2 Aluminium

Aluminium is either produced from alumina (primary aluminium), which is refined from bauxite, or is recycled from aluminium scrap (secondary aluminium) (The Aluminium Association, 2011). Bauxite for aluminium production is normally extracted in open mines which are restored after the bauxite has been mined (Das & Yin, 2007). According to the Aluminium Institute (2011) the rehabilitation rate of the land is 100%, meaning that as much land is rehabilitated as is opened up for mining. After bauxite has been mined, alumina is extracted from the ore. On average it takes around 2.9 tons of bauxite to produce one ton of alumina (IAI, 2013).

The process of alumina extraction involves crushing, washing and the application of chemicals (lime and caustic soda) to extract the alumina (The Aluminium Institute, 2011). Next to its water footprint (on average 2.57m³ of fresh water and 0.56m³ of sea water) the production of alumina is with around 12,520 MJ per ton very energy intensive[10]. Once the alumina has been extracted, it is ready for the production of primary aluminium. On average 1.9 tons of alumina are needed to produce one ton of primary aluminium (IAI, 2013).

Primary aluminium is produced through the reduction of alumina by means of electrolysis, applying the "Hall Héroult" smelting process. Alumina is put into a pot, a steel container with carbon or graphite inline, with molten cryolite electrolyte (sodium aluminium fluoride) and reduced to aluminium by passing electricity at a very high current, around 200,000 to 350,000 amperes, through the electrolyte (Yudken & Bassi, 2009). For the electricity to flow through the electrolyte, a carbon anode and a cathode are needed, whereby the carbon anode is typically inserted from the top, while the carbon or graphite lining of the pot serves as cathode (Das & Yin, 2007, Yudken & Bassi, 2009). Anodes, which are consumed during the process of electrolysis, are normally produced on site. The consumed anode stumps are typically recycled and then reused, which reduces the waste load for landfills (IAI, 2013). Once alumina has been reduced, molten aluminium is collecting at the bottom of the cell and taken out in regular intervals, blended to an alloy specification and then cast into ingots (Yudken & Bassi, 2009).

For this thesis, alumina and bauxite consumption will be calculated by multiplying the production quantity of aluminium with the respective yields. From the respective consumption rates, inputs, outputs and emissions will be calculated based on the average values from the IAI's report "Global life cycle inventory data for the primary aluminium industry" (2013). Using the average yields has the advantage that future investigations can simulate scenarios to assess the impact of decreasing yields on long-term viability and environmental performance of the industry.

[10] http://www.world-aluminium.org/statistics/metallurgical-alumina-refining-energy-intensity/

4. Model description

In the following sections the structure of the simulation models will be explained. In addition, the feedback loops that are driving the dynamics of the two models will be pointed out. The fisheries model includes the fish stock, vessel, processing- and distribution modules. The aluminium model includes primary production, aluminium bank society, recovery and a recycling sector. Both models contain one or more economical module(s) in which costs and indicated employment are derived from certain variables in the models.

After each section, a table that contains the main components of the model together with equation, units and description of the real world counterpart will be provided.

Brief introduction into the system dynamics terminology:

The figures in this section are representations of the SFDs that have been built for this study. The boxes represent stocks, which can be seen as 'containers' in which accumulation takes place. Typically stocks have units like 'ton', or 'vessel', but they can also be used to accumulate for example a production capacity where the unit would be 'ton per month'. Stocks are changed by flows over time. Flows are governed by decision rules, which can manmade or based on natural laws, and are represented by mathematical equations. They are represented by the double-lined arrows typically with an arrowhead either pointing **towards** the stock (inflow), or **away** from the stock (outflow). In some cases flows have an arrowhead on both sides, meaning towards and away from the stock. These flows are referred to as bi-flows and they are normally used if in- and outflow would underlie the same decision rule.

Next to stocks and flows, the model also contains variables that can be defined in different ways. Their values can depend on i) two or more other variables of the model (stocks, flows, parameters) in form of a mathematical equation, ii) an input-output function which is determined by a graphical function, or iii) their values cane be simply exogenous, meaning that this variable purely serves as an input for model calibration and simulation. Exogenous variables are represented in **BOLD** letters in the diagrams to make it possible to distinguish between variables that are calculated endogenously, and exogenous, thus external, inputs.

Next to the structural explanations, the different modules will be presented as well. The first time that a variable from one of the figures is mentioned in a section, its name will be displayed in '*italics*'.

4.1 Fisheries model

This section will provide a detailed description of the different modules of the fisheries model. First, an overview of the causal relationships is provided, next to screenshot of (parts of) the structure. A table with the main equations of each module is provided in the end of each section.

4.1.1 The fish stock

The fish stock module has two stocks: *spawnlings* and *adult fish*. The stock of spawnlings is increased by the spawning rate, and decreased by the '*natural death rate spawnlings*' and the '*maturation rate*', The stock of adult fish is increased by the 'maturation rate', and decreased by the '*natural death rate adult fish*' and the '*catching rate*'. **Fehler! Verweisquelle konnte nicht gefunden werden.** displays the structure of the fish stock module.

The spawning rate is calculated based on the *fertile population*, which has the value of the stock of adult fish, multiplied by a *reproduction fraction* (cf. Davidsen, 1991). The reproduction loop (R1) would cause exponential growth of the fish stock. For the maturation rate, a continuous flow is assumed, meaning that the stock level of spawnlings is divided by the '*time to mature*' to calculate the respective flow levels. The *natural death rates* for both stocks are calculated by multiplying the respective stock level by a '*natural death fraction*' for spawnlings and adult fish respectively. The natural death rates are introducing two balancing loops into the model (B2 and B3) that yearly decrease the amount of fish by a certain amount, depending on the stock level.

The model distinguishes between *capacity*, a stock from the fishing capacity module indicating the maximum amount of tons per month that can be caught, and the *actual catching capacity*, a variable that is calculated by multiplying the stock level of capacity by the catching efficiency. *Catching efficiency* is calculated by dividing the stock of adult fish by the *initial fish stock*, and captures the effect of fish stock depletion. The lower the level of the fish stock compared to its original value, catching efficiency is affecting the catching rate by decreasing the actual capacity to a level lower level than it would have been otherwise. The resulting, balancing, feedback loop has a significant impact on the capacity adjustment in the fishing capacity module. The initial fish stock is an estimation of the total amount of fish available for capture fisheries, which means that it is an exogenous input.

The *catching rate* is internalized and calculated by using the minimum value of either the actual catching capacity, or the expected demand for fish from capture fisheries from the fish demand module. It determines the annual amount of fish (in tons) that is caught and landed by capture fisheries. This structure is representing the business as usual scenario, meaning that percentages of by-catch or high-grading are not considered yet. These will be introduced in a later scenario for the purpose to test strategies. However, the catching rate is dominated by the catching efficiency and the strongly balancing effect introduced through it.

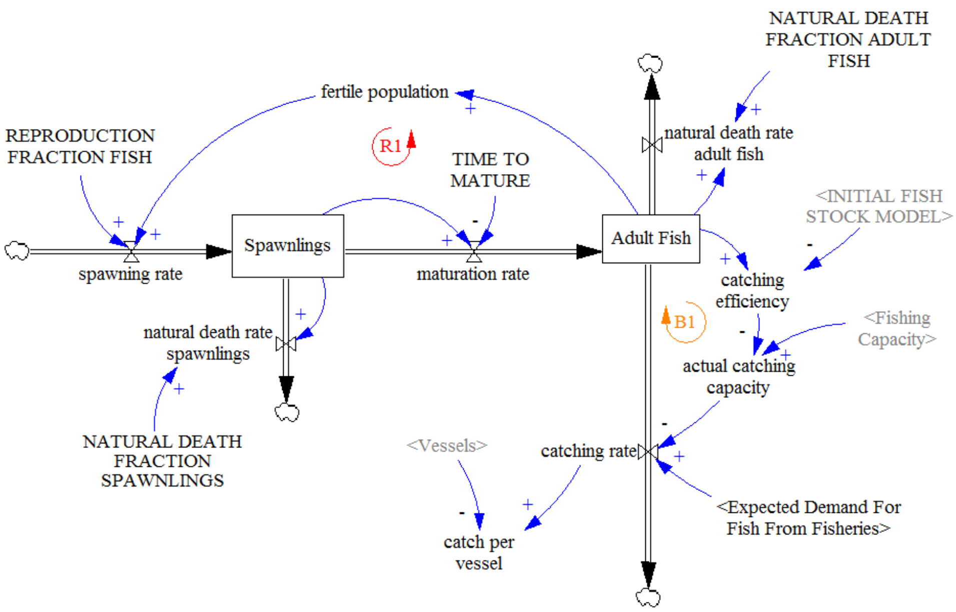


Figure 6 – SFD structure of the fish stock module

<table>
<tr><th><u>Name</u></th><th><u>Equation</u></th></tr>
<tr><td>Spawning rate</td><td>fertile population * REPRODUCTION FRACTION FISH</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The spawning rate captures the reproduction of the fish stock. The adult fish stock represents the fertile population and a reproduction fraction is used to determine the rate at which fish reproduces. The reproduction fraction is an assumption and can be used for sensitivity testing.</td></tr>
<tr><td>Natural death rate spawnlings</td><td>Spawnlings * NATURAL DEATH FRACTION SPAWNLINGS</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This death rate captures the natural deaths of spawnlings, either through predators, or disease. The death fraction is an assumption, since a unified parameter capturing the properties of all fish could not be found.</td></tr>
<tr><td>Natural death rate adult fish</td><td>Fish stock * NATURAL DEATH FRACTION ADULT FISH</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This death rate captures the natural deaths of spawnlings and adult fish, either through predators, disease, or because of age. The death fraction is an assumption, since a unified parameter capturing the properties of all fish could not be found.</td></tr>
<tr><td>Catching rate</td><td>MIN(actual catching capacity , Expected Demand For Fish from fisheries)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The catching rate represents the amount of fish that is caught each year. Catch in this model is constrained to either the actual catching capacity or the expected demand for fish. This assumption assures that fish catch cannot be higher than the available capacity, while at the same time is not exceeding the demand for fish. The second argument implies the awareness of fishermen that an oversupply of fish will bring prices down and harm their operational margins.</td></tr>
<tr><td>Catching efficiency</td><td>(Fish stock / INITIAL FISH STOCK)^1.5</td></tr>
<tr><td colspan="2"><u>Unit: Dimensionless</u>
Catching efficiency introduces a density effect of fishing activities. The underlying assumption is that the more fish there is, the more efficient fishing activities will be, because fishermen do not need to scan the fishing grounds to find fish.</td></tr>
</table>

Table 1 – Equations of the fish stock module

4.1.2 The fisheries module

The fishing capacity sector has four stocks: i) fishing capacity, ii) expected demand for fish from fisheries, iii) vessels under construction, and iv) vessels. The stocks of fishing capacity and expected demand are adjusted by bi-flows – ‘*change in capacity*’ and ‘*change in expected demand*’ respectively. The stock level of vessels under construction is increased by the inflow ‘*vessel order rate*’ and decreased by the outflow ‘*vessel construction rate*’, while the stock of vessels is increased by the vessel construction rate and decreased by the ‘vessel depreciation rate’.

The driving factor for the change in vessels and capacity is the expected demand for fish from fisheries, represented as stock with the units ton per year. The stock level is determined by the change in expected demand, which is a goal seeking function that adjusts the expected demand to the actual demand. The bi-flow is determined by the demand for fish less the aquaculture production (from the demand module), an adjustment factor that is used to account for demand growth and capacity queues, the stock level of expected demand itself and an adjustment time that serves as the period over which expectations about demand are adjusted. The desired adjustment is calculated by dividing the gap, demand less aquaculture production multiplied with the demand adjustment factor less the stock level of expected demand, by the ‘*time to adjust expected demand*’. The ‘*catching efficiency indicator*’, a variable that shows whether the actual capacity is sufficient to fulfil demand, is calculated by dividing the catching rate by the expected demand. The desired catching capacity is then determined by multiplying the expected demand by the capacity efficiency indicator.

The desired catching capacity is the desired amount of tons per year to be caught and it is used to determine the ‘*desired number of vessels’*. For this purpose, the desired catching capacity is divided by the ’*catch per vessel*’, an indicator from the fish stock module that is determined by dividing the catching rate by the number of vessels. Once the desired number of vessels is determined, the ‘*desired vessel adjustment*’ is calculated by subtracting the number of vessels from the desired number of vessels. The stock of vessels under construction is not taken into account in this equation under the assumption of the commons, meaning that several independent parties are taking the decision to order a vessel if it seems worthwhile doing so.

The desired vessel adjustment, the ‘*vessel replacement rate*’ and the ‘*time to process vessel orders*’ the vessel order rate are the base for calculating the vessel order rate. The vessel replacement rate is based on the ‘*vessel depreciation rate*’ from the stock of vessels, thus assuming replacement as long as fishing is worthwhile. For the vessel order rate, the annual amount of vessels ordered, the maximum value of either desired vessel adjustment divided time to process vessel orders plus the vessel replacement rate, or zero is used to safeguard the assumption that orders for vessels, once executed, cannot be cancelled. The vessel order rate is accumulating in the stock of vessels under construction. Vessel orders are executed through the vessel construction rate. A continuous flow is assumed for the vessel construction rate by dividing the amount of vessels under construction by the ‘*time to construct vessel*’, and then multiplying it by ‘*capacity constraint*’. The capacity constraint is representing the assumption that there are queues for vessel construction. The vessels construction rate is the outflow for the stock of vessels under construction and the inflow for the stock of vessels. The stock of vessels is decreased by the vessel depreciation rate, which is calculated by dividing the stock level of vessels by the ‘*lifetime of vessels*’. The vessel depreciation rate serves as input for the vessel replacement rate.

The stock of vessels is, together with the ‘*catching efficiency*’ variable from the fish stock module, and the exogenous variables ‘*capacity per ship*’ and ‘*catchment period*’, used to calculate the change in fishing capacity. The change in capacity is calculated by calculating the gap between the new value of capacity and the actual stock value – thus the number of vessels multiplied by the capacity per ship and the catching efficiency minus the actual stock value – and then divide it by the time step to make it a continuous adjustment.

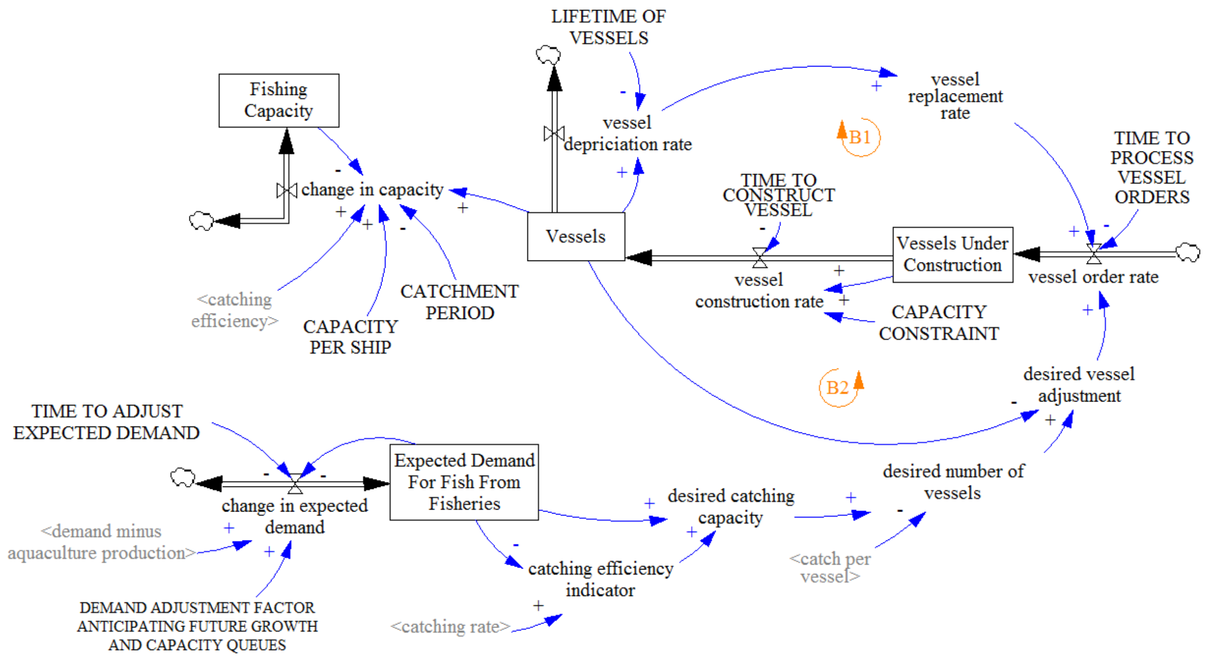


Figure 7: SFD structure of the fishing capacity module

The fishing capacity sector is dominated by several balancing loops. In Figure 7 the loops are highlighted in orange (B1 and B2). Two other loops are not visible at first glance because they run through several modules (one through catching rate and one through catch per vessel) .

These four loops regulate the adjustment of capacity and make sure that supply for fish from capture fisheries is satisfied. Due to the introduced delay through the stock vessels under construction, the system is likely to overshoot: there will still be vessels under construction once the desired capacity is reached.

As soon as catch per vessel, is decreasing, this will cause an increase in the desired fleet size as long as the capacity is not high enough to fulfil the expected demand. At the same time, the loop through catching rate from the fish stock module determines whether the actual catching rate is sufficient to satisfy demand.

Name	**Equation**
Catching efficiency indicator	ZIDZ(catching rate , Expected Demand For Fish from fisheries)
Unit: Dimensionless *The catching efficiency indicator is a ratio between the catching rate and the expected demand for fish, indicating the extent to which the capture sector is able to fulfil the expected demand. Expected demand in this model is derived by the total demand for fish less the amount of fish produces in aquaculture. The ratio is used to determine the sufficiency of the actual fishing capacity.*	
Desired catching capacity	ZIDZ(Expected Demand For Fish from fisheries , catching efficiency indicator)
Unit: Ton / Year *The desired catching capacity represents the capacity which is required to satisfy the expected demand for fish from capture fisheries. It is used to determine the desired number of vessels needed to have the desired capacity in place.*	

<table>
<tr><td colspan="2"></td></tr>
<tr><td>Catch per vessel</td><td>catching rate / Vessels</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The catch per vessel is derived by dividing the catching rate by the number of vessels. The catch per vessel is another indicator of how effective the fishing capacity is used.</td></tr>
<tr><td>Desired number of vessels</td><td>ZIDZ(desired catching capacity , catch per vessel)</td></tr>
<tr><td colspan="2"><u>Unit: Vessel</u>
In order to achieve the desired catching capacity, the number of vessels is compared to the catch per vessel to derive the number of vessels needed to satisfy the demand for fish.</td></tr>
<tr><td>Desired vessel adjustment</td><td>desired number of vessels-Vessels</td></tr>
<tr><td colspan="2"><u>Unit: Vessel / Year</u>
The desired vessel adjustment is derived by comparing the desired number of vessels to the actual number of vessels. This number can be interpreted as an indicator for possible new market entrants whether entering the market is worthwhile or not.</td></tr>
<tr><td>Vessel order rate</td><td>IF THEN ELSE
(desired vessel adjustment / time to process vessel orders>0,
MAX(desired vessel adjustment / time to process vessel orders + vessel replacement rate , 0),
0)</td></tr>
<tr><td colspan="2"><u>Unit: Vessel / Year</u>
The number of new fishing vessels ordered is represented by the vessel order rate. The IF-THEN-ELSE ensures that the vessel adjustment is only captured when the desired vessel adjustment is positive. Once a contract to build a vessel is closed, many agreements with third parties like banks have already been made, meaning orders normally cannot be cancelled[11].</td></tr>
<tr><td>Vessel depreciation rate</td><td>Vessels / lifetime of vessels</td></tr>
<tr><td colspan="2"><u>Unit: Vessel / Month</u>
The scrapping of vessels once they reached the end of their lifetime is represented by the vessel depreciation rate. The vessel depreciation rate is used for determining the vessel replacement rate. The vessel replacement rate captures the replacement of vessels by companies or individual fishermen.</td></tr>
<tr><td>Fishing capacity</td><td>INTEG (change in capacity,
(initial vessels*capacity per ship)/catchment period)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The stock fishing capacity is representing the capability to catch fish based on both, the physical assets and the fish density. It is changed by the bi-flow change in capacity.</td></tr>
<tr><td>Change in capacity</td><td>((Vessels * CAPACITY PER SHIP * catching efficiency) - Fishing Capacity) / CATCHMENT PERIOD</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year / Year</u>
The change in capacity is calculated by multiplying the number of vessels with a fixed capacity per ship and the density factor ‘catching efficiency’ from the fish stock module. The resulting number is then corrected by the actual capacity level and divided by the time period over which fishing takes place.</td></tr>
</table>

Table 2 – Equations from the fishing capacity module

[11] Special thanks at Mr. Hahn, from Pella Sietas GmbH, who answered several questions about the vessel building process on the phone, and provided insights which could not be found on the internet.

4.1.3 The fish demand module

The fish demand module consists of one stock – 'Total Demand For Fish'. The stock is changed by the bi-flow, '*change in demand for fish*'. The stock level is initialized with the historical value for the year 1970. Figure 8 shows the stock and flow structure that is used to calculate the different variables.

The change in total demand for fish is calculated by an IF-THEN-ELSE function. Before the year 2014, the change in demand for fish is calculated by a goal seeking function. First, the stock level of total demand for fish is multiplied with the 'historical growth rate demand' to determine the level of demand for the following time step. To derive the flow value, the stock level of total demand is deducted from this new value. After 2014, the change in demand is by deducting the actual stock level of total demand from the new stock level, which is by dividing the product of '*reference population*' and '*per capita fish consumption*' by the '*weighted average of production efficiency*'. The variable '*kg per ton*' is used as a correction factor, because the per capita consumption has the unit "kg per person".

The total demand for fish is used to calculate the '*demand for fish from secondary processing*', by multiplying it with the '*fraction of fish used for non-food purposes*'. The demand for fish from capture fisheries, which is represented by the variable '*demand for capture fish*, is calculated by a MAX function, that uses the maximum value of either total demand less '*aquafarming production rate'*, or the demand for fish from secondary processing. The variable '*supply fisheries and aquaculture*' is the sum of aquafarming production rate and '*catching rate*'. The '*demand supply ratio fish production sectors*' is calculated by dividing the total demand for fish by the total supply of fish from both production sectors. The '*supply fish for food processing*' is derived from deducting the demand for fish from secondary processing from the total supply.

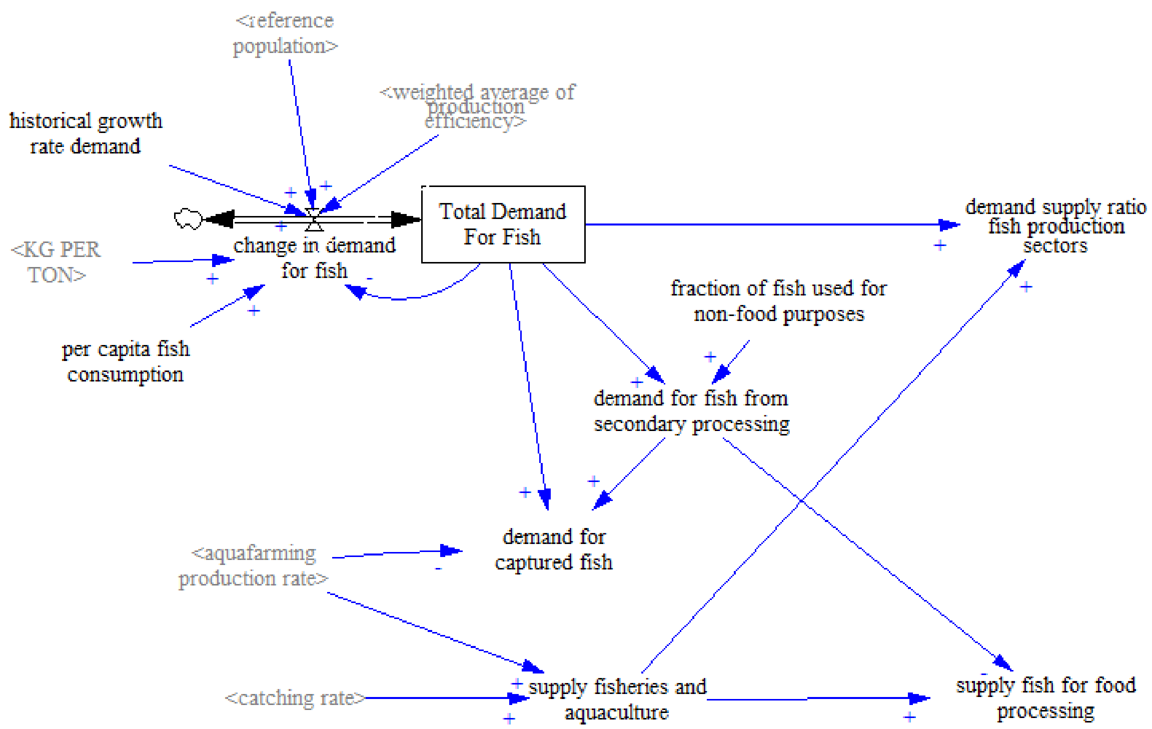
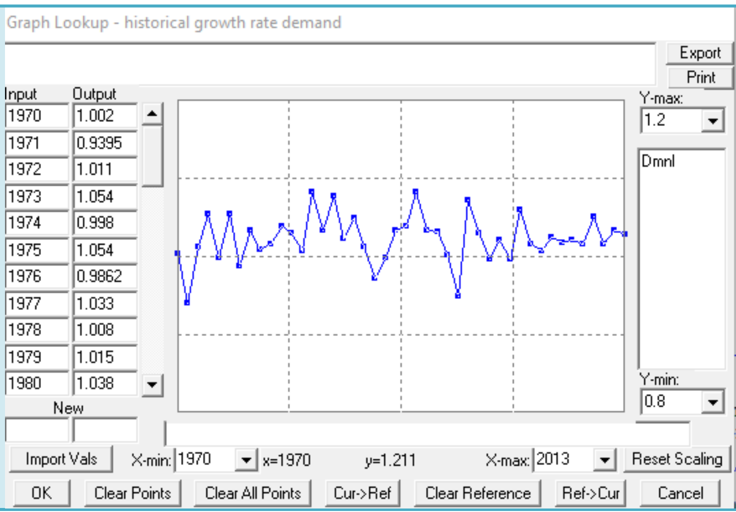


Figure 8 – SFD structure fish demand module

Name	**Equation**

<table>
<tr><td>historical growth rate demand</td><td>
</td></tr>
<tr><td colspan="2"><u>Unit: Dimensionless</u>
The growth rate for the total demand for fish between 1970 and 2014 (last value in 2013) has been derived from the historical data that was provided by the FishStatJ® software of the FAO. The respective values have been calculated by dividing the demand of one year by the demand of the previous year. Or mathematically: $gr_{t0} = D_{t0} / D_{t+1}$.</td></tr>
<tr><td>change in demand for fish</td><td>IF THEN ELSE (Time < 2014,
Total Demand For Fish * historical growth rate demand - Total Demand For Fish,
(per capita fish consumption / KG PER TON * reference population / weighted average of production efficiency) - Total Demand For Fish)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year / Year</u>
An IF-THEN-ELSE function was used to calculate the change in demand for fish before 2014 and after that. Historical values were used for the calibration of the demand, which is one of the main variables that was used for the calibration of the model. After 2014 the demand for fish is depending on the expected per capita consumption and the expected global population size, whereby a time dependent lookup variable was used to implement those values into the model. The variable ‘kg per ton’ was used to correct for the “kg / person” unit of per capita consumption.</td></tr>
<tr><td>demand for fish from secondary processing</td><td>Total Demand For Fish * "fraction of fish used for non-food purposes"</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This variable represents the amount of fish that is demanded for fish meal and fish oil production. It is calculated by multiplying the total demand for fish by the historical fraction that was derived from the FAO’s (2008) report. At the same time this variable is used as the floor for the demand for fish from capture fisheries.</td></tr>
<tr><td>demand for captured fish</td><td>MAX(Total Demand For Fish - aquafarming production rate , demand for fish from secondary processing)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The demand for fish from capture fisheries is defined as a MAX function that uses the maximum of the following two values: total demand for fish less aquafarming production rate, or the demand for fish from secondary production. This formulation is used to implement the assumption that fish from aquaculture is solely used for human consumption but never for secondary production.</td></tr>
<tr><td>supply fisheries and aquaculture</td><td>aquafarming production rate + catching rate</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This variable represents the total fish supply that is provided by capture fisheries and aquaculture together. It is the sum of the catching rate and the aqaufarming production rate.</td></tr>
<tr><td>demand supply ratio fish production</td><td>ZIDZ(Total Demand For Fish , supply fisheries and aquaculture)</td></tr>
</table>

sectors	
Unit: Vessel / Year *The demand supply ratio of the fish production sector is calculated by dividing the total demand for fish by the supply from fisheries and aquaculture, thus total demand divided by total supply. It indicates the ability of the production sector to satisfy demand, and is used to determine the sales price for capture fisheries.*	
supply fish for food processing	supply fisheries and aquaculture-demand for fish from secondary processing
Unit: Ton / Year *The supply fish for food processing is the amount of fish that is sent to the food processing sector. It is calculated by deducting the demand from secondary processing by the total supply of the fish processing sector.*	

Table 3 – Equations of the fish demand module

4.1.4 The fish processing module

The fish processing module has three stocks: i) fish at primary processing, representing the tons of raw material on stock, ii) fish processed for food, representing the tons of finished goods on stock of the processing facilities, and iii) processing capacity, representing the annual amount of fish in tons that the sector is able to process. The raw material stock of fish at processing has an inflow ‘*transport to primary processing*’ and one outflow, the ‘*resource consumption rate primary processing*’. The inflow of the finished goods stock of processed fish is the ‘*production rate primary processing*’, while the outflow are is the ‘*transportation to wholesaler*’, representing demand-based shipments to the wholesale sector. The processing capacity is increased by the inflow ‘*construction rate processing capacity*’ and decreased through its outflow ‘*depreciation processing capacity*’.

The capacity adjustment and therewith the production rate of the fish for food processing sector are supply driven. The available fish supply for food processing is taken as the ‘*max supply food processing*’, and is used as input for the raw material stock transport to primary processing. It represents the annual amount of fish that is shipped to the fish for food processing sector. Fish accumulates in the raw material stock, and flows out through the resource consumption rate primary processing, which is depending on the processing capacity.

The fish supply for food processing is at the same time the ‘*desired production capacity*’ of the primary processing sector. Capacity in this model follows supply, as anticipation might lead to overcapacity which is undesirable. The construction rate of processing capacity is calculated by dividing the gap between the desired production capacity and the actual stock level of processing capacity by the ‘*time to construct processing plant*’, and adding the ‘*capacity replacement rate*’ on top. The capacity replacement rate equals the depreciation rate of processing capacity, which is calculated by dividing the stock of processing capacity by the ‘*average lifetime production plant*’. Both, capacity construction and depreciation are thus a continuous process in this model.

The processing capacity, representing the annual amount of tons of fish that can be processed by the primary processing sector, is determining the resource consumption rate (outflow raw material) and the production rate (inflow finished goods). With the resource consumption rate is capturing the total amount of fish that is processed (=processing capacity), the production rate is calculated by multiplying the processing capacity with a ‘*weighted average of production efficiency*’, to account for fish waste and processing inefficiencies. This variable is a weighted average of the utilization fractions that indicate how much of a “fish” is used for different types of products. Data was collected and averaged from several different sources (e.g. ITP. 1992; AIT, 2007). The higher the production efficiency, the higher the production rate will be assuming a steady resource consumption rate at the same time. For the equation of this variable please check the table documenting the processing sector two pages down.

Finished goods accumulate in the fish processed for food stock, and flow out by being shipped to the wholesale sector. The transportation rate to the wholesale sector is defined as the minimum value of either ‘*demand wholesaler*’, or the ‘*max shipment rate*’, which is calculated by dividing the stock level by the ‘*transportation time to wholesaler / distributor*’.

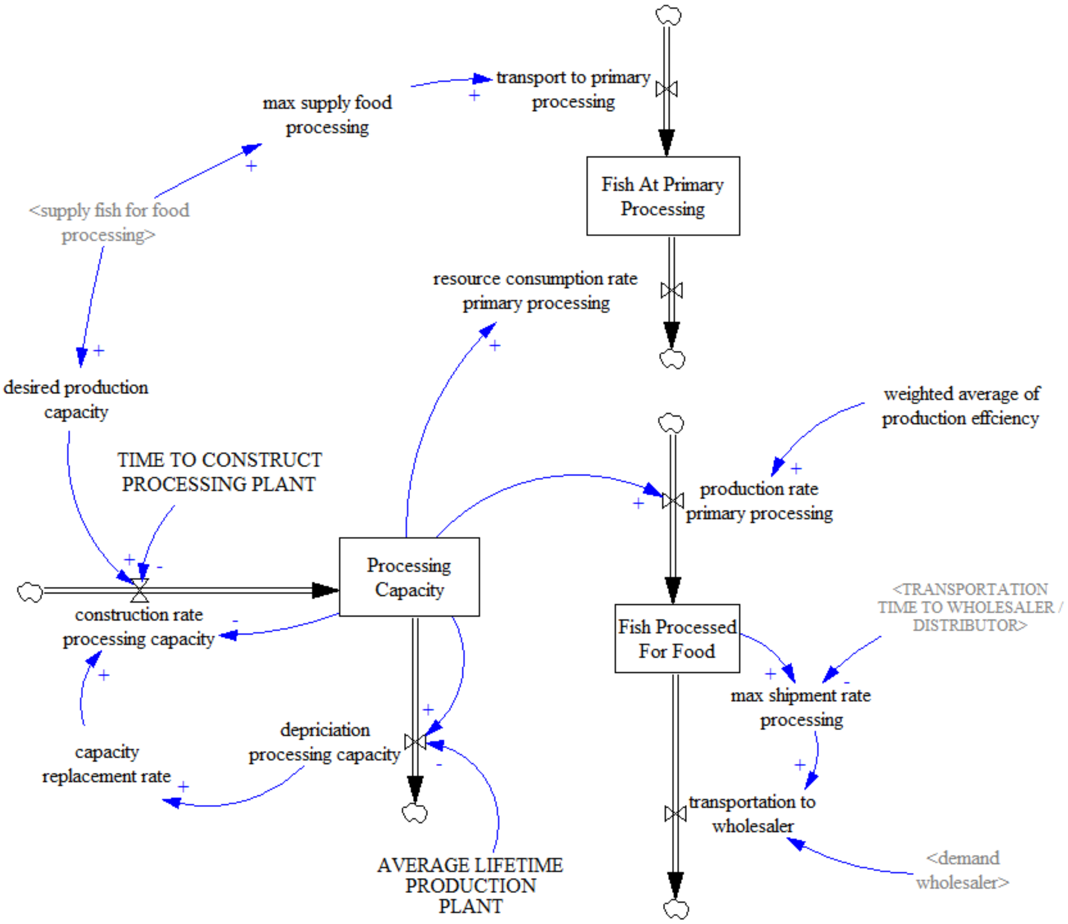


Figure 9: Primary fish processing module

Name	Equation
Fish supply for food processing	supply fisheries and aquaculture – demand for fish from secondary processing
Unit: Ton / Year *The fish supply for food processing is depending on the total supply from fisheries and aquaculture, less the amount of fish that is used to produce marine ingredients. It is the total amount of fish that is available to be processed for food and is shipped to the processing facilities.*	
Desired production capacity	supply fish for food processing
Unit: Ton / Year *The desired processing capacity is determined by the fish supply that is shipped to the processing sector. This formulation is based on the assumption that adjustments of processing capacity are supply driven.*	
Construction rate processing capacity	max((desired production capacity – Processing capacity) / time to construct processing plant + depriciation processing capacity , 0)
Unit: (Ton / Year) / Year *The construction rate of the processing capacity is the inflow of the processing capacity stock, and is defined as a MAX function to avoid a decrease of the stock through a negative inflow. To determine the construction rate, the fish supply shipped to the processing sector, thus the biomass to be processed, is compared to the capacity in place. The change in processing capacity then takes place over the time it takes to construct the capacity, which is assumed to be one year in this model.*	

Depriciation processing capacity	Processing capacity / average lifetime production plant
Unit: (Ton / Year) / Year *The depreciation rate is the outflow of the processing capacity. If not replaced, the depreciation rate is decreasing the processing capacity in place based on the lifetime of the production plants. In the BAU scenario the lifetime of capacity is assumed to be 40 years, but could be changed for purposes of sensitivity analysis.*	
Weighted average of production efficiency	efficiency canning operations * normalized fraction fish used for canning + efficiency fresh fish * normalized fraction fish used for fresh consumption + efficiency filleting operations * normalized fraction fish used for frozen produce + efficiency filleting operations * normalized fraction fish used for curled produce
Unit: Dimensionless *This variable is a weighted average of the utilization fractions that indicate how much of a "fish" is used for different types of products. Data was collected and averaged from several different sources (e.g. ITP. 1992; AIT, 2007). The higher the production efficiency, the higher the production rate while a decreasing resource consumption rate at the same time.*	
production rate primary processing	max(Processing capacity * weighted average of production efficiency , 0)
Unit: Dimensionless *The fish processing rate is the actual amount of fish which is produced for human consumption and then shipped to the wholesale sector, or exported. The output is depending on the processing capacity and the production efficiency. Production efficiency is a weighted average consisting of the processing efficiencies for four different fish products (canned, curled, fresh and frozen filets). As a weight for the average historical consumption fractions (FAO, 2008) are used.*	
resource consumption rate primary processing	Processing capacity
Unit: Ton / Year *The resource consumption rate of primary processing sector is the rate at which the fish that is shipped to the processing sector is processed. It is the outflow of the stock of fish at primary processing, which is accumulating the difference between the supply which is shipped to and the amount that actually is processed by the processing sector. The resource consumption of the processing sector thus depends on the processing capacity, but its maximum is the amount of fish which is shipped to the sector plus the amount which is still on stock.*	

Table 4 – Equations of the fish processing module

4.1.5 Remaining supply chain sectors

The wholesale sector

The wholesale sector has one stock and two flows. The stock represents the amount of finished fish foods that are stored at the wholesale level. It has an inflow, the '*transportation to wholesaler*' from the primary processing sector, and one outflow, '*transportation to retailer*'.

The shipment rate from the processing sector is, as explained in the previous section, depending on either the maximum amount of finished products to be shipped, or the demand from the wholesale sector. The dotted arrow indicates the connection between demand and transportation rate made in the processing sector. The '*demand wholesaler*' is derived from calculating the gap between the actual stock level and the '*desired inventory wholesaler*', and then dividing the gap by the '*transportation time to wholesaler / distributor*'. The desired inventory of the wholesale sector is calculate by multiplying the outflow transportation to retailer by the '*desired inventory coverage wholesaler*'. The transportation rate to the retail sector is the minimum of either the '*demand retailer*' from the retail module, or the '*max shipment rate wholesaler*', which is simply calculated by dividing the stock level by the '*transportation time to retailer*'. The MIN function is used to avoid that the stock reaches a negative level.

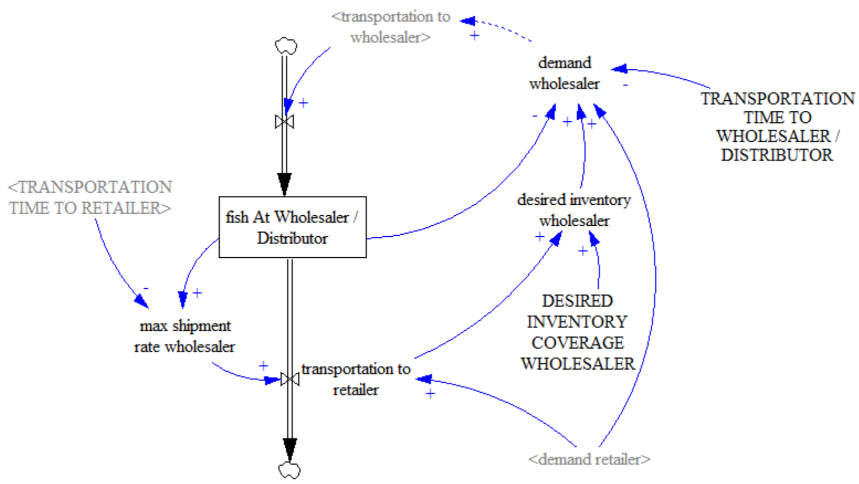


Figure 10: Wholesale module

The retail sector

The wholesale sector has one stock and two flows. The stock represents the amount of finished fish foods that are stored at the retail level. It has an inflow, the '*transportation to retailer*' from the wholesale sector, and as outflow the '*consumption rate*', representing the global fish consumption.

The shipments to the retail sector depend, as explained above, on either the demand for fish from the retailer, or the maximum shipment rate from the wholesale module. The dotted arrow indicates the connection between demand and transportation rate made in the wholesale sector. The '*demand retailer*' is derived from calculating the gap between the actual stock level and the '*desired inventory retailer*', divided by the '*transportation time to retailer*'. The desired inventory level of the retailer is calculated by multiplying the consumption rate with the '*desired inventory coverage retailer*'.
The consumption rate is the minimum of either the '*max sales rate retailer*' or the '*demand for fish for food*'. The MIN function is used to avoid that the stock reaches a negative level. The demand for fish for food is calculated by multiplying the '*reference population*' by the '*historical per capita*

consumption' and the '*weighted average of production efficiency*'. The multiplication with the weighted average is necessary to avoid that the demand for fish for food exceeds the historical levels. This is due to the fact that the FAO's calculation of per capita consumption is based on total supply and total population.

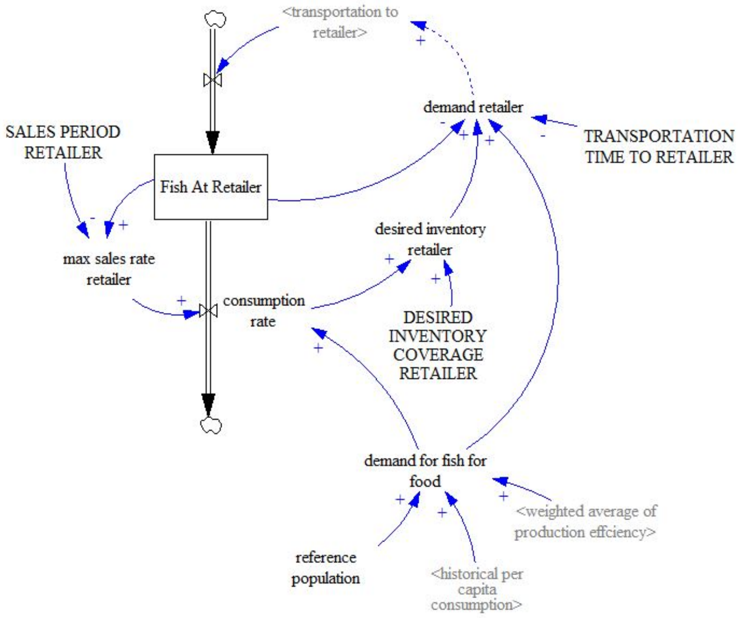


Figure 11: Retail module

Name	Equation
demand wholesaler	(desired inventory wholesaler - "Fish at wholesaler/distributor") / "TRANSPORTATION TIME TO WHOLESALER/DISTRIBUTOR" + demand retailer
Unit: Ton / Year *The wholesale demand for fish is derived from the discrepancy between the actual and the desired stock level, plus the demand for fish from the retail sector. The discrepancy is divided by the transportation time, because a continuous flow between wholesale and processing sector is assumed. The demand from the retail sector is added to the wholesale demand to avoid a steady state error in the stock, that would cause the stock to never reach its desired level.*	
transportation to wholesaler	MIN(demand wholesaler , max shipment rate processing)
Unit: Ton / Year *Shipments from the processing sector to the wholesale sector depend on either the demand from the wholesale sector, or the maximum amount of fish on stock at the processing level. The MIN function assures that the stock level at the process level is drawn to negative levels in case that the demand exceeds the stock level.*	
Fish at wholesaler / distributor	INTEG (-transportation to retailer + transportation to wholesaler , demand retailer * desired inventory coverage wholesaler)
Unit: Ton *This stock represents the fish supply which is stored at the wholesale level and is ready to distribution to the retailer. The inflow is the shipment rate from processing sector and the outflow is the transportation to the retailer. The stock level is initialized at the desired level by multiplying the retailers' demand with the desired inventory coverage level of the wholesaler.*	

demand retailer	(desired inventory retailer – Fish at retailer) / transportation time to retailer + demand for fish for food
Unit: Ton / Year *The demand from the retail level is based on the retailer's desired inventory coverage, the amount of fish on stock at the retailer, the transportation time to the retailer, and the demand from the consumption sector. First the desired inventory is compared to the stock level in order to determine the order rate of fish. The order rate is then divided by the shipment time to the retailer, which is based on the assumption that there is a continuous flow between the sectors.*	
transportation to retailer	MIN(demand retailer , max shipment rate wholesaler)
Unit: Ton / Year *The amount of fish shipped to the retail level is determined by a MIN function that, as with the transportation to the wholesale sector, ensures that the stock does not go negative. As long as there is enough fish on stock at the wholesale level, the retail demand will be satisfied. If there is not enough fish, then all the available fish on stock will be shipped.*	
Fish at retailer	INTEG (transportation to retailer – Consumption , 2.712e+007)
Unit: Ton *The fish stock at the retail level is increased by the shipments from the wholesale sector, and decreased by consumption rate. In this model, the fish stock at the retail level is the amount of fish that can be consumed by the population.*	
Demand for fish for food	historical per capita consumption * weighted average of production efficiency * reference population / kg per ton
Unit: Ton / Year *The demand for fish for food is representing human consumption of fish in the model on an aggregate level. It is depending in the global population and the per capita fish consumption (cf. FAO 1999). Since the per capita data is referring to the total fish supply, the consumption of the individual level is multiplied by the production efficiency to correct for the downstream quantity.*	
Consumption	demand for fish for food
Unit: Ton / Year *The consumption rate is depending on the demand for fish for food. It is the outflow from the fish stock at the retail level.*	

Table 5 – Equations of the retail sector

Value chain elements fisheries sector

Several variables from the supply chain are driving the value chain, which is representing the economic sphere of the model. The value chain of all sectors is subdivided into costs and income. Costs are further subdivided into operational costs and fixed costs, while the income depends on the sales price and the quantity of traded goods.

4.1.6 Fisheries value chain elements

The financial sector of the fisheries consists of one stock and two flows. The stock ‘*bank account fisheries*’ accumulates the difference between its inflow ‘*turnover fishers*’ and its outflow ‘*expenses fisheries*’. In the fisheries financial module, the following items of the UNEP report were used to calculate the operational costs (UNEP, 2011, p. 93) per ton of fish landed:

- Fuel costs
- Running costs for selling or treating fish
- Repair costs
- Labour costs

These are the variable costs of fishing and are calculated by multiplying the individual elements with the catching rate. Fixed costs are represented by depreciation costs and capital costs (cf. UNEP, 2011, p. 93), and are calculated the same way. Fixed costs in this model are internalized by using fixed factors as well, due to the heterogeneity of the fishing fleet and lack of data about financial variables in the fishing sector.

The income of the fisheries are calculated by multiplying the sales price of fish, which is the product of the ‘*mean average price of fish*’ and the ‘*effect of demand and supply ratio on fish sales price*’, by the sum of ‘*transport to primary processing*’ and ‘*transport to secondary processing*’, thus sales price times the total amount of fish which is sold in the market.

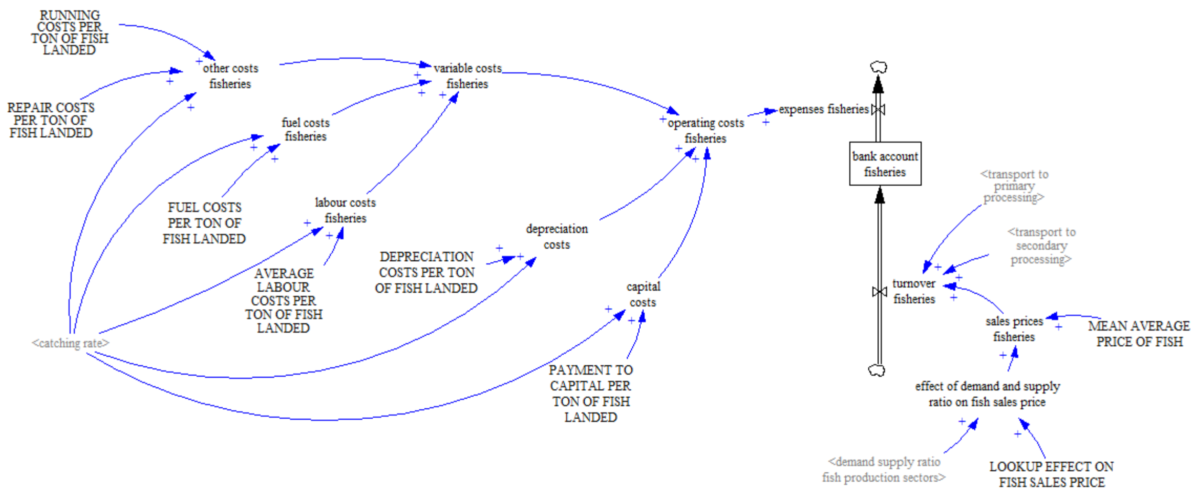


Figure 12: Finances Fisheries module

The overcapacity in the capture fisheries sector in combination with stagnating catching rates leads in the long run to a situation where capture fisheries have to be subsidized to remain viable. Subsidies in the fisheries sector are globally applied and play a complex role in ecological sustainability and sustainable development. They are out of the scope of the BAU scenario, but will be used in policy scenarios to see which effects can result from their application.

Name	Equation
fuel costs fisheries	actual catching rate * fuel costs per ton of fish landed
Unit: Euro / Year *The fuel cost of capture fisheries are calculated by multiplying the catching rate with the fixed factor of fuel costs per ton of fish landed (UNEP, 2011, p. 93).*	
labour costs fisheries	average labour costs per ton of fish landed * actual catching rate
Unit: Euro / Year *The labour costs of fisheries are calculated by multiplying the catching rate with the average labour costs per ton of fish landed (UNEP, 2011, p. 93).*	
other costs fisheries	actual catching rate * repair costs per ton of fish landed + actual catching rate * running costs per ton of fish landed
Unit: Euro / Year *The maintenance costs of fisheries are covering the repair costs and the running costs of the fishing operations. Running costs are costs that occur for example for selling fish on auctions or for treating fish on-sea. For both a fixed value is used (UNEP, 2011, p. 93). Both of these factors are multiplied by the catching rate and then added up.*	
variable costs fisheries	labour costs fisheries + fuel costs fisheries + other costs fisheries
Unit: Euro / Year *To calculate the variable costs of fishing operations, the three positions labour, fuel, and maintenance are added up. Fixed factors (as mentioned in the UNEP's report) are used for calculating these cost, while some of these costs could be further internalized.*	
depreciation costs	actual catching rate * depreciation costs per ton of fish landed
Unit: Euro / Year *The depreciation costs cover the loss of value, or the 'consumption' of capital in the fisheries sector. The depreciation costs are also dependent on the catching rate using a fixed factor per ton of fish landed (UNEP, 2011, p. 93).*	
capital costs	actual catching rate * payment to capital per ton of fish landed
Unit: Euro / Year *Payment to capital captures interest payments and payments to maintain the level of capital of the capture sector. The value of these costs is calculated by multiplying a fixed factor per ton of fish landed with the catching rate (UNEP, 2011, p. 93).*	
operating costs fisheries	variable costs fisheries + depreciation costs + capital costs
Unit: Euro / Year *Operating cost is a sum variable that captures the total costs of the capture fishery sector. This value is used as an outflow from the bank account of the fisheries. To arrive at the total costs of capture fisheries, the variable costs, the depreciation costs and the capital costs are added up.*	
turnover fishery	transport to primary processing * sales prices fisheries + transport to secondary processing * sales prices fisheries
Unit: Euro / Year *The turnover of fisheries depends on the shipment rates to primary (food) and secondary (non-food), and the sales price of fish. Both rates are multiplied with the sales price of fish and then added up to arrive at the total turnover.*	

Table 6 – Equations of the finances fisheries module

4.1.7 Processing value chain elements

The economic module of the fish for food processing sector has three stocks and six flows. The first stock is the stock 'bank account processing industry' and accumulates the difference between its inflow 'revenue food processing' and its outflow 'processing expenses'.

The operational costs of the fish processing sector have been compiled from several different sources (Johnston et al., 1994; Zugarramurdi & Parin, 1995; Gudmundsson et al., 2006; Yordana et al., 2014; Larsen, *Undated*). Figure 12 shows a causes tree of the variable '*total costs of processed orders*'. A causes tree is a graph that displays the variables that are used to calculate a variable plus the variables that are used to calculate these. In summary, the operational costs of the processing sector include

- Raw material costs
- Labour costs
- Shipment costs
- Costs for cooling goods

Raw material and labour costs are depending on the production rate of the processing sector. Raw material costs are calculated by multiplying the '*resource consumption rate primary processing*' by the '*sales price fisheries*'.

The '*labour costs of food processing*' are calculated by multiplying the '*average salary per employee*' by the '*indicated labour fish processing sector*'. Indicated labour is derived from multiplying the '*production rate primary processing'* by an external factor '*indicated employment fish processing per ton processed*'.

The '*shipment costs wholesaler*' are calculated by multiplying the amount of finished products, thus the flow '*transportation to wholesaler*', by the '*transportation costs per ton of fish*'.

The costs for cooling goods are depending on the raw material shipments to the processing sector, 'supply fish for food processing', and the production rate of processing. Since not all finished products are in need of cooling (e.g. canned fish), the production rate is multiplied by a '*fraction of finished products in need of cooling*' before being summed up to the raw material shipments. The sum of raw material deliveries and finished products in need of cooling is then multiplied by the '*energy costs per ton of fish to be cooled*'. This formulation assumes that all raw materials, but only a fraction of the processed fish is in need of cooling.

The fixed costs considered for the processing sector are represented by the '*capital costs processing industry*' and are calculated by multiplying the stock level of '*accumulated investment in processing facilities*' by a fixed '*percentage payment to fixed capital*'.

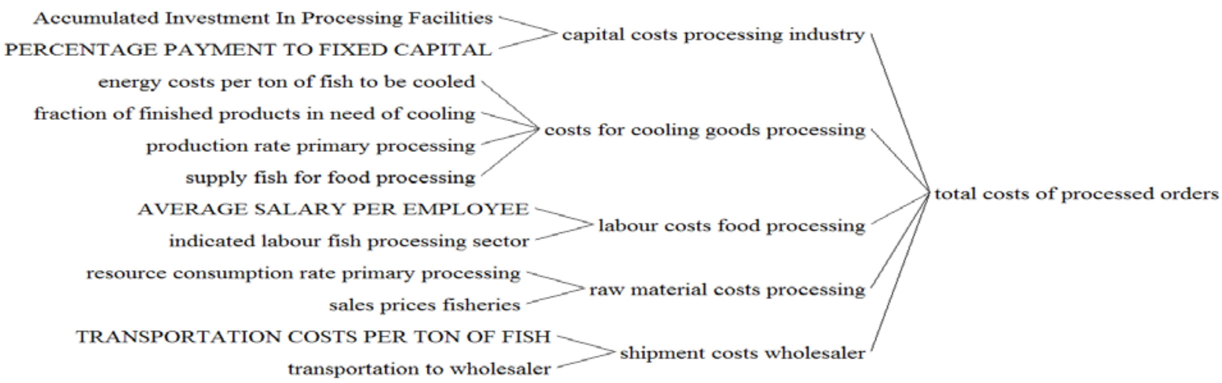


Figure 13: Causes tree 'total costs of processed orders' - Finances Fish Processing module

Accumulated investment is a stock that captures the difference between its inflow '*investment in processing capacity*' and its outflow '*depreciation of processing capital*'. It is a co-flow structure of the stock '*total sized of processing facilities*' which is depending on the construction and depreciation of processing capacity in the processing module. Its inflow '*increase in production plant size*' is calculated by multiplying the '*construction of processing capacity*' by a '*monthly productivity per sqm*' and its outflow '*decrease in production plant size*' is calculated by multiplying the '*depreciation processing capacity*' by the same productivity factor. The size of processing facilities is used to determine the capital costs, or accumulated investments, of the processing facilities. The inflow investment in processing capacity is calculated by multiplying the increase in production plant size by a cost factor, the '*construction costs per sqmtr fish plants*', and the outflow by multiplying the decrease of plant size by the same factor. Figure 14 on the next page shows the structure on the finances module for the fish processing sector.

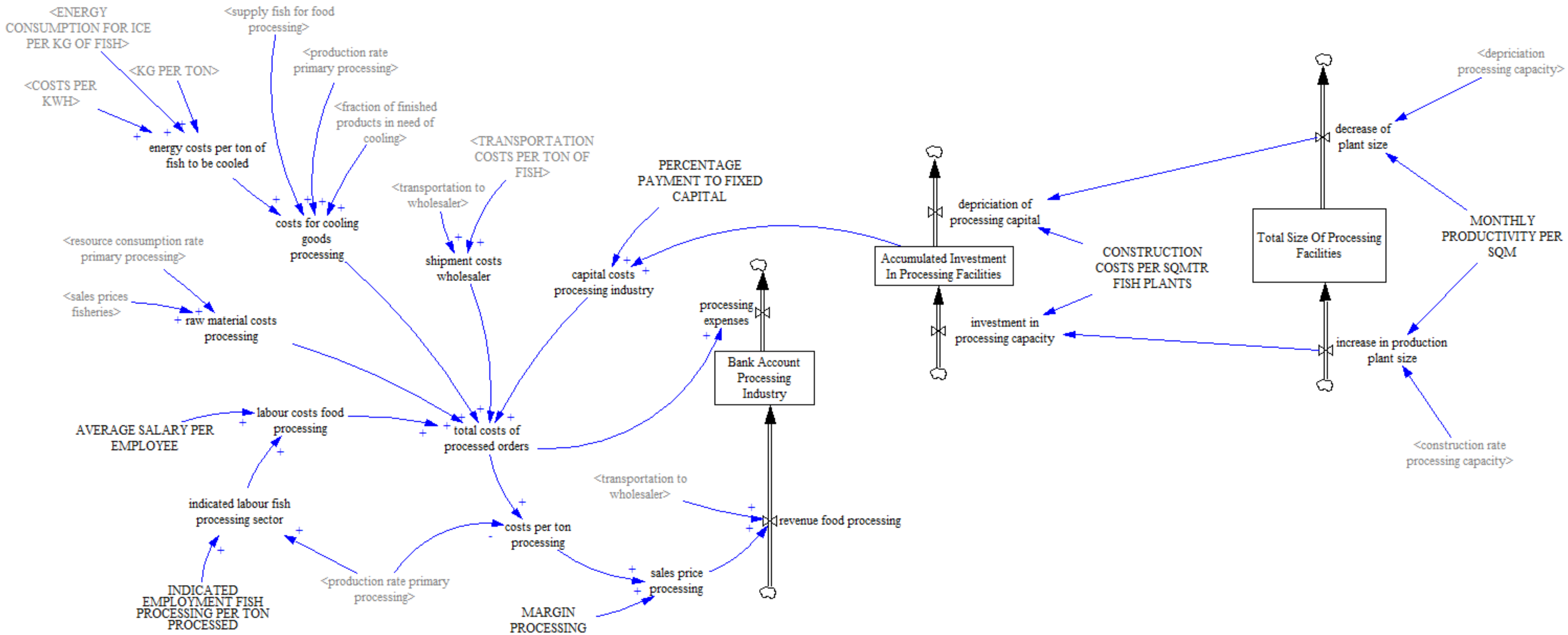


Figure 14: SFD of the Finances Primary Processing module

Name	Equation
indicated labour fish processing sector	production rate primary processing * indicated employment fish processing per ton processed
Unit: FTE / Year *The indicated labour in primary fish processing is derived from an average productivity per worker, or an indicated employment per ton of fish processed (Nasr-Allah, 2016). The indicated employment factor is then multiplied by the production rate to calculate the indicated employment of the processing sector.*	
labour costs food processing	AVERAGE SALARY PER EMPLOYEE * indicated labour fish processing sector
Unit: Euro / Year *The labour costs of the fish processing sector are calculated by using an average salary per employee in fish processing (STECF, 2013) and the indicated labour of the fish processing sector.*	
raw material costs processing	resource consumption rate primary processing * sales prices fisheries
Unit: Euro / Year *The costs for raw material of the processing sector depend on the amount of fish processed, thus the resource consumption rate of the processing sector, and the sales price of the fishery sector. The resource consumption rate multiplied by the sales price give the total raw material costs.*	
energy costs per ton of fish to be cooled	COSTS PER KWH * ENERGY CONSUMPTION FOR ICE PER KG OF FISH * KG PER TON
Unit: Euro / Ton *The costs of energy for keeping one ton of fish cool (UNEP, 2000) are calculated by multiplying the required energy for cooling one kilogram of fish with the conversion factor 'kg per ton', and then with the costs per kWh.*	
costs for cooling goods processing	energy costs per ton of fish to be cooled * ((production rate primary processing * fraction of finished products in need of cooling) + supply fish for food processing)
Unit: Euro / Year *The costs for cooling goods depend on the costs of energy per ton of fish to be cooled and the fraction of finished fish produce that is in need of cooling. The costs of cooling per ton of fish is then multiplied by the amount of products that need to be kept cool, which is calculated by using the production rate of primary processing and the fraction of products in need of cooling.*	
Accumulated investment in processing facilities	INTEG (investment in processing capacity – depreciation of processing capital , Total size of processing facilities * construction costs per sqmtr fish plants)
Unit: Euro / Year *The accumulated investments are a stock that one inflow, new investments in processing capacity, and one outflow, the depreciation of processing capital. The stock is initialized by multiplying the total size of processing facilities with the construction costs of per square meter of processing capacity (Zugarramurdi & Parin, 1995).*	
capital costs processing industry	Accumulated investment in processing facilities*percentage payment to fixed capital
Unit: Euro / Year *The payments to capital of the processing sector depend on the accumulated investments of the processing sector and a fixed percentage of payment to capital.*	
total costs of	capital costs processing industry + costs for cooling finished goods

processed orders	processing +raw material costs processing + labour costs food processing +transportation costs per ton of fish * transportation to wholesaler
Unit: Euro / Year *The total costs of processed orders in this model are the sum of the following 5 components: i) capital costs, ii) cooling costs for finished goods, iii) raw material costs, iv) labour costs, and v) transportation costs. The transportation costs are calculated by multiplying a fixed shipment price per ton of fish with the transportation rate from the processing sector to the wholesaler.*	

Table 7 – Equations of the finances fish processing module

4.1.8 Distribution market value elements

The wholesale and the retail modules have each one stock and three flows. They are identical in structure with the difference of transportation costs, which occur on wholesale, but not on retail level. The operational costs of the two sectors consist of

- Raw material costs
- Refrigeration costs, and
- Transportation costs (wholesaler only)

As raw material costs for these sectors the sales revenue of the upstream sectors, as for example '*revenue food processing*' for '*raw material costs wholesaler*' was used. Refrigeration costs for both sectors are calculated by multiplying the respective transportation rate with the '*fraction of finished products in need of cooling*' and the '*energy costs per ton of fish to be cooled*'. Transportation costs only occur on the wholesale sector and are calculated by multiplying the downstream flow '*transportation to retailer*' with the '*transportation costs per ton of fish*'.
Capital costs are not included in the model, since wholesalers and retailers have considerable facilities, making it difficult to calculate capacity and depreciation costs incurring for fish. This means that there are no fixed costs considered for the downstream distribution market.

Figure 15 and Figure 16 show the structures that calculate the costs of the wholesale and retail sector respectively.

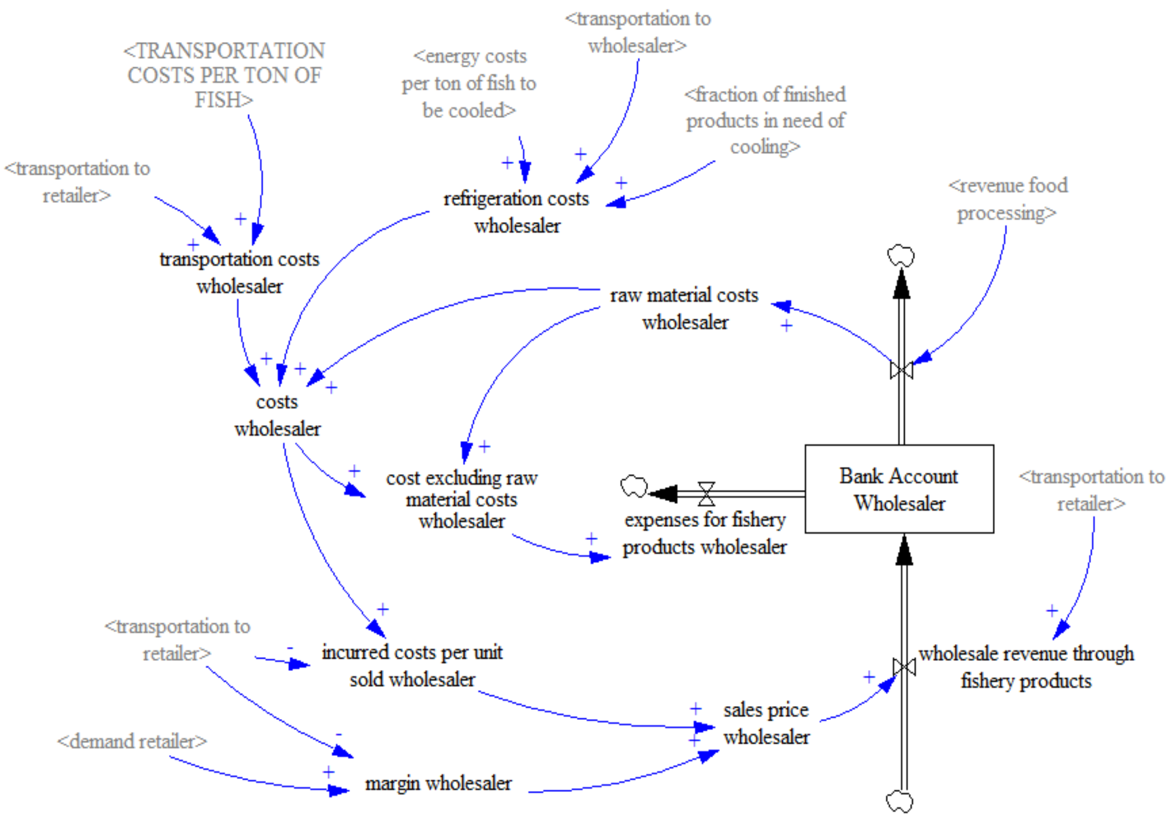


Figure 15: SFD Finances Wholesale module

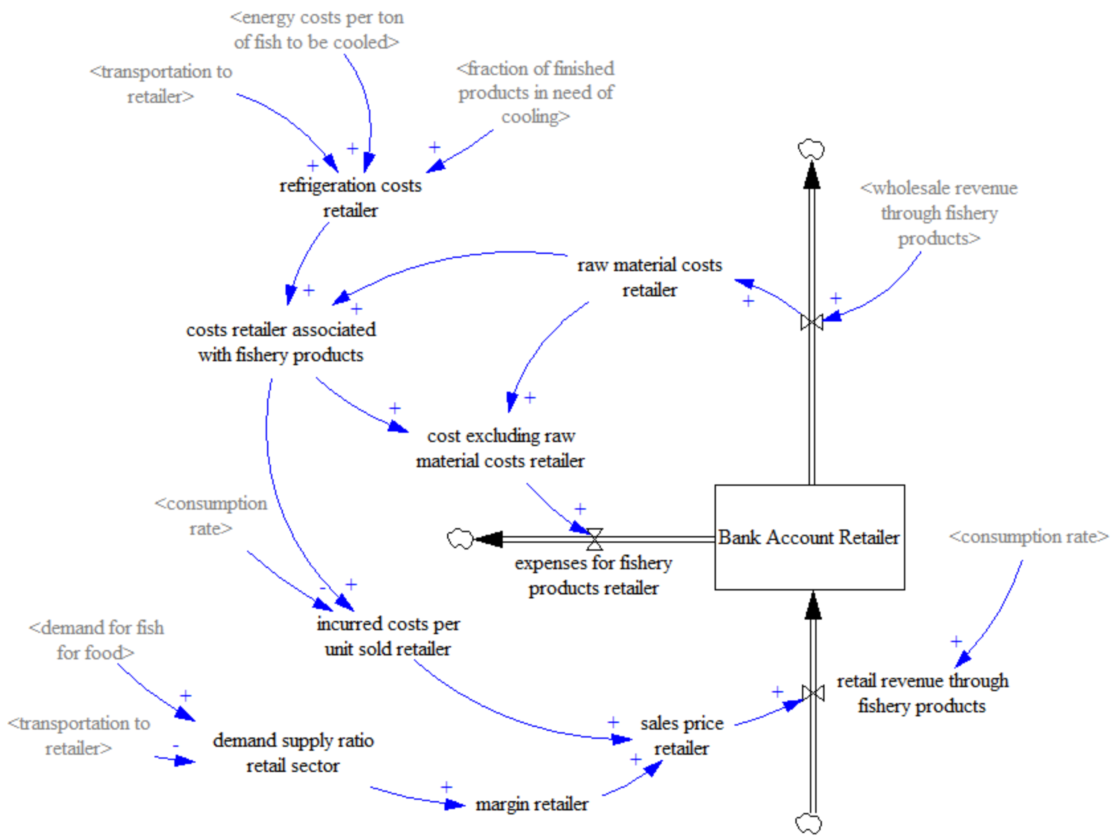


Figure 16: SFD Finances Retail module

Name	Equation
transportation costs wholesaler	transportation to retailer * TRANSPORTATION COSTS PER TON OF FISH
Unit: Euro / Year *The transportation costs of the wholesale sector depend on the amount of fish that is transported to the retail sector and the transportation costs per ton of fish. The product of these two variables are the shipping costs of the wholesale sector.*	
refrigeration costs wholesaler	(transportation to wholesaler * fraction of finished products in need of cooling) * energy costs per ton of fish to be cooled
Unit: Euro / Year *The refrigeration costs of the wholesale sector depend on the fraction of fish in need of cooling and the shipping rate of fish to the wholesaler. The cooling costs are calculated by multiplying the transportation rate to the wholesale sector with the fraction of products that are in need of cooling, and multiplying the quantity of fish in need of cooling by the energy costs per ton of fish to be cooled.*	
raw material costs wholesaler	revenue food processing
Unit: Euro / Year *The raw material costs of the wholesale sector is represented by the revenue of the processing sector, which is calculated by multiplying the transportation rate to the wholesale sector by the sales price of the processing sector.*	
costs wholesaler	raw material costs wholesaler + refrigeration costs wholesaler + transportation costs wholesaler
Unit: Euro / Year	

The total costs of the wholesale sector are calculated by adding up the raw material costs, the refrigeration costs and the transportation costs. Labour or capital costs are not included since it is assumed that wholesale operations do not only focus on fishery products and therefore already have the people and the capital in place independent of the product.	
expenses for fishery products wholesaler	cost excluding raw material costs wholesaler
Unit: Euro / Year *The expenses of the wholesale sector are the total costs of the wholesale sector less the raw material costs.*	
cost excluding raw material costs wholesaler	costs wholesaler – raw material costs wholesaler
Unit: Euro / Year *The costs excluding the raw material of the wholesale sector represent the operational costs that occur through doing business. To calculate these costs, the raw material costs are deducted from the total costs of the wholesale sector.*	
incurred costs per unit sold wholesaler	costs wholesaler / transportation to retailer
Unit: Euro / Ton *The costs per unit sold of the wholesale sector are calculated by dividing the total costs of the wholesale sector by the total quantity that is shipped to the retail sector.*	
demand supply ratio wholesaler	demand retailer / transportation to retailer
Unit: Dimensionless *The demand-supply ratio of the wholesale sector is calculated by dividing the demand from the retail sector by the transportation rate to the retail sector. It indicates whether the wholesale sector is able to cover the demand of the retailing sector.*	
margin wholesaler	demand supply ratio wholesaler
Unit: Dimensionless *This model assumes the demand supply ratio of the wholesale sector as the margin of its operations, which is in line with macro economic theory. Once the demand exceeds the supply, the prices start to rise due to a scarcity in the market, and vice versa.*	
sales price wholesaler	incurred costs per unit sold wholesaler * margin wholesaler
Unit: Euro / Year *The sales price of the wholesale sector is calculated by multiplying the 'per unit costs' with the margin of the wholesale operations.*	
wholesale revenue through fishery products	transportation to retailer * sales price wholesaler
Unit: Euro / Year *The wholesale sectors' revenue from fish trading activities is calculated by multiplying the amount of fish transported to the retail sector by the sales prices of the wholesaler.*	
refrigeration costs retailer	(transportation to retailer * fraction of finished products in need of cooling) * energy costs per ton of fish to be cooled
Unit: Euro / Year *The refrigeration costs of the retail sector depend on the fraction of fish in need of cooling and the shipping rate of fish to the wholesaler. The cooling costs are calculated by multiplying the transportation rate to the retail sector with the fraction of products that are in need of cooling, and multiplying the quantity of fish in need of cooling by the energy costs per ton of fish to be cooled.*	
raw material costs	wholesale revenue through fishery products

retailer	
Unit: Euro / Year *The raw material costs of the wholesale sector is represented by the revenue of the processing sector, which is calculated by multiplying the transportation rate to the retail sector by the sales price of the processing sector.*	
costs retailer associated with fishery products	raw material costs retailer + refrigeration costs retailer
Unit: Euro / Year *The total costs of the retail sector are calculated by adding up the raw material costs and the refrigeration costs Regarding labour and capital, the same assumptions as with the wholesale sector were made, in that capital and people are in place regardless whether the retail sector sells fish or not.*	
cost excluding raw material costs retailer	costs retailer associated with fishery products – raw material costs retailer
Unit: Euro / Year *The costs excluding the raw material of the retail sector represent the operational costs that occur through doing business. To calculate these costs, the raw material costs are deducted from the total costs of the wholesale sector.*	
expenses for fishery products retailer	cost excluding raw material costs retailer
Unit: Euro / Year *The expenses of the retail sector are the total costs of operations less the raw material costs. In this model they only represent refrigeration costs, since labour and capital are excluded and the retailer is assumed to be the last element of the supply chain.*	
incurred costs per unit sold retailer	costs retailer associated with fishery products / consumption rate
Unit: Euro / Ton *The costs per unit sold of the retail sector are calculated by dividing the total costs of the retail sector by the total quantity that is consumed by the population.*	
demand supply ratio retail sector	demand for fish for food / transportation to retailer
Unit: Dimensionless *The demand supply ratio of the retail sector is calculated by dividing the demand for fish for food from the population and the average per capita consumption by the supply that is transported to the retailer.*	
margin retailer	demand supply ratio retail sector
Unit: Dimensionless *This model assumes the demand supply ratio of the retail sector as the margin of its operations, which is in line with macro economic theory. Once the demand exceeds the supply, the prices start to rise due to a scarcity in the market, and vice versa.*	
sales price retailer	incurred costs per unit sold retailer * margin retailer
Unit: Euro / Ton *The sales price of the retail sector is calculated by multiplying the costs per unit with the margin of the retail operations.*	

Table 8 – Equations of the finances wholesale and retail modules

4.2 Aluminium model

The Aluminium model has a traditional supply chain structure, as can be found for example in Sterman (2000). Therefore, the production sphere of the model can be divided into primary Aluminium production and Aluminium recycling. In addition, there is the economical sphere, and the energy sphere.

4.2.1 Primary aluminium production module

The primary production module consists of three stocks and five flows. The three stocks are: i) aluminium capacity under construction, ii) primary aluminium production capacity, and iii) primary aluminium. The units of measure for the two capacity stocks are tons per year, while the stock of primary aluminium is measured in tons.

The stock of primary aluminium is changed by its inflow, the '*primary aluminium production rate*', and its outflow '*consumption of primary aluminium*'. The production rate is the annual amount of aluminium that can be produced and is equal to the stock level of primary aluminium production capacity. The consumption of primary aluminium is based on the assumption that all the available secondary aluminium will be consumed before primary aluminium is consumed. Therefore the '*demand for primary aluminium*' is calculated by deducting the '*secondary aluminium consumption*' for the '*demand for aluminium*'. The flow equation of the consumption of primary aluminium is subsequently defined as a MIN function that selects the minimum value of either the demand for primary aluminium, or the '*max aluminium consumption rate*'. The maximum consumption rate is the sum of the stock level of primary aluminium divided by the '*time to utilize aluminium*', and the production rate of the respective time step.

The construction of primary aluminium capacity is demand driven. First, the '*capacity gap*' is calculated by deducting actual stock level of production capacity from the value of '*desired production capacity*'. The desired production capacity is calculated by multiplying the demand for primary aluminium by the '*supply adjustment factor for lead times and future demand growth*', which is used to anticipate demand and prevent future capacity shortages.
In order to account for capacity that has been constructed during that time step - the outflow of capacity under construction and inflow of production capacity '*construction aluminium production capacity*' - '*desired capacity adjustment*' accounts for that flow value by dividing the capacity gap by the '*time to adjust aluminium production capacity*' and subtracting it from the resulting quotient.

The '*order rate capacity*', the inflow of the capacity under construction stock, is the maximum value of either the sum of the desired capacity adjustment and the '*capacity replacement rate*', or zero. Adding the capacity replacement rate, which equals the '*depreciation rate capacity*', is based on the assumption that built capacity is maintained as long as the future prospects for primary aluminium production are good. The MAX function ensures that the order rate cannot take negative values and therewith safeguards the assumption that capacity, once ordered, will be build. The flow 'construction aluminium production capacity' is calculated by dividing the stock level of capacity under construction by the '*time to construct capacity*'. Built capacity is accumulating in the stock primary aluminium production capacity, which is reduced by the outflow 'depreciation rate capacity'. The depreciation rate is calculated by dividing the stock level of production capacity by the '*average lifetime smelter*', and serves as input for the capacity replacement rate.

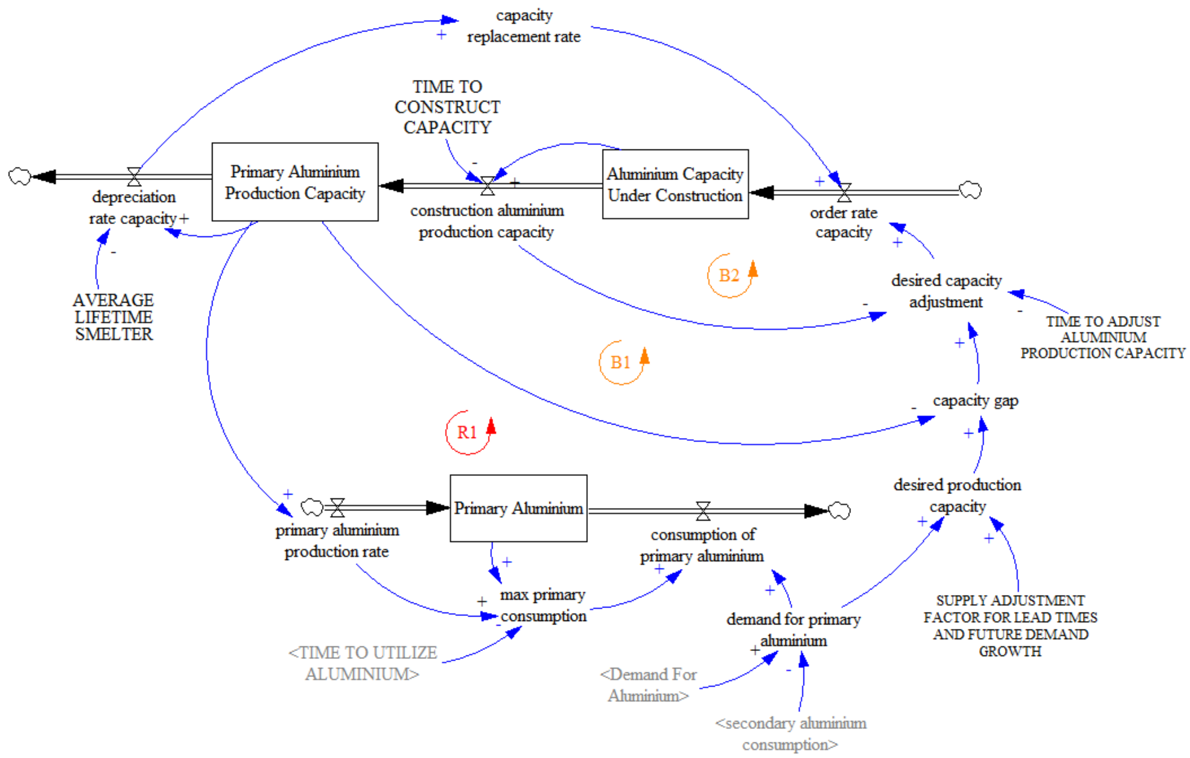
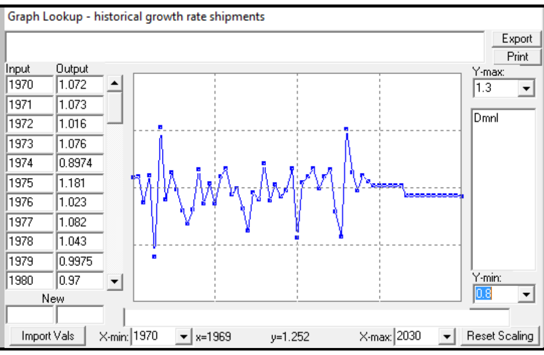


Figure 17: SFD Primary Aluminium Production module

<table>
<tr><th><u>Name</u></th><th><u>Equation</u></th></tr>
<tr><td>Demand for Aluminium</td><td>INTEG (change in demand for Aluminium , 1.88936e+007)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The demand for aluminium is the total yearly amount of aluminium which is demanded by all sectors. The stock level is changed by a bi-flow (change in demand for aluminium). The demand for Aluminium is internalized by using the historical growth rate deducted from the material flow model of the International Aluminium Institute (2014). This makes it possible to use demand for Aluminium as a variable for sensitivity analysis and to evaluate the outcomes of changes in the demand for Aluminium.</td></tr>
<tr><td>change in demand for Aluminium</td><td>((Demand for Aluminium * (historical growth rate shipments + expected future growth rate Aluminium)) - Demand for Aluminium)
/ time to perceive demand for aluminium</td></tr>
<tr><td colspan="2"><u>Unit: (Ton / Year) / Year</u>
This bi-flow changes the demand for aluminium based on the historical growth fraction, which was derived from the values in the IAI model. The fractions are exogenous until the year 2030. From 2030 onwards the ‘expected future growth rate’ is used to determine the changes in demand for aluminium. This variable can be used to run different scenarios about how the demand for aluminium might look like, and what the implications might be.</td></tr>
</table>

<table>
<tr><td>historical growth rate shipments</td><td>
</td></tr>
<tr><td colspan="2"><u>Unit: Dimensionless</u>
A graphical function was used for the historical growth rate of the change in demand for aluminium. The exact values can be found in the separate SDMdoc documentation. The values were derived from the IAI’s reported historical shipments and are the percentage by which historical shipments increased/decreased.</td></tr>
<tr><td>Consumption of primary aluminium</td><td>MIN(demand for primary aluminium , max primary consumption)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
A MIN function is used to avoid that more aluminium can be consumed than is available. The maximum amount of primary aluminium depends on the production of primary aluminium and the amount of primary aluminium on stock.
As long as there is sufficient primary aluminium to satisfy the demand, the full amount of secondary aluminium and part of the primary production is consumed, while the non-consumed primary aluminium is accumulating in the stock ‘Primary Ingots’. If the demand less secondary production exceeds the primary production plus the amount that has accumulated on stock, all the available primary aluminium will be consumed and the stock will be drained to zero.</td></tr>
<tr><td>Demand for primary aluminium</td><td>MAX(Demand For Aluminium – secondary aluminium consumption , 0)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The consumption of primary aluminium is depending on the available amount of secondary aluminium (internal and old scrap) that is available from recycling each year. It is assumed that all the secondary aluminium is consumed first due to lower prices. Therefore the demand for primary aluminium is defined as the total demand for aluminium less the amount of secondary aluminium that has been consumed during that time step. A MIN function is used to avoid that the demand for aluminium can take a negative value. The consumption rate of primary aluminium is used as an indicator for the demand for primary aluminium.</td></tr>
<tr><td>Desired production capacity</td><td>demand for primary aluminium * SUPPLY ADJUSTMENT FACTOR FOR LEAD TIMES AND FUTURE DEMAND GROWTH</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
In order to calculate the desired production capacity for primary aluminium, the demand for primary aluminium is multiplied by a supply adjustment factor. The supply adjustment factor is used to account for lead times in capacity construction and future growth in demand to ensure that there is always sufficient capacity is in place.</td></tr>
<tr><td>Capacity gap</td><td>MAX(0 , desired production capacity - Primary aluminium production capacity)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The capacity gap represents the discrepancy between the desired and actual value of primary production capacity. It is used to determine the rate at which the construction of primary aluminium capacity is ordered. A MAX function is used to ensure that this variable does not take a negative value, which would be the case in a scenario of overcapacity. In this case, the gap is assumed to be zero, since already too much capacity is in place.</td></tr>
</table>

<table>
<tr><td>desired capacity adjustment</td><td>capacity gap / TIME TO ADJUST ALUMINIUM PRODUCTION CAPACITY
– construction aluminium production capacity</td></tr>
<tr><td colspan="2"><u>Unit: (Ton / Year) / Year</u>
The desired capacity adjustment is basically calculating the desired order rate. By dividing the capacity gap by the time to adjust aluminium production capacity and subtracting the construction of production capacity, it accounts for capacity that has been built during that time step, and thus avoids a steady state error in the capacity adjustment process.</td></tr>
<tr><td>Order rate capacity</td><td>MAX(desired capacity adjustment + capacity replacement rate , 0)</td></tr>
<tr><td colspan="2"><u>Unit: (Ton / Year) / Year</u>
The order rate of primary production capacity is accumulated into the stock aluminium capacity under construction. It adds up the capacity gap and the depreciation rate, and accounts for the construction of capacity in the respective time step. The depreciation rate is accounted for based on the assumption that capacity will stay in place as long as demand is growing. A MAX function is used to avoid the order rate to take a negative value, assuming that ordered capacity cannot be cancelled.</td></tr>
<tr><td>Aluminium Capacity under construction</td><td>INTEG (order rate capacity-construction aluminium production capacity
, 1e+006)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This stock accumulates the order rate for primary aluminium production capacity, and serves as a base to determine its construction rate. The initial value of the stock is an assumption, derived from trial and error simulation runs.</td></tr>
<tr><td>Construction aluminium production capacity</td><td>aluminium Capacity under construction / time to construct capacity</td></tr>
<tr><td colspan="2"><u>Unit: (Ton / Year) / Year</u>
The construction rate of aluminium production capacity captures the increase in primary capacity within that time step. It is derived by dividing the amount of accumulated orders by the construction time of capacity, assuming that capacity is added continuously. This flow is used to avoid a steady-state error (order rate higher than necessary) in the order rate of primary production capacity.</td></tr>
<tr><td>Primary aluminium production capacity</td><td>INTEG (construction aluminium production capacity - depreciation rate capacity
, 1.0507e+007)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This stock represents the capacity to produce primary aluminium. It is increased by its inflow, the construction of aluminium production capacity, and decreased by an outflow that captures the capacity depreciation rate. The stock is calibrated based on the value obtained from the IAI's historical primary production capacity data[12].</td></tr>
<tr><td>primary aluminium production rate</td><td>Primary Aluminium Production Capacity</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This flow represents the amount of aluminium that is produced in a certain time step. It is based on the actual aluminium production rate, which is based on the stock of primary aluminium capacity.</td></tr>
</table>

Table 9 – Equations of the primary production module

[12] http://www.world-aluminium.org/media/filer_public/2015/02/23/primary_aluminium_annual_production_capacity_1973_to_2016_historical_data.xlsx

4.2.2 Aluminium in society

The total amount of aluminium that accumulates in the different sectors of society is represented in eleven different stocks. All the eleven modules are structurally built in the same way, with the exception of the construction sector which is modelled in more detail to capture geographical variation. The structure of the modules consists of one stock with three flows. Figure 18 displays as an example the aerospace module.

The first flow in the example captures the inflow '*increase aluminium in aerospace*' and is calculated by multiplying the '*demand for aluminium*' by the '*fraction of demand for aerospace*', a historical value of how the total demand was distributed over the different sectors. Semi processing and fabrication of aluminium products are not captured in much detail in this model, but are based on the inflow of aluminium into the sector and utilization fractions of semi-processors and fabricators.
The amount of '*semi fabricator scrap generated in aerospace*' is calculated by multiplying the aluminium shipments into the sector with the fraction aluminium that is not utilized by the semi-fabricators; in other words one minus '*semi fabricator utilization fraction in aerospace*'. Subsequently, the amount of '*fabricator scrap aerospace*' is calculated by subtracting the amount of semi-fabricator scrap from the inflow of aluminium into the sector, and then multiply it with the fraction of aluminium that is not utilized by the fabrication sector – or, one minus the '*fabricator utilization fraction aerospace*'. The sum of semi-fabricator scrap and fabricator scrap defines the outflow '*industrial scrap aerospace*'. Through this formulation it is ensured that the model corrects instantaneously for the amount of internal scrap. A second outflow, '*scrap aluminium from aerospace*', is representing the amount of old aluminium scrap from the aerospace sector that is recovered after its time of use. It is calculated by dividing the stock level of aluminium in aerospace by the '*average lifetime aerospace*'.

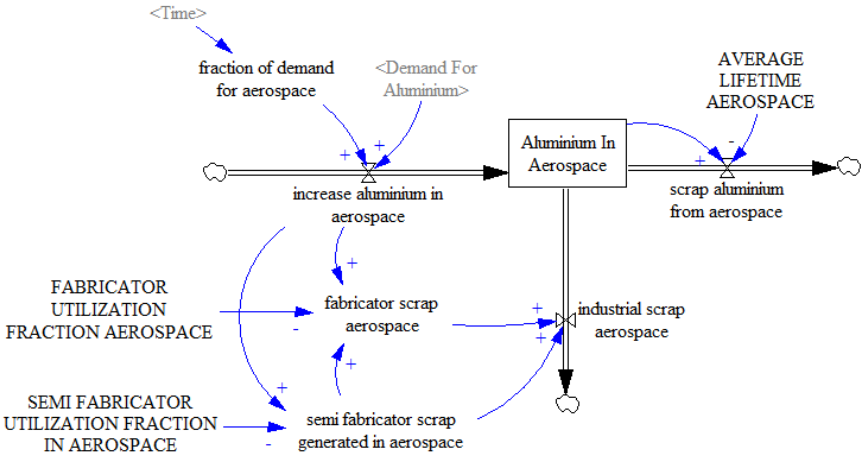


Figure 18: SFD Aluminium In Aerospace module

As already indicated, the accumulation of aluminium in the construction sector also discriminates between geographical regions. Modelling this detail was particularly interesting because the share of aluminium used in construction has change significantly in geographical regions (e.g. Europe VS China). The construction sector differentiates between three (in Europe four) age-classes of buildings regarding their lifetime: i) less than 20 years, ii) 40 years, and iii) 60 years – in Europe a fourth category, 100 years, is added.

Figure 19 shows the SFD on how aluminium in constructions is flowing and accumulating in Europe. Each geographical region has three (Europe four) stocks with one inflow and one outflow respectively. The initial stock values are calculated endogenously by multiplying an initial total amount of aluminium in constructions in a geographical region by the fractions of how this aluminium is distributed over different building types. All the values and fractions are from the IAI's report on sustainable cities (2015).

The amount of aluminium that is accumulating in the different age classes is determined through the respective inflows to the stocks that represent these age classes. The amount by which the stock '*constructions – Lifetime 40 Years Europe*' changes is determined by its inflow, '*increase aluminium constructions 40 years europe*', and its outflow, '*recovery rate aluminium constructions 40 years europe*'.
The inflow is calculated by multiplying the total demand from constructions by the fraction of the aluminium that has been used in the geographical region Europe, 'historical share in construction europe', and then multiplying this value by the share of that aluminium which has been used to build constructions with an expected lifetime of 40 years, '*fraction of aluminium in constructions 40 years europe*'.
The outflow of the stock are defined as a fixed delay of the amount of aluminium that flows into the sector, with the lifetime of the buildings as delay time. In this case it would be a fixed delay of the inflow, with the '*lifetime constructions 40 years europe*'. The recovery rates represent the amount of old scrap that is recovered from buildings that reached the end of their lifetime. The four outflows are then summed up in the variable '*recovery from constructions europe*'. The sum of the recovery rates from the seven different geographical regions form the 'total scrapping rate from constructions', which is also mentioned in Table 10.

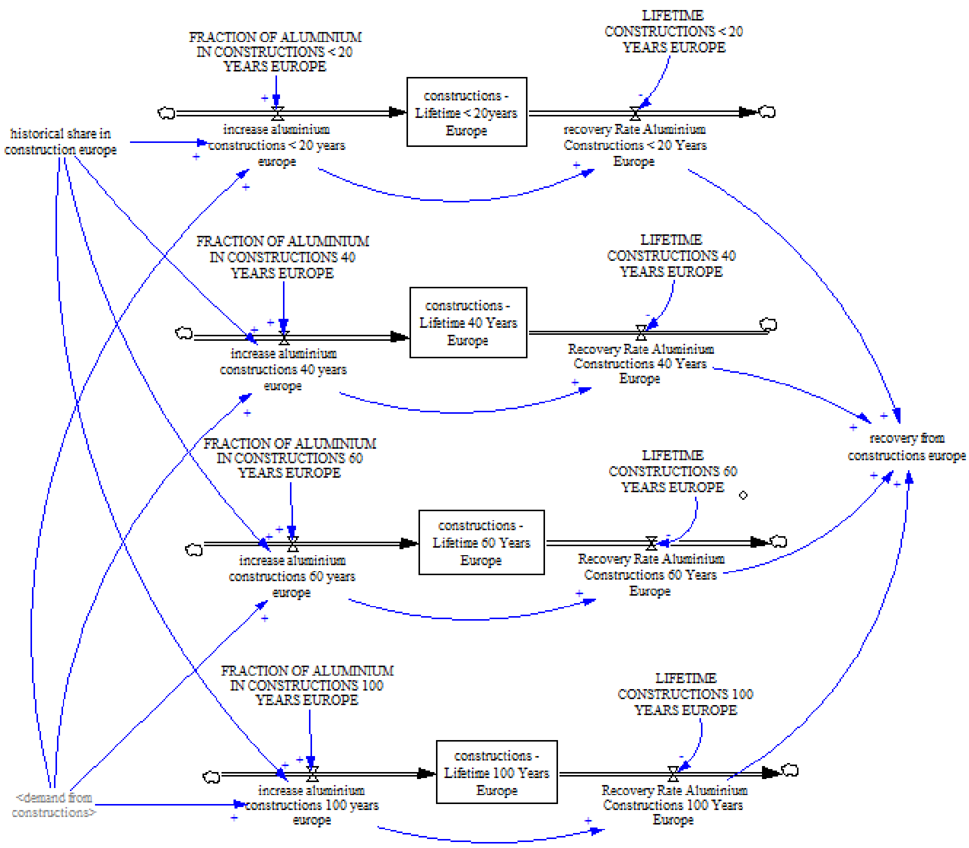


Figure 19: SFD Aluminium in Constructions Europe module

Name	Equation
Aluminium in society	aluminium in aerospace + aluminium in cable + aluminium in cars + aluminium in consumer durables + aluminium in houses + aluminium in machinery + aluminium in other Electricals + aluminium in other applications + "aluminium in Packaging (Cans)" + "aluminium in packaging (Foil)" + aluminium in trucks
Unit: Ton *This stock represents the total amount of aluminium that is accumulated in the different sectors of society. It is calculated by summing up the eleven separate stock that accumulate the aluminium that is shipped to the different sectors.*	
increase aluminium in aerospace	Demand For Aluminium * fraction of demand for aerospace
Unit: Ton / Year *This flow captures the total aluminium shipments to the aerospace sector and is the inflow to the stock 'aluminium in aerospace'. It is calculated by multiplying the total demand for aluminium by the historical fraction of demand that was shipped to the aerospace sector.*	
Aluminium In Aerospace	INTEG (increase aluminium in aerospace – industrial scrap aerospace-scrap aluminium from aerospace , 433113)
Unit: Ton *This stock represents to total accumulated aluminium that is used in the aerospace sector (e.g. airplanes). It is increased by the inflow 'increase aluminium in aerospace' and decreased by two outflows. One outflow, 'industrial scrap aerospace' corrects for the (semi) fabrication process, while the other one, 'scrap aluminium from aerospace', is capturing the amount of old scrap that is produced through end-of-lifetime aeronautic items.*	
scrap aluminium from aerospace	Aluminium In Aerospace / AVERAGE LIFETIME AEROSPACE
Unit: Ton / Year *This flow represents the amount of old scrap that is produced through end-of-lifetime aeronautic items. It is calculated by dividing the amount of aluminium in aerospace by the average lifetime of aeronautic vehicles.*	
industrial scrap aerospace	fabricator scrap aerospace + semi fabricator scrap generated in aerospace
Unit: Ton / Year *This flow captures the total amount of semi fabricator and fabricator scrap that is produced during the processing of aluminium to components for aeronautic vehicles. It is the sum of the fabricator scrap and the semi fabricator scrap that is generated in this sector.*	
semi fabricator scrap generated in aerospace	increase aluminium in aerospace * (1 – SEMI FABRICATOR UTILIZATION FRACTION IN AEROSPACE)
Unit: Ton / Year *The amount of semi fabricator scrap is calculated by multiplying the total shipments into the aerospace sector by one minus the utilization fraction of the semi fabrication for aeronautic products. It represents the internal aluminium scrap that is produced on the semi fabrication level when processing aluminium to semi finished products for the aerospace sector.*	
fabricator scrap aerospace	(increase aluminium in aerospace – semi fabricator scrap generated in aerospace) * (1-FABRICATOR UTILIZATION FRACTION AEROSPACE)
Unit: Ton / Year *The amount of fabricator scrap is calculated by multiplying the total shipments minus the semi fabricator scrap by one minus the utilization fraction of the fabrication for aeronautic products. It*	

represents the internal aluminium scrap that is produced on the fabrication level when processing aluminium to finished components for the aerospace sector.	
Aluminium in Houses	INTEG (increase of aluminium in houses - industrial scrap construction - recovery rate constructions , 2.1217e+007)
Unit: Ton *This stock represents the total amount of the aluminium that is in use in constructions at a certain point in time. It is increased by the inflow 'net increase of aluminium in houses' and decreased by two outflows: the recovery rate constructions and the industrial scrap outflow.*	
increase of aluminium in houses	Demand For Aluminium * fraction of demand construction
Unit: Ton / Year *The increase of aluminium in houses is the inflow of the stock 'aluminium in houses' that represents how much aluminium is accumulated in constructions at a given point in time. This inflow represents the total yearly shipments of aluminium that are shipped to the construction sector. The increase of aluminium in houses is calculated by multiplying the total demand for aluminium by the fraction of demand from constructions that has been derived by the IAI's calculations.*	
industrial scrap construction	fabricator scrap construction + semi fabricator scrap generated in construction
Unit: Ton / Year *This outflow captures unutilized quantities of aluminium from processing before final products are used for constructions. This outflow is also referred to as internal scrap. The amount of internal scrap is calculated by summing up the amount of fabricator scrap and semi fabricator scrap.*	
semi fabricator scrap generated in construction	increase of aluminium in houses * (1 - semi fabricator utilization fraction in construction)
Unit: Ton / Year *Semi fabrication is the first processing sector that aluminium is shipped to after its production/recovery. The semi fabricator scrap of the construction sector is depending on the shipments to the aluminium sector and the utilization fraction of the semi-fabrication sector. The utilization of the semi-fabrication sector is represented by a fraction that is also used in the IAI's Global Mass Flow model. The amount of semi fabricator scrap generated is calculated by multiplying the shipments to the aluminium sector by one minus the utilization fraction of the semi-fabrication sector.*	
fabricator scrap construction	(increase of aluminium in houses - semi fabricator scrap generated in construction) * (1 - fabricator utilization fraction in construction)
Unit: Ton / Year *The fabrication sector is the sector in which the products from semi-fabrication are processed for their final application in the construction sector. The amount that is processed is calculated by deducting the semi-fabricator scrap from the shipments to the aluminium sector. Like this the net amount of aluminium that is shipped to final processing is calculated. Then it is multiplied by the fraction of non-utilized aluminium from the fabrications sector.*	
total scrapping rate from construction	recovery from constructions China + recovery from constructions Europe + recovery from constructions Japan + recovery from constructions middle east + recovery from constructions North America + recovery from constructions South America + recovery from constructions other Asia
Unit: Ton / Year *This variable represents the total amount of old aluminium scrap that is recovered from the construction sector. The total scrapping rate is calculated by adding up the scrap recovery from the*	

different geographical sectors that are represented in the model.	
recovery rate constructions	total scrapping rate from construction
Unit: Ton / Year *The recovery rate from constructions captures the total annual amount of aluminium that is recovered globally.*	
"initial al in cons < 20y Europe"	INITIAL AL IN CONS OTHER ASIA * "FRACTION OF ALUMINIUM IN CONSTRUCTIONS < 20 YEARS OTHER EUROPE"
Unit: Ton *This variable calculates the initial value for the stock of buildings that have an expected lifetime lower than 20 years. The value is derived by a total amount of aluminium in Europe and a fraction that has been taken from the IAI's report (2015) on sustainable cities.*	
"constructions - Lifetime < 20years Europe"	INTEG ("increase aluminium constructions < 20 years Europe" - "recovery Rate Aluminium Constructions < 20 Years Europe , "initial al in cons < 20y Europe")
Unit: Ton *This stock represents the aluminium that is accumulated in buildings with an expected lifetime less than 20 years in the geographical region 'Europe'. It is increased by the inflow 'increase aluminium constructions < 20 years other Asia' and decreased by the outflow of old scrap, 'recovery rate aluminium constructions < 20 years Europe'. The initial value is calculated by using the initial amount of aluminium in the geographical region multiplied by a fraction for the respective building type.*	
"increase aluminium constructions < 20 years europe"	demand from constructions * historical share in construction europe * "FRACTION OF ALUMINIUM IN CONSTRUCTIONS < 20 YEARS EUROPE"
Unit: Ton / Year *The increase of aluminium in constructions with an expected lifetime lower than 20 years is determined by the shipments to the construction sector, the fraction of the total shipments that went to the region 'Europe' and the respective fraction of aluminium that was used to build a building that has an expected lifetime lower than 20 years.*	
"Recovery Rate Aluminium Constructions < 20 Years Europe"	DELAY FIXED ("increase aluminium constructions < 20 years europe" , "LIFETIME CONSTRUCTIONS < 20 YEARS EUROPE" , 1500)
Unit: Ton / Year *This outflow represents the old aluminium scrap that is recovered from buildings with an expected lifetime lower than 20 years in the region 'other Asia'. The outflows of the construction sector are modelled as a fixed delay, based on the assumption that aluminium used in constructions will be recovered at the end of the lifetime of the construction. The shortcomings of this assumption are discussed in the model validation section.*	

Table 10 – Selected equations from the aluminium in society module

4.2.3. Aluminium recycling module

The aluminium recycling module itself consists of two stocks and five flows. The stock of '*recycled aluminium*' accumulates all the secondary aluminium (internal and old scrap) that has been recycled during one time step and serves as the based to calculate the possible consumption of secondary aluminium. The second stock 'dross from ingot production' captures a by-product of the aluminium production and recycling process[13], and is increased through the '*dross creation ingot production*', and decreased through the outflows '*dross recycling ingot production*' and '*dross loss*'.

The main inflow '*total aluminium recovery rate*' is calculated by the adding up the variables '*total internal scrap collected (semi fabrication)*', '*total fabricator scrap collected*', and the '*recycling rate*'. It represents the total available aluminium scrap that is collected or recycled during one time step. The main outflow is '*secondary aluminium consumption*' and represents the amount of secondary aluminium that is consumed. For the consumption rate of secondary aluminium the minimum of either the '*demand for aluminium*' or the '*max secondary consumption*' is selected through a MIN function. The maximum secondary production is calculated by dividing the stock level of secondary aluminium by the '*time to utilize aluminium*'. The recovery rate is not added to the maximum consumption rate, since it is assumed that the collected metal has to be recycled first.

Aluminium dross is a by-product of the production and recycling process and is implemented by a simple one-stock-two-flow structure. The dross creation rate, an outflow of the stock recycled aluminium and inflow to the stock dross from ingot production, depends on the amount of aluminium that is produced and recycled. It is the sum of '*dross from primary production*', '*dross from old scrap*' and '*dross from internal scrap*'. Each of the processes yields a different amount of dross, meaning that each of the three components is calculated individually. Dross from primary production is calculated by multiplying the '*primary aluminium production rate*' with the fraction of dross that is created additional to the amount of aluminium, '*fraction of primary production dross*'. Dross from old scrap is calculated by multiplying the '*recycling rate*' by '*fraction of old scrap dross*', and dross from internal scrap is calculated by multiplying the sum of semi-fabricator scrap and fabricator scrap by the '*fraction of internal scrap dross*'

The outflows of the stock of accumulated aluminium dross are depending on the stock level and the '*recycling fraction ingot dross*'. The IAI's Global Mass Flow model assumes a fixed recycling fraction for all types of aluminium dross, and the same approach was used to define the flows in this model. It is assumed that all the all the dross that is collected is either recycled or disposed during a year. The dross recycling rate is calculated by multiplying the stock level times the recycling fraction, and the dross loss rate, thus the fraction of the total weight that is not aluminium, is calculated by multiplying the stock level by one minus the dross recycling fraction. This formulation ensures that the stock is emptied every time step, but does not reach negative values.
(**Note**: The recycling fraction ingot dross is a fraction in 'percent per year')

The variables that are used to calculate the secondary aluminium production are derived from different modules of the model. The total semi fabricator scrap and the fabricator scrap is calculated based on the total shipments into the different sectors and the respective (semi-) fabricator utilization fractions, as explained in the previous section that explained the accumulation of aluminium in the different sectors of society. To arrive at the total values the semi fabrication scrap and the fabricator scrap of the eleven sectors is summed up. The recycling rate of old scrap is calculated in a separate module.

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[13] During the production and recycling of aluminium, a disposable liquid called dross is produced. It consists of liquid aluminium metal, salt oxides and non metallic substances (Adeosun et al., 2014). The aluminium dross is collected, and aluminium and other substances are recovered from it.

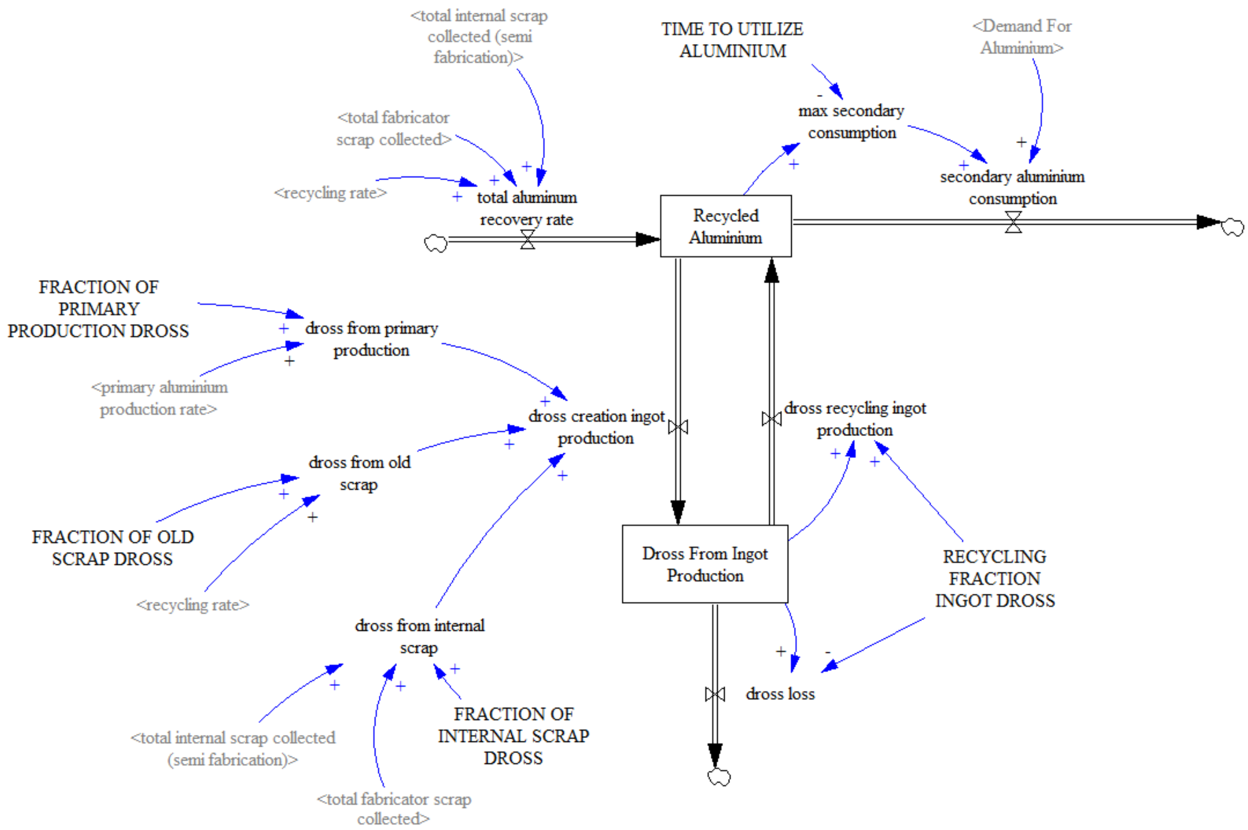

Figure 20: SFD Total Secondary Production module

4.2.4 Recovery of old scrap - The recycling rate

The recovery of old scrap is based on the outflows of the eleven different sectors and a recovery fraction. To arrive at the recovered material from the different sectors, the outflow of old scrap (stock level divided by lifetime) is multiplied with a recovery fraction. Historical recovery and recycling fractions from the IAI's Global Mass Flow model were used as a function of time. Figure 20 shows a causes tree of how the variable '*recovery from aerospace*' is compiled.

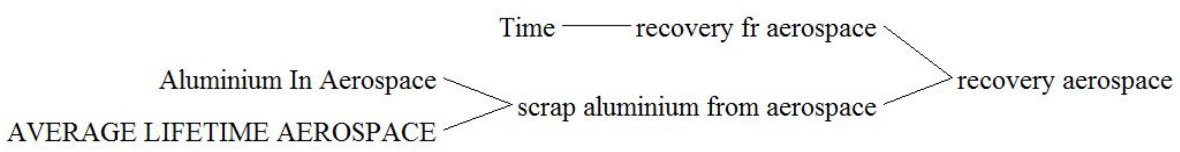

Figure 21: Causes tree of the variables used to calculate the value of 'recovery aerospace'

This calculation is done for all eleven sectors individually, and the respective products are then summed up to the variable '*total recovery*'. Based on the total recovery and the eleven individual values, the contributions of the different sectors regarding the amount of recovered aluminium can be calculated, by dividing, as in the case from aerospace, the '*recovery aerospace*' by '*total recovery*'.

Once the eleven *fractions of recovery* are calculated the '*weighted average recycling rate*' is calculated by summing up the products of each sectors' fraction of recovery with its respective recycling fraction. The weighted average is formed because historical values that change over time were used for both, recovery and recycling fraction.

Figure 23 shows all the variables that are used to calculate the weighted average of the recycling fraction in the aluminium model. For the full equation please consult Table 11. The weighted average has the advantage that it can be used as an indicator of the overall recycling performance of the secondary aluminium production sector, and individual improvements in recycling rates can be tested.

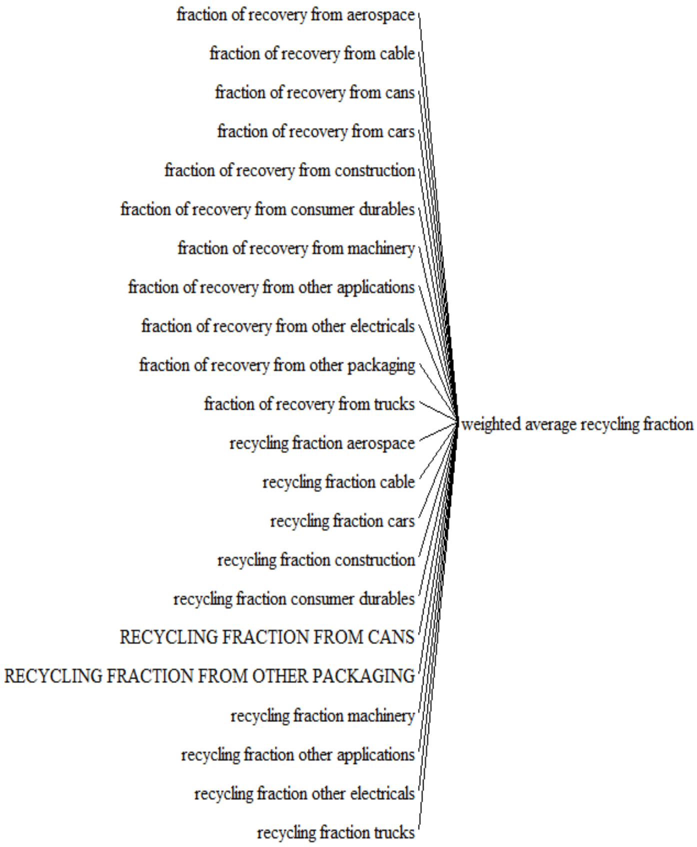

Figure 22 – Variables to calculate the weighted average recycling rate

The module of old scrap recycling has one stock and three flows. The amount of aluminium that is recovered is accumulating in the stock '*recovered aluminium*'. The variable 'total recovery' is used as input for its inflow '*aluminium recovery rate*'. The two outflows of the stock are the '*recycling rate*' and '*non-recycled aluminium*'. The recycling rate is calculated by multiplying the stock level of recovered aluminium with the weighted average recycling fraction, and dividing it by the '*production time step*'. The non-recycled aluminium is determined by multiplying the stock level by one minus the weighted average recycling fraction and dividing it by the production time step.

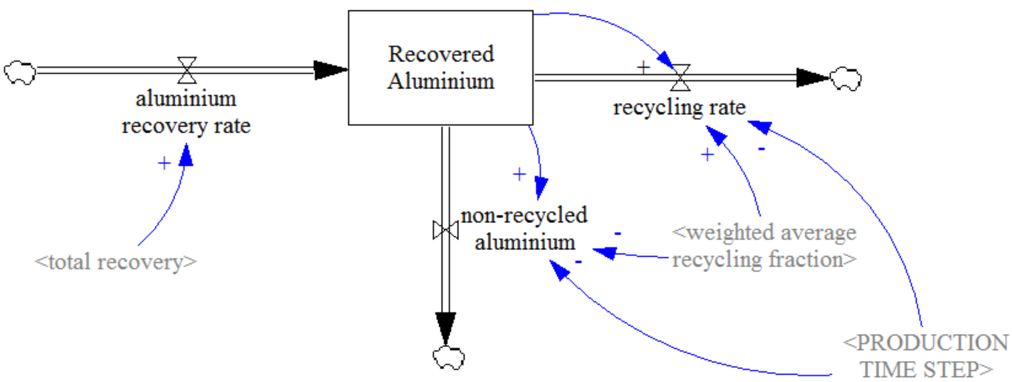

Figure 23: SFD Old Scrap Aluminium Recovery module

Name	Equation
total aluminium recovery rate	"total internal scrap collected (semi fabrication)" + recycling rate + total fabricator scrap collected
Unit: Ton / Year *The total aluminium recovery rate consists of the scrap produced by semi- and final processing of the respective sectors (new scrap) and the old scrap recycling rate. The recycling of old scrap makes up approximately 40% of the total recovery rate.*	
dross from primary production	primary aluminium production rate * FRACTION OF PRIMARY PRODUCTION DROSS
Unit: Ton / Year *The amount of dross created from internal scrap is derived from multiplying the amount of scrap with a fraction (obtained from the IAI Global Mass Flow Model) of dross per ton of aluminium.*	
dross from internal scrap	("total internal scrap collected (semi fabrication)" + total fabricator scrap collected) * FRACTION OF INTERNAL SCRAP DROSS
Unit: Ton / Year *The amount of dross created from internal scrap is derived from multiplying the amount of scrap with a fraction (obtained from the IAI Global Mass Flow Model) of dross per ton of aluminium.*	
dross from old scrap	recycling rate * FRACTION OF OLD SCRAP DROSS
Unit: Dimensionless *The amount of dross created from old scrap is derived from multiplying the amount of scrap with a fraction (obtained from the IAI Global Mass Flow Model) of dross per ton of aluminium.*	
dross creation ingot production	dross from internal scrap + dross from primary production + dross from old scrap
Unit: Ton / Year *During the production and recycling of aluminium, a disposable liquid called dross is produced. It consists of liquid aluminium metal, salt oxides and non metallic substances (Adeosun et al., 2014). The aluminium dross is collected, and aluminium and other substances are recovered. The dross creation is calculated by adding up the created dross from the different aluminium flows (primary, secondary production).*	
Dross From Ingot Production	INTEG (dross creation ingot production - dross loss - dross recycling ingot production , 300000)
Unit: Ton *This stock accumulates the dross produced from aluminium production. It serves as a base to calculate the recycling of aluminium from dross, based on the 'RECYCLING FRACTION INGOT DROSS'. One outflow, dross loss, captures the non-aluminium share of the dross that is recycled, while the other outflow, dross recycling ingot production, feeds the recycled dross back into the system.*	
dross recycling ingot production	Dross Of Ingot Production * RECYCLING FRACTION INGOT DROSS
Unit: Ton / Year *The aluminium dross is collected, and aluminium and other substances are recovered. The aluminium is fed back into circulation, and other substances are used for example as filling material in asphalt. A wider application of the use of recycling by-products is under investigation. The dross recycling rate is assumed to be a fixed fraction of the collected dross.*	
Recycled Aluminium	INTEG (dross recycling ingot production + total aluminium recovery rate – dross creation ingot production - secondary ingot processing , 1e+007)
Unit: Ton *This stock accumulates the total amount of recycled aluminium of the model and the dross recycling rate, the total recovery rate which consists of the new and old scrap recovery rate.*	

<table>
<tr><td>secondary aluminium consumption</td><td>MIN(Demand For Aluminium , max secondary consumption)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This flow is defined as a MIN function to avoid the stock of secondary aluminium going negative. The maximum secondary consumption rate is the stock value divided by the time step. The minimum function is used in case that the demand for aluminium should be lower than the total available amount of recycled aluminium.</td></tr>
<tr><td>recovery construction</td><td>recovery fr construction * total scrapping rate from construction</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The scrap recovery of the construction sector is calculated by multiplying the total scrapping rate, or the old scrap, by the recovery fraction of the construction sector.</td></tr>
<tr><td>total recovery</td><td>recovery cable + recovery cars + recovery construction
+ recovery consumer durables + recovery machinery
+ recovery other applications + recovery other electrical
+ recovery trucks + recovery aerospace
+ recovery cans + recovery other packaging</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The total recovery rate of the old scrap recycling sector is the sum of the old scrap recovery from all the individual sectors. Scrap recovery of the individual sectors is calculated by multiplying the old scrap from each of the sectors by the respective recovery fraction (see above ‘recovery construction’).</td></tr>
<tr><td>fr from construction</td><td>recovery construction / total recovery</td></tr>
<tr><td colspan="2"><u>Unit: Dimensionless</u>
The fraction from construction is the share that the old scrap aluminium from construction when compared to the total amount of recovered old scrap. This fraction is then used to calculate a weighted average recycling fraction (see underneath).</td></tr>
<tr><td>weighted average recycling fraction</td><td>fraction of recovery from aerospace * recycling fraction aerospace
+ fraction of recovery from cable * recycling fraction cable
+ fraction of recovery from cars * recycling fraction cars
+ fraction of recovery from construction * recycling fraction construction
+ fraction of recovery from consumer durables
* (recycling fraction consumer durables)
+ fraction of recovery from machinery * recycling fraction machinery
+ fraction of recovery from other applications
* recycling fraction other applications
+ fraction of recovery from other electricals
* recycling fraction other electricals
+ fraction of recovery from trucks * recycling fraction trucks
+ fraction of recovery from other packaging
* (RECYCLING FRACTION FROM OTHER PACKAGING)
+ fraction of recovery from cans
* RECYCLING FRACTION FROM CANS</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
In order to calculate the recycling rate, thus the percentage of aluminium that is recycled from old scrap, a weighted average is calculated. The weighted average uses the fraction of scrap that a sector makes up (see above ‘fr from consulting’ and multiplies it with the respective recycling efficiency (fraction) of each sector. The weighted average thus accounts for the respective shares of each sector, and weighs the respective recycling fraction by that share. This weighted average is then used to determine the amount of aluminium that is recycled.</td></tr>
<tr><td>Recovered aluminium</td><td>INTEG (aluminium recovery rate - recycling rate, 1e+006)</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
This stock accumulates the amount of aluminium that is recovered. It is increased through its</td></tr>
</table>

inflow, the aluminium recovery rate, and decreased through the recycling of aluminium, or the recycling rate.	
Fraction recycled aluminium	recycling rate / demand for primary aluminium
Unit: Dimensionless *The fraction of recycled aluminium is, as in the IAI's report (2009) on global aluminium recycling, calculated by dividing the recycled old scrap by the amount of primary aluminium that has been consumed in that time step.*	
Recycling rate	Recovered aluminium * weighted average recycling rate / PRODUCTION TIME STEP
Unit: Ton / Year *The recycling rate of old scrap aluminium is determined by the amount of recovered aluminium multiplied by the weighted average recycling fraction. The amount is then divided by the time step of the model, since recycling of aluminium is a continuous process.*	

Table 11 – Equations of the aluminium recycling sector

4.2.5 Calculation of inputs to the processes

The model calculates on each level the flows of inputs that are used for production of bauxite, alumina and aluminium. Based on the sum of all the flows it is possible to calculate the footprint that aluminium has in terms of resource consumption from a life cycle point of view. Life cycle refers to the total amount of inputs that are consumed from bauxite mining to the final aluminium metal. The IAI's report (2013) on life cycle data for primary aluminium provided data on average consumption and emissions, while the IAI's website provided information about the energy intensity of the alumina and aluminium refining[14]. The following inputs are considered in this model:

- fresh water
- heavy oil
- natural gas
- pitch
- alumina
- electricity
- sea water
- diesel oil
- coal
- petrol coke
- bauxite

For each resource the respective consumption during the different processes is calculated based on the respective production rate and an average amount of input used for this process. The inputs to the following processes are taken into account:

- bauxite mining
- alumina refining
- Prebake anode production
- Söderberg paste production
- primary aluminium production (prebake electrolyse)
- primary aluminium production (Söderberg electrolyse)
- ingot casting

The annual fresh water consumption for bauxite mining for example is calculated based on the bauxite '*bauxite consumption rate*', which is derived by multiplying the '*alumina consumption rate*' with the '*ratio bauxite to alumina*', and an average value of '*fresh water per ton of bauxite*' that is used for extraction. The product is the yearly amount of fresh water that is used for the production of bauxite that is used for alumina production. The resulting flows of the different processes are then totalled into one flow, for example '*total fresh water consumption*', that accumulates in a respective stock, in the case of fresh water '*accumulated fresh water consumption*'.

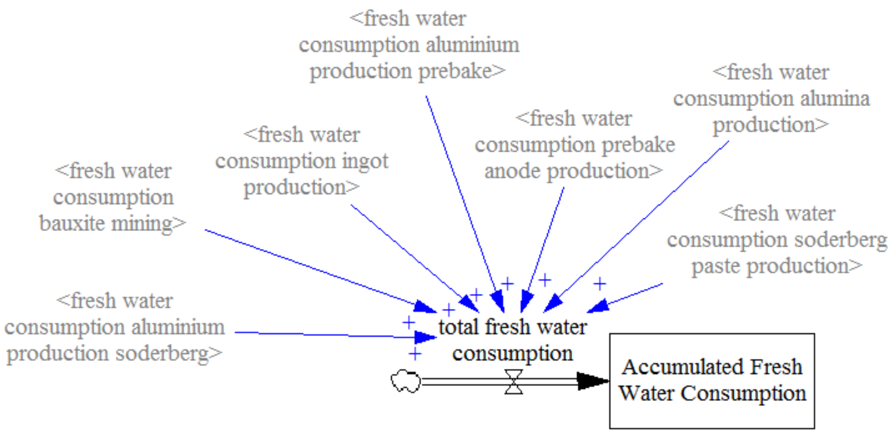

Figure 24: SFD Life Cycle fresh water consumption

[14] http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/

Figure 23 shows the way how the different fresh water consumption flows are added up in one flow and then accumulated in a stock. Fresh water is consumed in six different processes throughout the primary aluminium production chain. In each of the processes, the respective production rate was multiplied with an average input value of water consumption to calculate the flows.

<u>**Name**</u>	<u>**Equation**</u>
total fresh water consumption	fresh water consumption alumina production + fresh water consumption aluminium production prebake + fresh water consumption aluminium production soderberg + fresh water consumption bauxite mining + fresh water consumption ingot production + fresh water consumption prebake anode production + fresh water consumption soderberg paste production + fresh water consumption aluminium recycling
<u>Unit: Ton / Year</u> *This flow captures the total amount of fresh water that is consumed in the aluminium production process. It is calculated by summing up the fresh water consumption from the different stages in the aluminium production process that consume fresh water. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.*	
total sea water consumption	sea water consumption alumina production + sea water consumption aluminium production prebake + sea water consumption aluminium production soderberg + sea water consumption bauxite mining
<u>Unit: Ton / Year</u> *This flow captures the total amount of fresh sea that is consumed in the aluminium production process. It is calculated by summing up the sea water consumption from the different stages in the aluminium production process that consume sea water. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.*	
total electricity consumption	electricity consumption alumina production + electricity consumption aluminium production prebake + electricity consumption aluminium production soderberg + electricity consumption ingot production + electricity consumption bauxite mining + electricity consumption prebake anode production + electricity consumption soderberg paste production + electricity consumption aluminium recycling
<u>Unit: Ton / Year</u> *This flow captures the total amount of electricity that is consumed in the aluminium production process. It is calculated by summing up the electricity consumption from the different stages in the aluminium production process that consume electricity. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.*	
total heavy oil consumption	heavy oil consumption alumina production + heavy oil consumption bauxite mining + heavy oil consumption ingot production + heavy oil consumption prebake anode production + heavy oil consumption soderberg paste production
<u>Unit: Ton / Year</u> *This flow captures the total amount of heavy oil that is consumed in the aluminium production process. It is calculated by summing up the heavy oil consumption from the different stages in the aluminium production process that consume heavy oil. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.*	

total diesel oil consumption	diesel oil consumption alumina production + diesel oil consumption bauxite mining + diesel oil consumption ingot production + diesel oil consumption prebake anode production + diesel oil consumption soderberg paste production
<u>Unit: Ton / Year</u> *This flow captures the total amount of diesel oil that is consumed in the aluminium production process. It is calculated by summing up the diesel oil consumption from the different stages in the aluminium production process that consume diesel oil. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.*	
total natural gas consumption	natural gas consumption alumina production + natural gas consumption ingot production + natural gas consumption prebake anode consumption + natural gas consumption soderberg paste production
<u>Unit: Ton / Year</u> *This flow captures the total amount of natural gas that is consumed in the aluminium production process. It is calculated by summing up the natural gas consumption from the different stages in the aluminium production process that consume natural gas. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.*	
total coal consumption	coal consumption alumina production + coal consumption ingot production
<u>Unit: Ton / Year</u> *This flow captures the total amount of coal that is consumed in the aluminium production process. It is calculated by summing up the natural gas consumption from the different stages in the aluminium production process that consume natural gas. Dividing this amount by the production rate of primary aluminium would give an indication of the life cycle footprint per ton of aluminium.* ***Note****:* *This variable represents the total amount of coal that is produced during the production process. The amount of coal used to generate the electricity for the electrolysis process is not captured in this variable.*	
total pitch consumption	pitch consumption prebake anode production + pitch consumption soderberg paste production
<u>Unit: Ton / Year</u> *This flow captures the total amount of pitch that is consumed in the process of anode production. It is calculated by summing up the pitch consumption from of the prebake anode and Söderberg paste production processes. The pitch consumption is depending on the productivity of the anode in terms of tons of aluminium per anode production ratio; thus the more efficient the anodes would be, the lower the pitch consumption and vice versa.*	
total petrol coke consumption	petrol coke consumption prebake anode production +petrol coke consumption soderberg paste production
<u>Unit: Ton / Year</u> *This flow captures the total amount of petrol coke that is consumed in the process of anode production. It is calculated by summing up the pitch consumption from of the prebake anode and Söderberg paste production processes. The petrol coke consumption is depending on the productivity of the anode in terms of tons of aluminium per anode production ratio; thus the more efficient the anodes would be, the lower the pitch consumption and vice versa.*	

Table 12 – Equations to calculate the inputs to the production process

4.2.6 The emissions module

The emissions of the aluminium production are calculated in several different modules of the model. Emissions are calculated for the bauxite, alumina and aluminium production individually. The flows of emissions are then summed up, depending on type, are then accumulated into respective stocks so that life cycle emissions per ton of aluminium and total accumulated emission can be calculated. Life cycle emissions refer to the total amount of emissions that are created from bauxite mining to aluminium metal. Next to emissions, the flows of several inputs to the production process are summed up and accumulated. The flow quantity gives insight into the total consumption of specific resources that are used for the production process, and the accumulation sheds light into the scale on which resources have been consumed, and possibly will be consumed. The following flows of emissions are calculated and accumulated in this model:

- fresh water emissions
- sea water emissions
- gaseous fluorides
- particulate fluorides
- nitrous oxides
- sulphur dioxide
- mercury
- particulate emissions
- waste for land filling
- bauxite residues
- carbon dioxide (direct emissions)

The emission flows are captured for the same processes that serve for the calculation of the inputs. Emission rates are calculated by multiplying the respective production rate. The '*sulfur dioxide emissions aluminium production prebake*' for example are the product of '*aluminium production prebake*' and '*sulfur dioxide per ton of aluminium produced*', an average value of SO_2 emitted per ton of aluminium produced via the prebake process.

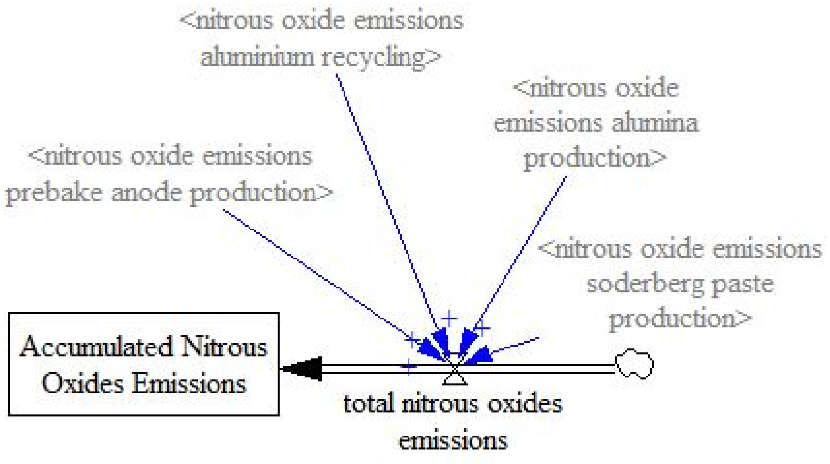

Figure 25: SFD Life Cycle Nitrous Dioxide emissions

Name	Equation
total fresh water emissions	fresh water emissions alumina production + fresh water emissions aluminium production prebake + fresh water emissions aluminium production soderberg + fresh water emissions bauxite mining + fresh water emissions ingot production + fresh water emissions prebake anode production + fresh water emissions soderberg paste production
Unit: Litre / Year *The total fresh water emissions are the sum of the fresh water that is used during the different stages of the aluminium production process, from bauxite mining to ingot casting. They are calculated by summing up the fresh water emissions of the respective sectors.*	
total sea water emissions	sea water emissions alumina production + sea water emissions aluminium production prebake + sea water emissions aluminium production soderberg + sea water emissions bauxite mining
Unit: Litre / Year *The total sea water emissions are the sum of the fresh water that is used during the different stages of the aluminium production process, from bauxite mining to ingot casting. They are calculated by summing up the sea water emissions of the respective sectors.*	
total gaseous flouride emissions	gaseous fluoride emissions aluminium production prebake + gaseous fluoride emissions aluminium production soderberg
Unit: Ton / Year *The gaseous fluoride emissions are calculated by summing up the fluoride emissions of prebake and Söderberg production processes and aluminium recycling. The amount of gaseous fluoride is calculated by multiplying an average amount of gaseous fluorides with the respective production rates of primary aluminium (Prebake and Söderberg).* *Fluoride emissions during the process of primary aluminium production occur through anode effects. An anode effect is a situation in which the alumina ore level in the pot is lower than the required level for electrolysis, which results in rapid voltage increases that cause the carbon from the anode and the cryolite bath to react (Gibbs et al., 2001, p. 197). The amount of fluoride emissions that leak into the environment depend on the technology of the emissions capture system of the production plant and the frequency of anode effects. The fluoride emissions are calculated by summing up the fluoride emissions of prebake and Söderberg production processes.*	
total particulate fluoride emissions	particulate fluoride emissions aluminium production prebake + particulate fluoride emissions aluminium production soderberg
Unit: Ton / Year *The particulate emissions are calculated by summing up the fluoride emissions of prebake and Söderberg production processes. The amount of particulate fluoride is calculated by multiplying an average amount of particulate fluorides with the respective production rates of primary aluminium (Prebake and Söderberg).* *Fluoride emissions occur during the process of primary aluminium production through anode effects. An anode effect is a situation in which the alumina ore level in the pot is lower than the required level for electrolysis, which results in rapid voltage increases that cause the carbon from the anode and the cryolite bath to react (Gibbs et al., 2001, p. 197). The amount of fluoride emissions that leak into the environment depend on the technological state of the emissions capture system of the production plant and the frequency of anode effects.*	
total nitrous oxides emissions	nitrous oxide emissions prebake anode production + nitrous oxide emissions soderberg paste production + nitrous oxide emissions alumina production + nitrous oxide emissions aluminium recycling

Unit: Ton / Year *This variable captures the total amount of nitrous oxides (NO_x) that are emitted during the anode production, the alumina refining processes, and aluminium recycling. They are calculated by summing up the nitrous oxides from prebake anode and Söderberg paste production, the alumina refining process, and the aluminium recycling process.*	
total sulfur dioxide emissions	sulfur dioxide emissions alumina production + sulfur dioxide emissions aluminium production prebake + sulfur dioxide emissions aluminium production soderberg + sulfur dioxide emissions ingot production + sulfur dioxide emissions prebake anode production + sulfur dioxide emissions soderberg paste production + sulfur dioxide emissions aluminium recycling
Unit: Ton / Year *This flow captures the total amount of sulphur dioxide emissions. It is calculated by summing up the sulphur dioxide emissions that occur during the different stages of the aluminium production process, from the alumina refining to the ingot casting and aluminium recycling process.*	
total mercury emissions	mercury emissions alumina production
Unit: Ton / Year *Mercury emissions occur only during the alumina refining process. Trace elements of mercury that are contained in the bauxite ore are vaporized during the refining process, and gaseous mercury escapes from the refinery (Alcoa, 2007). The amount of mercury emissions is calculated by multiplying an average amount of mercury per ton of alumina produced by the alumina consumption rate. This variable is then used as input for the total mercury emissions.*	
total particulate emissions	particulate emissions aluminium production prebake + particulate emissions aluminium production soderberg + particulate emissions bauxite mining + particulate emissions ingot production + particulate emissions prebake anode production + particulate emissions soderberg paste production + particulate emissions aluminium recycling
Unit: Ton / Year *This flow captures the total particulate emissions that occur during the processing of bauxite ore to aluminium metal. Particulate emissions occur throughout the aluminium production process from bauxite mining, anode/paste production, electrolysis up to the ingot production and aluminium recycling process. The total particulate emissions are calculated by summing up the particulate emissions of the different stages.*	

Table 13 – Equations to calculate the emissions of the production process

4.2.7 Energy consumption and carbon dioxide (CO_2) emissions

Aluminium production is a very energy and resource intensive process. The energy consumption of primary aluminium production is calculated by multiplying the primary aluminium production rate with the energy intensity of the electrolysis process (in kWh per ton of primary Al).
Direct CO2 emissions (emitted during the production process itself) and indirect CO2 emissions (derived from the electricity consumption and the power mix) are accounted for in the model. For the direct emissions an average amount of emissions per ton of aluminium from the IAI report (2013) was multiplied with the '*primary aluminium production rate*'.
The energy intensity data from the World Aluminium website[15] is multiplied with the two production rates, '*aluminium production prebake*', and '*aluminium production Söderberg*' and summed up in order to calculate the '*global electricity consumption of primary aluminium production*'. Subsequently, the data on the global power mix in aluminium production (IAI, 2013) provided the fractions ($\sum = 1$) to determine the share of energy from different power sources (hydro, coal, natural gas, and nuclear). The amount of the four different energy sources used for aluminium production is calculated by multiplying the global electricity consumption by the respective shares. The amount of '*coal energy used for aluminium production*' for example is calculated by multiplying the global electricity consumption of primary aluminium production by the '*fraction of coal energy used*'.
Indirect emissions are those emissions that originate from the production of the electricity that is used for the electrolysis process. In the model, the different shares of electricity per power source are used to calculate the emissions that origin from producing the energy that is consumed during the electrolysis process (indirect emissions). Furthermore, these shares are also used to calculate the electricity costs of the electrolysis process.

The indirect emissions are calculated by multiplying the shares of the four different energy sources in use by the CO2 equivalent for the respective power source. In the case of coal energy the '*CO_2 equivalent coal energy used for electrolysis*' would be calculated by multiplying the amount of coal energy used for aluminium production with the '*kg CO_2 equivalent per kWh of coal energy*'.

Figure 24 shows the 'uses tree' of the global electricity consumption of primary aluminium production. As explained above, it becomes clear that this variable serves as the base to calculate the different CO2 equivalent emissions and the costs of energy, depending on the respective shares of power sources.

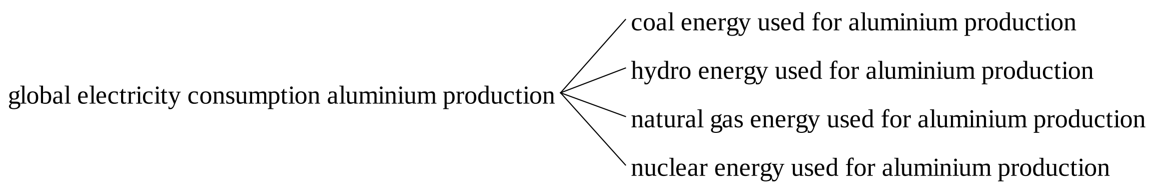

Figure 26: Uses tree for' global electricity consumption of primary aluminium production

The '*indicated energy costs of electrolysis*' are calculated by summing the four different cost positions up. The four variables that represent the emissions that are caused through the electricity consumption of the electrolysis process are summed up to calculate the variable '*indirect CO_2 emissions electrolysis process*'.

[15] http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/

The model distinguishes between two different types of CO_2 emissions: direct and indirect. The flow of '*total direct CO_2 emissions*' is the sum of the carbon dioxide emissions of the prebake anode production process, '*CO_2 emissions from non-fuel combustion sources prebake anode production*', and the emissions of the two different primary production technologies, '*CO_2 emissions aluminium production prebake*' and '*CO_2 emissions aluminium production soderberg*'. The 'total CO_2 emission rate aluminium production' is calculated by adding the '*indirect CO_2 emissions electrolysis process*' to the total direct CO_2 emissions.

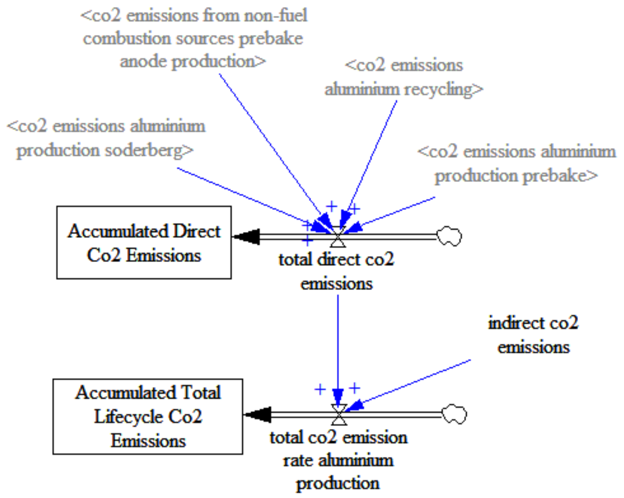

Figure 27: SFD total CO2 emissions aluminium production, Lifecycle module

Figure 28 and Figure 29 on the next page show the SFD structures that are used to determine energy consumption and emissions of the primary production and aluminium recycling module. The equations for the variables in the figures are provided in Table 14.

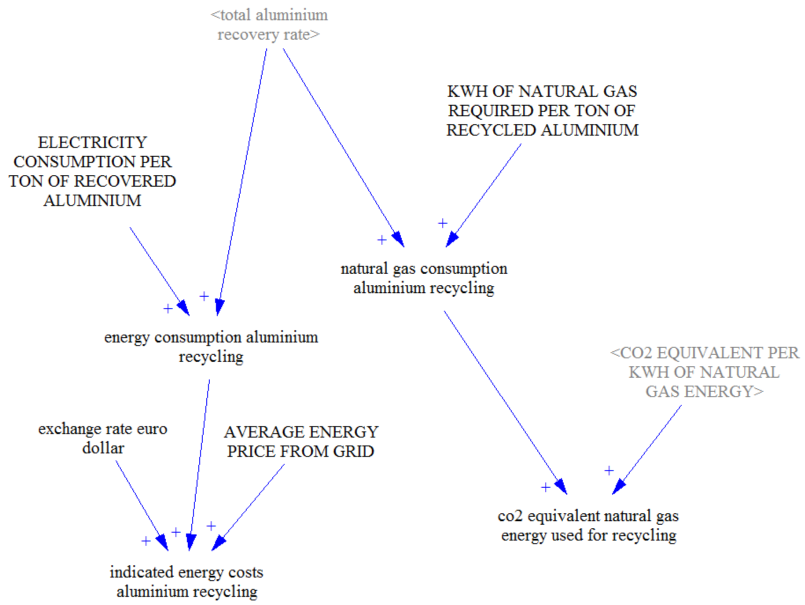

Figure 28: Structure to calculate CO2 equivalent emissions and energy costs of recycling

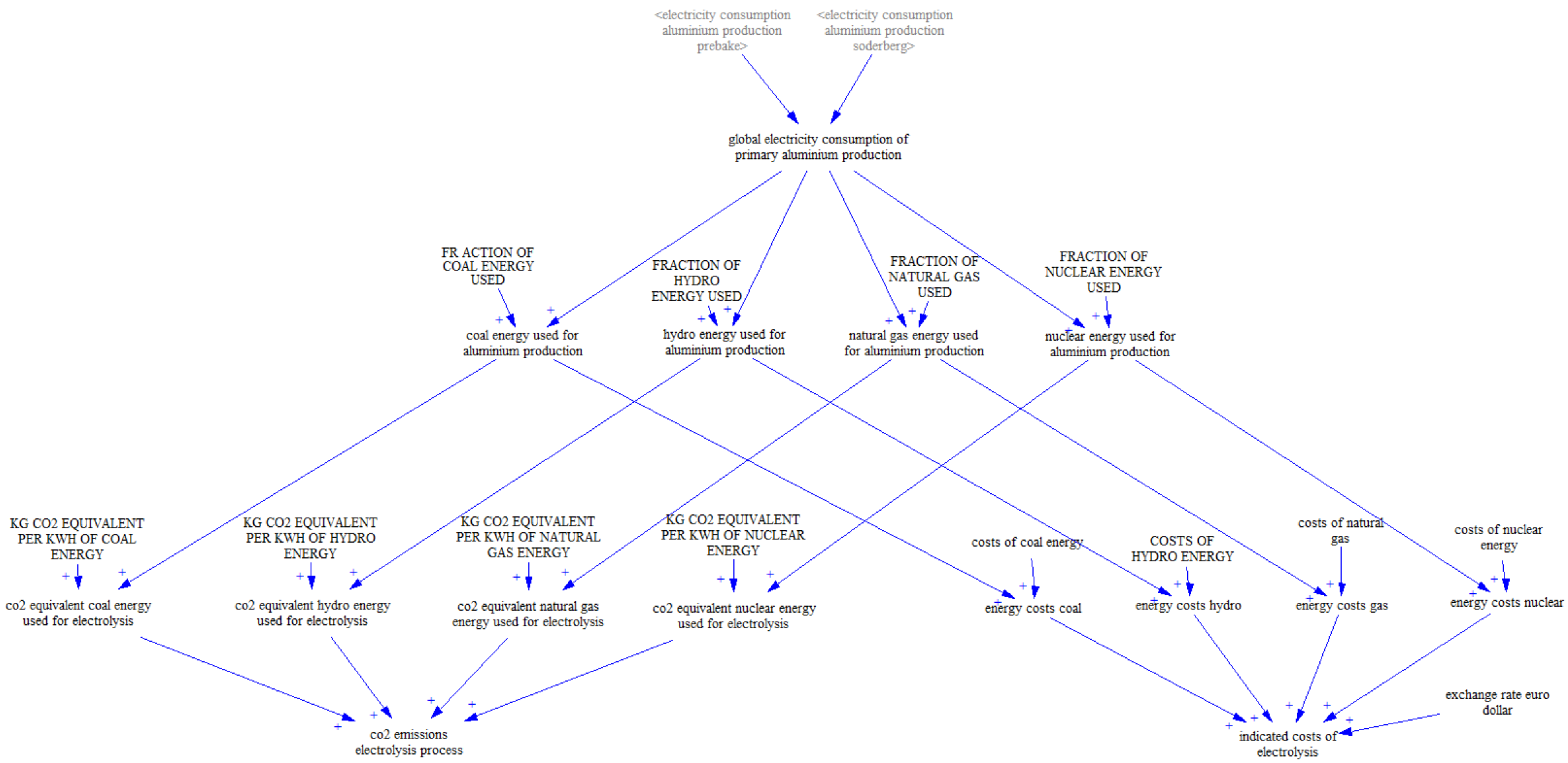

Figure 29: Structure to calculate CO2 equivalent emissions and indicated cost of electrolysis

Name	Equation
global electricity consumption aluminium production	electricity consumption aluminium production prebake + electricity consumption aluminium production soderberg
Unit: kWh / Year *The global electricity consumption of aluminium production is derived from both different electrolyse processes, prebake and Söderberg. These values are determined by the production rate and the application of the two different process types. This value is used as base to determine the different power sources used to satisfy the electricity consumption.*	
coal energy used for aluminium production	FR COAL ENERGY USED * global electricity consumption aluminium production
Unit: kWh / Year *The amount of coal energy used for aluminium production is determined by the total global electricity consumption for electrolysis, and the fraction of this energy that is produced by coal power plants (IAI, 2013). This variable is subsequently used for calculating CO2 emissions of and costs for the electricity of the electrolyses process.*	
hydro energy used for aluminium production	FR HYDRO ENERGY USED * global electricity consumption aluminium production
Unit: kWh / Year *The amount of coal energy used for aluminium production is determined by the total global electricity consumption for electrolysis, and the fraction of this energy that is produced by hydro energy plants (IAI, 2013). This variable is subsequently used for calculating CO2 emissions of and costs for the electricity of the electrolyses process.*	
natural gas energy used for aluminium production	FR NATURAL GAS USED * global electricity consumption aluminium production
Unit: kWh / Year *The amount of coal energy used for aluminium production is determined by the total global electricity consumption for electrolysis, and the fraction of this energy that is produced through natural gas (IAI, 2013). This variable is subsequently used for calculating CO2 emissions of and costs for the electricity of the electrolyses process.*	
nuclear energy used for aluminium production	FR NUCLEAR ENERGY USED * global electricity consumption aluminium production
Unit: kWh / Year *The amount of coal energy used for aluminium production is determined by the total global electricity consumption for electrolysis, and the fraction of this energy that is produced by nuclear power plants (IAI, 2013). This variable is subsequently used for calculating CO2 emissions of and costs for the electricity of the electrolyses process.*	
energy costs coal	costs of coal energy * coal energy used for aluminium production
Unit: Euro / Year *The costs of coal energy are calculated based on the share of electricity that is used from coal as a power source, and the costs of coal energy.*	
energy costs hydro	COSTS OF HYDRO ENERGY * hydro energy used for aluminium production
Unit: Euro / Year	

<table>
<tr><td colspan="2">The costs of hydro electricity are calculated based on the share of electricity that is used from hydro plants as a power source, and the costs of hydro energy.</td></tr>
<tr><td>energy costs gas</td><td>costs of natural gas * natural gas energy used for aluminium production</td></tr>
<tr><td colspan="2"><u>Unit: Euro / Year</u>
The costs of natural gas energy are calculated based on the share of electricity that is used from natural gas as a power source, and the costs of energy from natural gas.</td></tr>
<tr><td>energy costs nuclear</td><td>costs of nuclear energy * nuclear energy used for aluminium production</td></tr>
<tr><td colspan="2"><u>Unit: Euro / Year</u>
The costs of nuclear energy are calculated based on the share of electricity that is used from nuclear power plants as a power source, and the costs of nuclear energy.</td></tr>
<tr><td>indicated costs of electrolysis</td><td>(energy costs coal + energy costs gas + energy costs hydro + energy costs nuclear)
/exchange rate euro dollar</td></tr>
<tr><td colspan="2"><u>Unit: Euro / Year</u>
The indicated costs of electrolysis are the sum of the costs for the four different power sources calculated above. The sum is divided by the exchange rate dollar to euro, since the model uses euro, but all the prices are in dollar.</td></tr>
<tr><td>co2 equivalent coal energy used for electrolysis</td><td>coal energy used for aluminium production * CO2 EQUIVALENT PER KWH OF COAL ENERGY</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The CO2 equivalent emissions are calculated by multiplying the share of electricity that is used from coal power plants with the CO2 equivalent per kWh of coal energy.</td></tr>
<tr><td>co2 equivalent hydro energy used for electrolysis</td><td>hydro energy used for aluminium production * CO2 EQUIVALENT PER KWH OF HYDRO ENERGY</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The CO2 equivalent emissions are calculated by multiplying the share of electricity that is used from hydro power plants with the CO2 equivalent per kWh of hydro energy.</td></tr>
<tr><td>co2 equivalent natural gas energy used for electrolysis</td><td>natural gas energy used for aluminium production * CO2 EQUIVALENT PER KWH OF NATURAL GAS ENERGY</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The CO2 equivalent emissions are calculated by multiplying the share of electricity that is used from natural gas power plant with the CO2 equivalent per kWh of natural gas energy.</td></tr>
<tr><td>co2 equivalent nuclear energy used for electrolysis</td><td>nuclear energy used for aluminium production * CO2 EQUIVALENT PER KWH OF NUCLEAR ENERGY</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
The CO2 equivalent emissions are calculated by multiplying the share of electricity that is used from nuclear power plants with the CO2 equivalent per kWh of nuclear energy.</td></tr>
<tr><td>co2 emissions electrolysis process</td><td>co2 equivalent coal energy used for electrolysis
+ co2 equivalent hydro energy used for electrolysis
+ co2 equivalent natural gas energy used for electrolysis
+ co2 equivalent nuclear energy used for electrolysis</td></tr>
<tr><td colspan="2"><u>Unit: Ton / Year</u>
CO2 emissions from the electrolysis process are the sum of the emissions that were emitted through</td></tr>
</table>

the consumption of the 4 different power sources.	
energy consumption aluminium recycling	total aluminium recovery rate * ELECTRICITY CONSUMPTION PER TON OF RECOVERED ALUMINIUM
<u>Unit: kWh / Year</u> *This variable captures the electricity consumption of the aluminium recycling sector. It is calculated by multiplying the amount of recycled aluminium with a fixed amount of electricity that is needed to recycle one ton of aluminium.*	
indicated energy costs aluminium recycling	energy consumption aluminium recycling * AVERAGE ENERGY PRICE FROM GRID * exchange rate euro dollar
<u>Unit: Euro / Year</u> *The indicated energy costs of aluminium recycling are the total electricity costs of the aluminium recycling sector, and are calculated by multiplying the amount of consumed electricity by a fixed energy price and the exchange rate dollar to euro. An average energy price was used, since the composition of the electricity that the secondary sector utilizes is often depending on local energy suppliers.*	
natural gas consumption aluminium recycling	total aluminium recovery rate * KWH OF NATURAL GAS REQUIRED PER TON OF RECYCLED ALUMINIUM
<u>Unit: kWh / Year</u> *The aluminium recycling process utilizes natural gas energy for process heating. The amount of natural gas is represented in kWh, and calculated by multiplying the recycling rate with the amount of gas consumed per ton of aluminium recycled.*	
co2 equivalent natural gas energy used for recycling	natural gas consumption aluminium recycling * CO2 EQUIVALENT PER KWH OF NATURAL GAS ENERGY
<u>Unit: Ton / Year</u> *This variable calculates the CO_2 equivalent emissions of the consumed gas of the aluminium recycling process by multiplying the amount of natural gas used by the CO_2e value of natural gas.*	

Table 14 – Equations to calculate energy consumption and emissions

5. Scenarios

This section of the thesis presents the results of different scenario runs in the fisheries and the aluminium model. The implemented strategies in the scenarios were chosen based on a literature review on possible strategies that are able to meet the targets of improved environmental performance and a steady or improved profitability of the private sector.

5.1 Scenarios in the fisheries model

1) **Inefficiencies of capture fisheries (IoCF): How does the fish stock change if the model accounts for by-catch?**

By-catch is mentioned as malpractices in capture fisheries that destroy biomass every year. To model by-catch, a co-flow of the catching rate will be modelled. This co-flow will be called "shadow catching rate" and account for by-catch. It will be calculated by multiplying the catching rate with a by-catch multiplier. Two scenarios will be simulated: the by-catch multiplier values for the scenarios will be 1.1 (IoCF1) and 1.25 (IoCF2), representing 10% and 20% by-catch respectively.
This allows for quantifying these aspects of capture fisheries. Furthermore the discrepancy between reported catch and actual catch will become visible, and economical and environmental consequences can be evaluated (as for example: actual price per ton landed, value of the destroyed biomass, and effects on regeneration and fish stock behaviour and an eventual collapse).

2) **Reducing capacity (RC): How would a decrease in capacity influence total fish supply, fish stock, sustainability and profits?**

In this scenario the catching capacity will be reduced in order to evaluate the effects of capacity reduction. To do so, the equation of the desired catching capacity will be changed to a MIN function that introduces the chosen policy values as a cap, and thereby affect the balancing loops that are responsible for adjusting the amount of vessels to the desired level.
Three different values for catching capacity will be examined: 90 million tons per year (RC1), 95 million tons per year (RC2), and 100 million (RC3). The phasing out of the capacity takes place via an incremental reduction through the depreciation rate. This will give input to the discussion on the effects of policy implementation speed.
It will be examined whether the demand for fish from capture fisheries still can be met, and what the effects of a reduced fishing capacity will be for the fish stock, price and profitability of the capture sector.

3) **Aquaculture growth (AG): To what extent does the growth of the aquaculture sector remove pressures from the wild fish stock, and how does that affect the profitability of the capture fishery sector?**

According to FishStatJ®, aquaculture production rate has increased on average by 6.6% annually over the last two decades, and is today producing around one third of the world fish supply. As an important contributor of fish for food, future growth of aquaculture is important for food security. Two scenarios with different aquaculture growth rates will be simulated to examine the effects on total fish supply, and on the performance indicators of capture fisheries. AG1 will be simulated under the assumption that the aquaculture sector grows by an annual 4% until 2050, and AG2 assumes a growth fraction of 2% per year. Both values lie above the chosen values for the BAU scenario, which assumes that the aquaculture growth rate is declining from 6% in 2015, to an annual 1.5% in 2050.

1) Inefficiencies of capture fisheries

The catching rate of the BAU scenario in the simulation model is calculated under the assumption that the operations of capture fisheries are 100% efficient in the sense that they only catch what is needed. The issue of by-catch, sea animals (fish, turtles, sea birds) that are accidentally caught while aiming at catching a specific species, is recently gaining more attention in the scientific community. Issues related to by-catch are related to the protection of species, ecosystem destruction and operational efficiency.

In order to simulate the issue of by-catch, a by-catch multiplier has been implemented into the model. In the two simulated scenarios the by-catch multiplier has a value of 1.1 (IoCF1) and 1.25 (IoCF2), representing 10% and 25% by-catch. By-catch is simulated over the whole timeframe of the simulation (1970-2050) to examine the effects that operational inefficiency has in terms of sustainability and profitability.

It is assumed that there is the same amount of useful catch, so that the demand is satisfied. This amount of catch is then multiplied by the by-catch multipliers, so that the effect of by-catch on the fish stock can be examined, while the catching rate itself remains the same. Changes respective the BAU values for chosen variables are shown in Table 15.

		Model outputs by scenario. Changes are differences relative to the BAU value.					
Name	**Scenario**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Vessels	**BAU**	**1.76**	**1.92**	**2.26**	**2.54**	**3.18**	**5.02**
million of vessels	IoCF1	1.76	1.84	1.86	1.85	2.24	2.84
	Δ IoCF1	*0.0%*	*-3.8%*	*-17.6%*	*-27.0%*	*-29.7%*	*-43.5%*
	IoCF2	1.76	1.84	1.86	1.93	2.50	2.97
	Δ IoCF2	*0.0%*	*-3.8%*	*-17.5%*	*-23.9%*	*-21.4%*	*-40.8%*
Catch per vessel	**BAU**	57.3	52.0	46.6	42.8	33.5	25.4
million tons per year	IoCF1	51.8	45.7	39.5	35.2	27.1	19.0
	Δ IoCF1	*-9.7%*	*-12.1%*	*-15.3%*	*-17.7%*	*-19.2%*	*-25.2%*
	IoCF2	44.2	37.9	32.3	27.3	19.1	11.9
	Δ IoCF2	*-22.9%*	*-27.2%*	*-30.6%*	*-36.2%*	*-43.1%*	*-53.2%*
Adult fish stock	**BAU**	8.33	8.09	7.84	7.56	7.02	6.36
billion tons	IoCF1	8.04	7.77	7.48	7.16	6.53	5.80
	Δ IoCF1	*-3.5%*	*-3.9%*	*-4.5%*	*-5.3%*	*-7.0%*	*-8.9%*
	IoCF2	7.61	7.29	6.96	6.57	5.82	4.96
	Δ IoCF2	*-8.6%*	*-9.8%*	*-11.2%*	*-13.1%*	*-17.1%*	*-22.0%*
Profitability indicator capture fisheries	**BAU**	**1.05**	**1.04**	**0.95**	**0.94**	**1.00**	**0.90**
dimensionless	IoCF1	0.99	0.98	0.87	0.85	0.92	0.80
	Δ IoCF1	*-5.1%*	*-5.7%*	*-8.9%*	*-9.5%*	*-8.4%*	*-11.3%*
	IoCF2	0.88	0.89	0.77	0.75	0.80	0.70
	Δ IoCF2	*-16.2%*	*-14.8%*	*-18.7%*	*-20.2%*	*-20.1%*	*-21.5%*
Operating costs fisheries	**BAU**	**93.69**	**93.69**	**100.50**	**105.28**	**107.24**	**135.01**
Euro per year	IoCF1	99.58	99.66	110.31	116.37	114.73	151.84
	Δ IoCF1	*6.3%*	*6.4%*	*9.8%*	*10.5%*	*7.0%*	*12.5%*
	IoCF2	112.68	108.58	123.59	132.00	129.75	173.84
	Δ IoCF2	*20.3%*	*15.9%*	*23.0%*	*25.4%*	*21.0%*	*28.8%*
Capacity utilization factor	**BAU**	**0.76**	**0.73**	**0.69**	**0.65**	**0.59**	**0.51**
dimensionless	IoCF1	0.79	0.75	0.69	0.64	0.58	0.49
	Δ IoCF1	*4.4%*	*3.6%*	*0.7%*	*-1.5%*	*-1.4%*	*-4.3%*
	IoCF2	0.83	0.78	0.73	0.65	0.56	0.44
	Δ IoCF2	*9.3%*	*7.0%*	*5.5%*	*-0.9%*	*-5.6%*	*-13.9%*

Catching efficiency indicator	**BAU**	**1.00**	**0.94**	**1.00**	**1.00**	**0.92**	**0.98**
dimensionless	IoCF1	0.98	0.92	1.00	1.00	0.89	0.99
	Δ IoCF1	*-2.2%*	*-2.3%*	*0.0%*	*0.0%*	*-3.2%*	*0.5%*
	IoCF2	0.99	0.89	1.00	1.00	0.87	0.95
	Δ IoCF2	*-1.4%*	*-5.4%*	*0.0%*	*0.0%*	*-5.1%*	*-2.9%*
Amount of by-catch	**BAU**	**0**	**0**	**0**	**0**	**0**	**0**
million tons per year	IoCF1	9.88	9.75	10.52	10.86	10.34	12.81
	IoCF2	24.92	23.59	26.31	27.15	25.33	30.95

Table 15 – Results of the inefficiencies scenarios

Direct impacts

When adding a by-catch multiplier to the model the value chain of the capture fishery sector changes significantly. Adding the by-catch multiplier to the model increases the operations costs of the sector above the level they have in the BAU scenario. However, the changes are not proportional to the multiplier values. In the scenario with a 10% by-catch multiplier (IoCF1) the operations cost are 6.3% higher by the year 2015, and rise further up to 12.5% above the BAU value by 2050. In the same years, simulation outputs of the IoCF2 scenario indicate that costs are 20.3% higher in the year 2015, and 28.8% higher by 2050 when compared to the BAU scenario. Figure 30 shows the operations costs of the capture fishery sector for all three scenarios.

The faster depletion of the fish stock than in the BAU scenario is causing the catch per vessel to decline at a faster rate. By 2015, the catch per vessel would roughly 10% (IoCF1) and 23% (IoCF2) lower compared to the BAU case, and in 2050 catches per vessel would have declined by between 25.2% (IoCF1) and 53.2% (IoCF2). This decrease in catch per vessel is the result of a lower fish density, or a lower catching efficiency. Faster depletion of the stock reduces the overall fish density and makes it more difficult to catch fish efficiently.

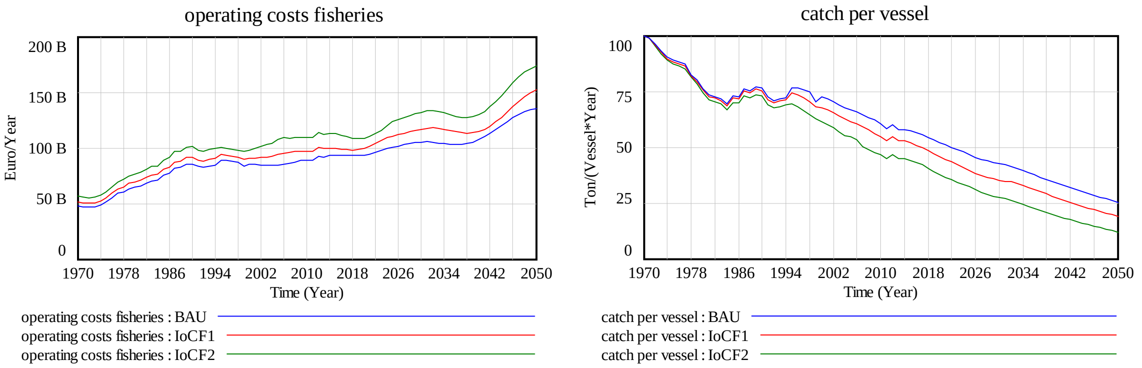

Figure 30: Operating costs and catch per vessel IoCF1+2

The increase in operation costs has direct implications for the profitability of the sector, as illustrated in Figure 31. Under BAU circumstances the capture fisheries sector remains profitable until the mid 2020's, while the simulation results in which the by-catch multiplier is included indicate that capture fisheries are not profitable anymore long before that point in time. By the end of the simulation from 1970 to 2050 the results show a 12.5% reduction in profitability in the scenario IoCF1, and a 28.8% reduction in profitability in the IoCF2 scenario.

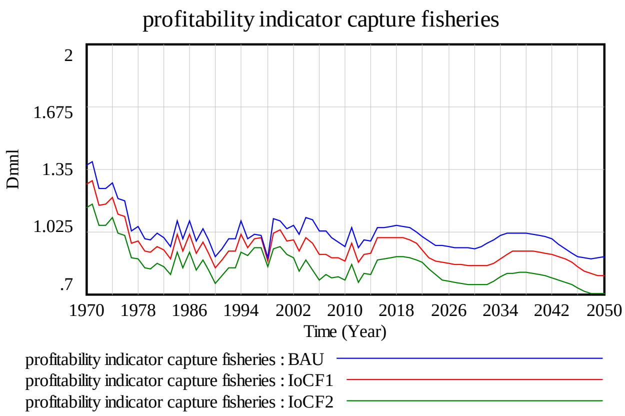

Figure 31: Profitability indicator IoCF1+2

The extraction of more biomass from the ocean than required is directly affecting the health of the resource base as well. Since by-catch per se is catch that is not desired, and often thrown back into the sea to die, it can be seen as one of the major threats for the regeneration rate and stock level. Assuming an inefficiency factor of 10%, by 2015 the regeneration rate of the fish stock is 3.5% lower than in the BAU scenario, and 8.9% by 2050. In IoCF2 (25% inefficiency) the respective values are -8.6% and -22% respectively.

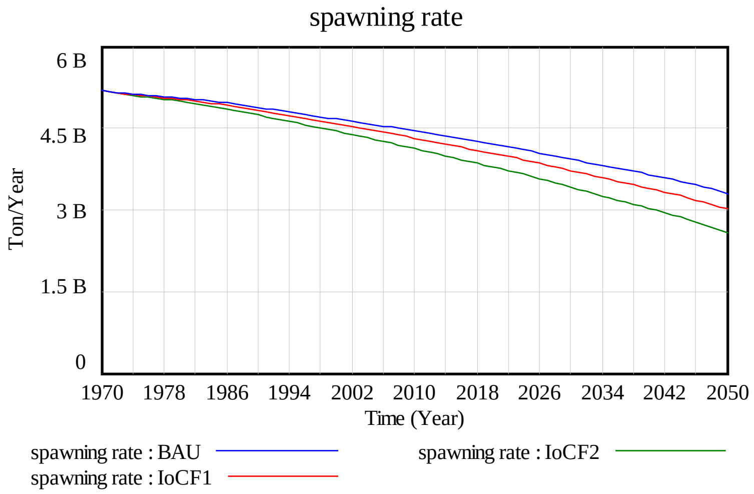

Figure 32: Spawning rate IoCF1+2

Indirect impacts

Accounting for the inefficiencies of capture fisheries is initially increasing the capacity utilization, while reducing it in the long run. Steady demand combined with decreasing catching rates per vessel leads to a situation that allows for overcapacity to emerge. The simulation run show that the capacity utilization of the two scenarios is higher until the year 2025 when compared to the BAU scenario. By 2015 it is still 4.4% (IoCF1) and 9.3% (IoCF2) higher than it would be without accounting for by-catch. After 2025 it gradually starts decreasing below the BAU value, and by 2050 the capacity utilization would have decreased by 4.3% (IoCF1) and 13.9% (IoCF2) respectively.

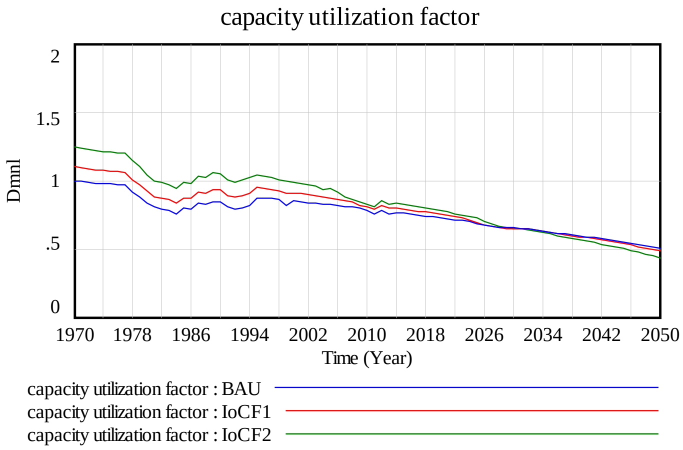

Figure 33: Capacity utilization in the IoCF1+2

Figure 34 shows the catching efficiency indicator for the three simulation runs. If the indicator value is ‘1’ it means that the capture fishery sector is able to meet the demand for fish from capture fisheries. Values below ‘1’ indicate a supply shortage. In between the period between 1994 and 2008 the simulation outputs indicate some supply shortages for all three scenarios, which is caused through a decrease of catching efficiency below the level of expected demand. This does not mean that there is a shortage of vessels, but that there has been a situation in which the capacity of the capture fisheries sector was, due to density effects, not able to catch as much fish as demanded. The outputs also indicate future supply shortages from between 2016 and 2022, and from 2028 into the future. Calculations of the differences are provided in Table 15 above, but are speculative because the results are highly dependent on the level of the fish stock for which an adequate estimate is not available.

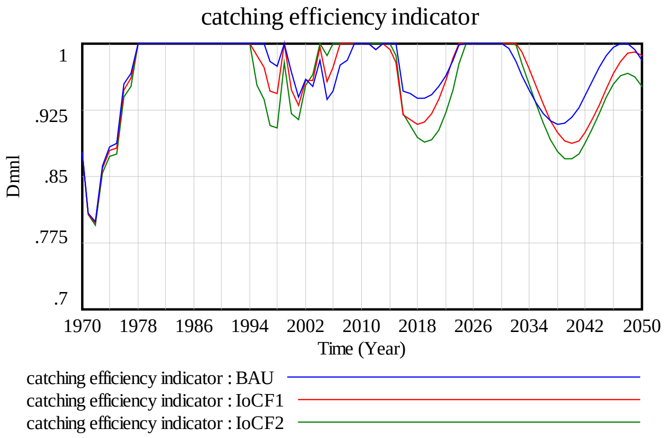

Figure 34: Catching efficiency indicator IoCF1+2

<u>Induced impacts</u>

Inefficiency in this model are constrained to the extraction of biomass only, and therefore do not account for impacts that those inefficiencies have on marine life in general. Food chain effects and detrimental impacts on the resource base of marine life, which are the main driver for the regeneration of the resource, are not captured in this model. This implies that the impacts of the capture fisheries inefficiencies are likely to be much larger than illustrated in this analysis. The reduction of certain species can lead to a shift in species dominance in ecosystems, and therefore change underwater ecosystems forever with unforeseeable consequences.

The unintended removal of biomass from the oceans has the potential to lead to an even faster depletion of the resource base than predicted by many researchers. The erosion of the resource base can force many fishermen to stop fishing due to decreasing turnovers, and motivate them to look for an alternative livelihood in the long run.

In addition, a depletion of the marine resources as a nutrition source for humanity can have disastrous consequences in terms of food security. With an annual catching rate of approximately 100 million tons a year, fish is one of the main resources in human diet, meaning that a total depletion of the fish stocks would put immense pressures on humanity to replace that food, and protein, source. The depletion of fish stocks by a few thus gradually shifts the burden to ensure long term food security onto society.

2) Reductions in fishing capacity

For the purpose of evaluating a fixed level of capacity, the equation of "desired catching capacity" will be changed to the following equation:

desired catching capacity =

IF THEN ELSE (Time > 2015,**MIN**(**ZIDZ** (Expected Demand For Fish From Fisheries , catching efficiency indicator) , RC catching capacity),ZIDZ(Expected Demand For Fish From Fisheries , catching efficiency indicator))

An IF THEN ELSE function is used to determine at what point in time the policy is implemented. The MIN function ensures that the adjustment process only takes place if the level of catching capacity is bigger than the policy level.

The chosen policy capacities are 90 million tons per year (RC1), 95 million tons per year (RC2), and 100 million tons per year (RC3). The BAU capacity and reductions over time can be found in Table 16 underneath.

		Model outputs by scenario. Changes are differences relative to the BAU value.					
Name	**Scenario**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Vessels	**BAU**	**1.76**	**1.92**	**2.26**	**2.54**	**3.18**	**5.02**
million of vessels	RC1	1.76	1.84	1.86	1.85	2.24	2.84
	Δ RC1	*0.0%*	*-3.8%*	*-17.6%*	*-27.0%*	*-29.7%*	*-43.5%*
	RC2	1.76	1.84	1.86	1.93	2.50	2.97
	Δ RC2	*0.0%*	*-3.8%*	*-17.5%*	*-23.9%*	*-21.4%*	*-40.8%*
	RC3	1.76	1.85	1.93	2.11	2.72	3.21
	Δ RC3	*0.0%*	*-3.7%*	*-14.5%*	*-16.6%*	*-14.7%*	*-36.1%*
Fishing capacity	**BAU**	**133.09**	**137.24**	**153.18**	**165.83**	**181.43**	**251.28**
millions of tons per year	RC1	133.09	134.55	130.98	125.10	136.51	160.83
	Δ RC1	*0%*	*-2%*	*-14%*	*-25%*	*-25%*	*-36%*
	RC2	133.09	134.55	130.98	128.86	151.47	165.91
	Δ RC2	*0%*	*-2%*	*-14%*	*-22%*	*-17%*	*-34%*
	RC3	133.09	134.55	134.17	139.44	163.07	174.27
	Δ RC3	*0%*	*-2%*	*-12%*	*-16%*	*-10%*	*-31%*
Catching rate	**BAU**	**101.06**	**99.79**	**105.23**	**108.59**	**106.79**	**127.46**
million tons per year	RC1	101.06	97.85	91.38	84.01	85.19	91.42
	Δ RC1	*0.0%*	*-2.0%*	*-13.2%*	*-22.6%*	*-20.2%*	*-28.3%*
	RC2	101.06	97.85	91.38	86.49	93.51	92.48
	Δ RC2	*0.0%*	*-2.0%*	*-13.2%*	*-20.4%*	*-12.4%*	*-27.4%*
	RC3	101.06	97.85	93.56	93.23	99.06	95.07
	Δ RC3	*0.0%*	*-2.0%*	*-11.1%*	*-14.1%*	*-7.2%*	*-25.4%*
Adult fish stock	**BAU**	**8.33**	**8.09**	**7.84**	**7.56**	**7.02**	**6.36**
billion tons	RC1	8.33	8.09	7.87	7.67	7.30	6.86
	Δ RC1	*0.0%*	*0.0%*	*0.4%*	*1.4%*	*4.0%*	*7.9%*
	RC2	8.33	8.09	7.87	7.67	7.25	6.77
	Δ RC2	*0.0%*	*0.0%*	*0.4%*	*1.3%*	*3.2%*	*6.5%*
	RC3	8.33	8.09	7.86	7.65	7.17	6.68
	Δ RC3	*0.0%*	*0.0%*	*0.4%*	*1.1%*	*2.1%*	*5.0%*

Profitability indicator capture fisheries *dimensionless*	**BAU**	**1.05**	**1.04**	**0.95**	**0.94**	**1.00**	**0.90**
	RC1	1.05	1.07	1.09	1.12	1.11	1.08
	Δ RC1	*0.0%*	*2.5%*	*14.6%*	*19.9%*	*10.3%*	*20.4%*
	RC2	1.05	1.07	1.09	1.11	1.07	1.07
	Δ RC2	*0.0%*	*2.5%*	*14.6%*	*18.5%*	*6.6%*	*19.2%*
	RC3	1.05	1.07	1.08	1.08	1.04	1.05
	Δ RC3	*0.0%*	*2.5%*	*13.4%*	*14.9%*	*3.9%*	*17.3%*
Sales price fisheries Euro per ton	**BAU**	**989.5**	**992.7**	**969.0**	**971.2**	**1009.1**	**986.7**
	RC1	989.5	1002.8	1035.1	1081.6	1091.8	1097.9
	Δ RC1	*0.0%*	*1.0%*	*6.8%*	*11.4%*	*8.2%*	*11.3%*
	RC2	989.5	1002.8	1035.1	1069.4	1058.4	1094.2
	Δ RC2	*0.0%*	*1.0%*	*6.8%*	*10.1%*	*4.9%*	*10.9%*
	RC3	989.5	1002.8	1024.1	1037.4	1037.2	1085.5
	Δ RC3	*0.0%*	*1.0%*	*5.7%*	*6.8%*	*2.8%*	*10.0%*
Indicated employment capture fisheries *million FTE per year*	**BAU**	27.84	27.49	28.99	29.92	29.42	35.12
	RC1	27.84	26.96	25.17	23.15	23.47	25.19
	Δ RC1	0.0%	-2.0%	-13.2%	-22.6%	-20.2%	- 28.3%
	RC2	27.84	26.96	25.17	23.83	25.76	25.48
	Δ RC2	0.0%	-2.0%	-13.2%	-20.4%	-12.4%	- 27.4%
	RC3	27.84	26.96	25.78	25.68	27.29	26.19
	Δ RC3	0.0%	-2.0%	-11.1%	-14.1%	-7.2%	- 25.4%

Table 16 – Results of the capacity reduction scenarios

The implementation of a capacity constraint has effects throughout supply- and value chain. Improvements like a higher fish stock level come at the cost of higher fish prices which are caused by supply shortages. Next to improvements with regard to the health of the resource base, improvements regarding the profitability of the sector can be observed. Through a reduction in capacity, the overall sector performance is improved because capacity that otherwise would be idle is phased-out.

Direct impacts

An incremental reduction in capacity is directly affecting several feedback loops. By limiting the maximum capacity the capacity adjustment loop is directly affected in the sense that capacity adjustment just takes place when the capacity is below the desired (fixed) value. This influences the fleet size by determining the desired number of vessels. The number of vessels by 2025 is 17.6% (RC1), 17.5% (RC2), and 14.5% (RC3) lower than in the BAU scenario.

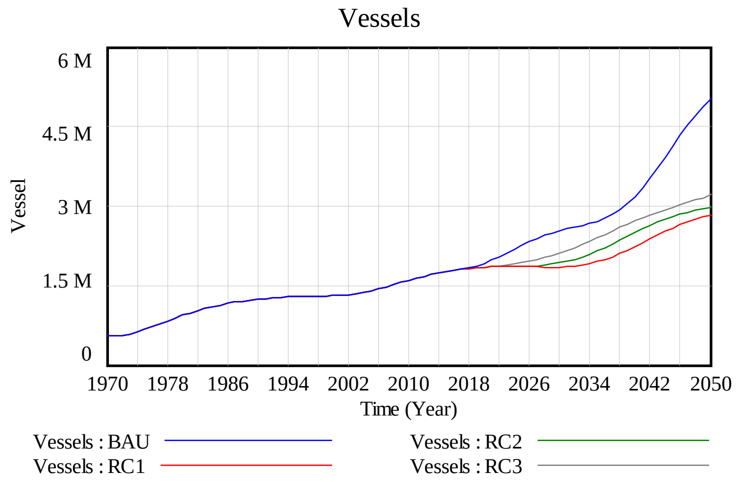

Figure 35: Number of vessels RC 1-3

The capacity restriction has a direct effect on the catching rate as well, since a reduction in capacity is causing a reduction in catch as well. While the catching rate in the BAU scenario is exceeding the FAOs’ maximum sustainable catch value of 100 million tons per year from around 2020 onwards, all three simulated capacity restriction scenarios help to keep the catching rate well below this value. The incremental reduction is causing the catching rate to decline from between 2% in 2020 in all three scenarios, up to between 28.3% (RC1) and 25.4% (RC3) until the mid of the century.

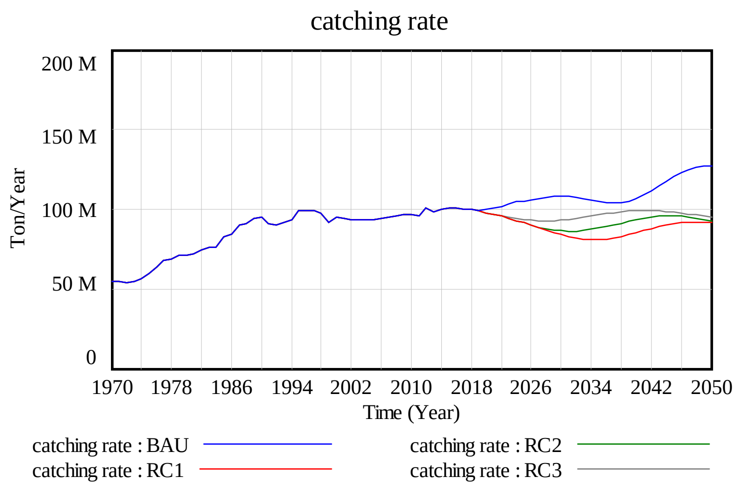

Figure 36: Catching rate RC 1-3

The reduction of the catching rate is causing the fish stock to decline at a lower rate than it does in the BAU scenario. Due to the incremental decrease in capacity it takes until 2025 until the first difference (+0.4% in all scenarios) is measurable. This means that policy makers need to pay attention to the delay that is involved when choosing a policy that aims at not replacing old vessels. By 2050 the fish stock is between 5% (RC3) and 7.9% (RC1) higher than it would be in the BAU scenario. Figure 37 shows the development of the stock of adult fish over time. The initial value of the fish stock is estimated which means that the results of this analysis should be regarded as an estimate and not hard facts. However, it becomes visible that even if capacity is constrained to 90 million tons per year, the stock of adult fish is still declining,

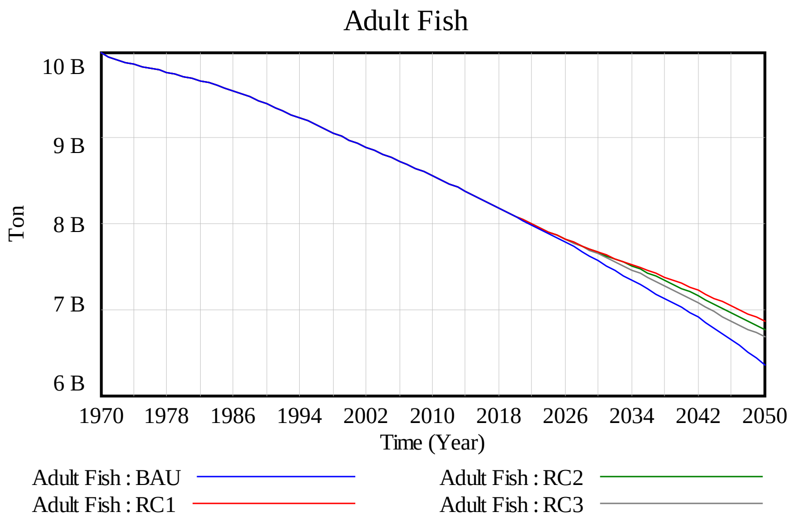

Figure 37: Development of the fish stock RC 1-3

The higher stock levels of the fish stock are one the one hand caused through the reduction in catching capacity, and the fact that there is more fish to reproduce than there is in the BAU scenario. This has a positive effect on the regeneration rate of the fish that, in this scenario delays, but does not counterbalance the depletion of the resource. However, with the current initial level of the fish stock the regeneration is not sufficient to keep the fish stock on a constant level and leads to a total depletion of the resource in the long run.

Indirect impacts

The indirect impacts of an incremental decrease in capacity are affecting the regeneration of the fish stock, the sales price of fish, indicated employment and the profitability of capture fisheries.

A reduction in capacity basically implements a catch limit on the capture fishery sector. Phasing out fishing capacity will cause people to lose their jobs and take away their livelihoods. The indicated employment of the capture fishery sector decreases, due to the model formulation, proportional to the catching rate. Until 2025 between 13.2% (RC1+2) and 11.1% of the people employed in capture fishery sector will lose their jobs. If the industry will complies with the strategy of phasing out capacity until the desired catching capacity is reached, employment is likely to contract between 25.4% (RC3) and 28.3% (RC1) by the year 2050. As a consequence, an amount of roughly 9 to 10 million jobs would disappear. The period over which jobs disappear is longer the lower the desired policy catching capacity is, and while there is a considerable difference between the scenarios RC1 and RC3 during the period from 2030 (8.5%) to 2040 (13%), this gap is starting to close from 2040 to a difference of 2% in job losses compared to the BAU in the year 2050.

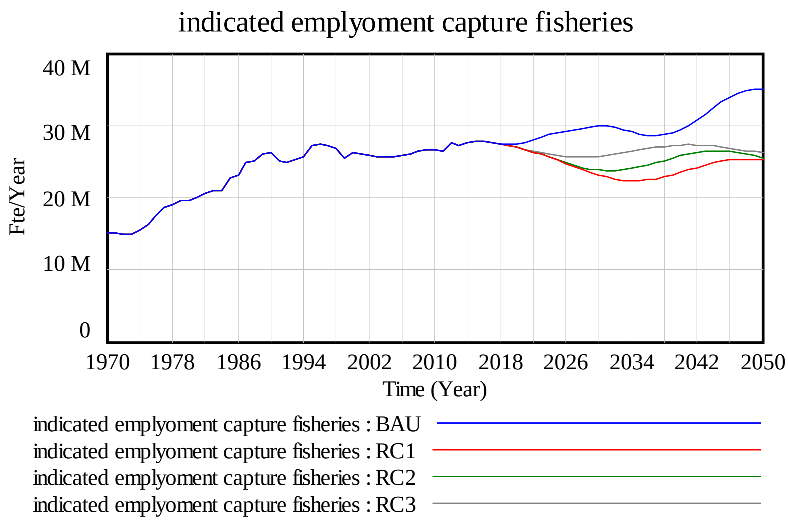

Figure 38: Indicated employment capture fisheries scenarios RC1-3

The reduction of capacity has positive effects on the profitability of the fishing industry. The profitability indicator is calculated by dividing total income by total costs. A reduction in capacity is increasing this ratio since overcapacity is phased out and overall sector capacity utilization increases. This prevents payments to capital for idle capacity and increases profitability over what it otherwise would have been in the BAU. The profitability of the capture fishery sector increases by between 13.4% (RC3) and 14.6% (RC1+2) by the year 2025, and by between 17.3% and 20.4% until 2050.

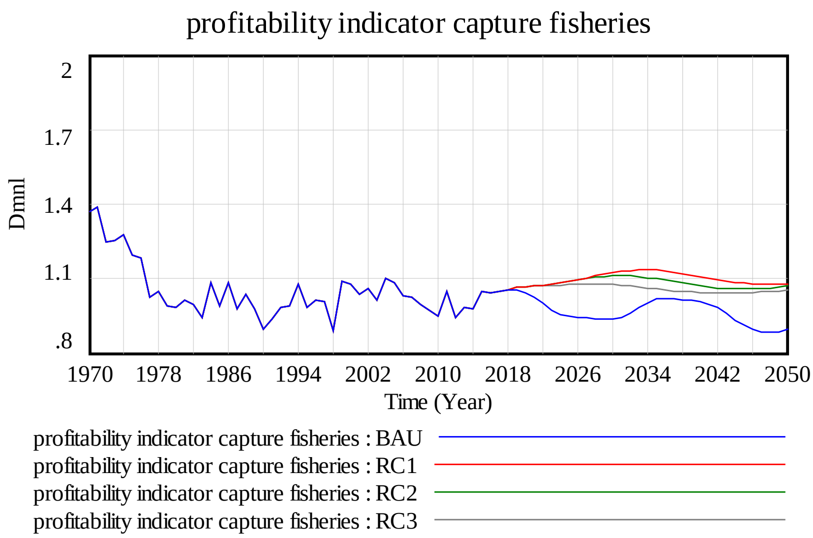

Figure 39: Profitability of capture fisheries scenarios RC1-3

<u>Induced impacts</u>

A reduction of total catching capacity also affects loops that are outside of the boundaries of the model. It is safe to say that the increasing profitability of the capture fishery sector will lead to a situation where subsidies that flow into maintaining the BAU scenario at the moment can be invested into projects and activities that help to maintain and protect fish stocks and ocean life. All involved actors, from the fishermen, over governments as society will benefit from healthy oceans and a secure supply of fish in the long run.

A reduction in capacity will come at the cost of jobs and therefore cause unemployment on country level to increase above the level of the BAU scenario. Using former fishing capacity for different purposes, as surveillance of coastal regions and/or for research purposes could be a temporary solution until former fishermen can be accommodated in different sectors.

The transformation of the capture fishery sector can lead to an unbalance in terms of the availability of quotas. There is the risk that large corporations start accumulating fishing quotas which means that there are less quotas left for a large group of people that directly depend on fish as a livelihood in many cases. An insufficient amount of quotas would force even more fishermen to look for alternative employment if. This does not mean that a higher amount of quotas should be issued, but that policy makers should pay attention that fish, as a resource of the commons, is not monopolized and depleted for the profit of a few. More information on the actual state of affairs and possible consequences of monopolization will be provided in the discussion section.

3) *Aquaculture growth scenarios*

AG1 will be simulated under the assumption that the aquaculture sector grows by an annual 6% until 2050, and AG2 assumes a growth fraction of 4% per year. Both values lie above the chosen values for the BAU scenario, which assumes that the aquaculture growth rate is declining from 5% in 2015, to an annual 2.3% in 2050.

In addition a scenario in which the aquaculture capacity is lower than expected will be examined. In scenario AG3 the aquaculture growth rate will be decreasing from 5% to 1.5% in the scenario.

Note:

The equation that is used for the demand for captured is a MAX-function that determines its value. The following equation was used:

MAX (Total Demand For Fish – aquafarming production rate , demand for fish from secondary processing)

This formulation was used to implement the assumption that only captured fish is used to produce fish meal and fish oil. Therefore the aquacultures' dependency is indirectly implemented into the model structure. Furthermore, it prevents the demand for captured fish to drop to zero, and causes the demand for captured fish to take the same value as soon as the aquaculture sector is able to cover the full demand for fish for food.

		Model outputs by scenario. Changes are differences relative to the BAU value.					
Name	**Scenario**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
Demand for captured fish	**BAU**	98.9	97.4	97.2	99.9	106.3	117.5
million tons per year	AG1	98.9	89.6	73.7	51.1	40.3	49.2
	Δ AG1	0.0%	-8.0%	-24.2%	-48.8%	-62.1%	-58.2%
	AG2	98.9	97.1	95.2	93.9	80.5	49.2
	Δ AG2	0.0%	-0.3%	-2.0%	-6.0%	-24.3%	-58.2%
	AG3	98.9	97.5	98.1	102.6	117.4	145.8
	Δ AG3	0.0%	0.1%	0.9%	2.7%	10.4%	24.0%
Aquafarming capacity	**BAU**	76.95	94.25	113.03	133.92	181.28	233.76
million tons per year	AG1	76.95	102.01	136.51	182.68	327.15	585.88
	Δ AG1	0.0%	8.2%	20.8%	36.4%	80.5%	150.6%
	AG2	76.95	94.52	115.00	139.92	207.11	306.58
	Δ AG2	0.0%	0.3%	1.7%	4.5%	14.2%	31.1%
	AG3	76.95	94.12	112.11	131.17	170.21	205.55
	Δ AG3	0.0%	-0.1%	-0.8%	-2.0%	-6.1%	-12.1%
Adult fish stock	**BAU**	8.33	8.09	7.84	7.57	7.05	6.41
billion tons	AG1	8.33	8.09	7.88	7.74	7.67	7.55
	Δ AG1	0.0%	0.0%	0.5%	2.2%	8.8%	17.8%
	AG2	8.33	8.09	7.84	7.59	7.11	6.80
	Δ AG2	0.0%	0.0%	0.0%	0.2%	0.9%	6.1%
	AG3	8.33	8.09	7.84	7.57	7.02	6.27
	Δ AG3	0.0%	0.0%	0.0%	-0.1%	-0.4%	-2.1%
Profitability indicator	**BAU**	1.04	1.03	0.95	0.95	1.00	0.91
capture fisheries	AG1	1.04	0.92	0.84	0.71	0.58	0.50
dimensionless	*Δ AG1*	0.0%	-10.9%	-11.2%	-25.4%	-41.7%	-44.6%
	AG2	1.04	1.02	0.94	0.92	0.87	0.76

	Δ *AG2*	0.0%	-0.4%	-1.1%	-3.2%	-12.9%	-16.1%
	AG3	1.04	1.03	0.96	0.98	1.01	0.95
	Δ *AG3*	0.0%	0.2%	0.5%	3.4%	0.6%	4.6%
Sales price fisheries Euro per ton	**BAU**	988.1	988.2	969.1	973.5	1001.7	989.6
	AG1	988.1	953.0	958.9	960.2	818.8	615.6
	Δ *AG1*	0.0%	-3.6%	-1.1%	-1.4%	-18.3%	-37.8%
	AG2	988.1	986.8	967.4	968.6	971.7	976.0
	Δ *AG2*	0.0%	-0.1%	-0.2%	-0.5%	-3.0%	-1.4%
	AG3	988.1	988.8	969.9	983.2	1010.0	1016.2
	Δ *AG3*	0.0%	0.1%	0.1%	1.0%	0.8%	2.7%
Indicated employment capture fisheries *million FTE per year*	**BAU**	27.84	27.45	28.61	29.27	29.15	33.40
	AG1	27.84	27.29	22.79	16.76	11.68	14.28
	Δ *AG1*	0.0%	-0.6%	-20.4%	-42.8%	-59.9%	-57.2%
	AG2	27.84	27.45	28.18	27.95	24.47	14.70
	Δ *AG2*	0.0%	0.0%	-1.5%	-4.5%	-16.0%	-56.0%
	AG3	27.84	27.45	28.82	29.37	31.55	38.62
	Δ *AG3*	0.0%	0.0%	0.7%	0.3%	8.2%	15.6%

Table 17 – Results of the aquaculture growth scenarios

Direct impacts

Fish from aquaculture and fish from fisheries are supplementary products. The simulation model works under the assumption that fish from aquaculture is completely used to satisfy demand before fish from the capture fishery sector is demanded. The change in growth rate is directly affecting the capacity adjustment loop and thereby changing production capacity levels and aquaculture production rate. AG1 (6%) results in an aquaculture production capacity of 586 million tons per year by 2050, representing a more than twofold increase compared to the BAU. An annual growth rate of 4% (AG2), thus slightly lower than the historical growth rate, would increase aquaculture capacity to a level 31.1% higher than the BAU scenario, with an annual production of 430 million tons per year.
A gradual reduction of the growth rate from 4% in 2016 down to 1.5% in 2050, which represents a 0.7% reduction by 2050 compared to the BAU scenario, will result in a capacity reduction of 12.1% by 2050. Figure 40 illustrates how the aquaculture production capacity develops in the different scenarios.

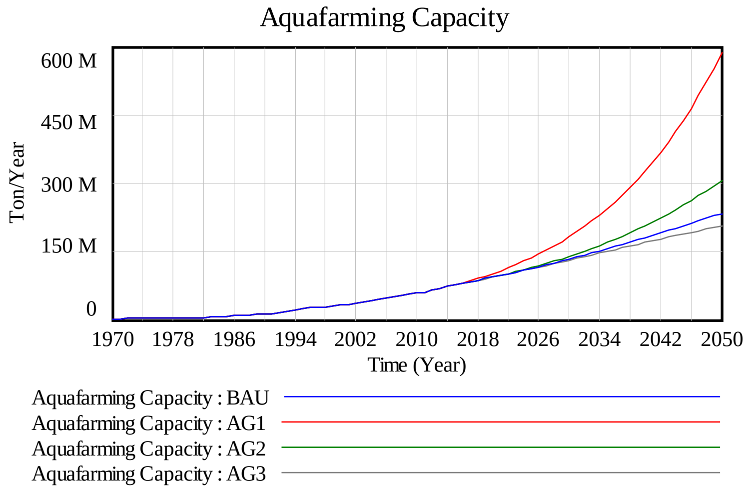

Figure 40: Aquafarming capacity AG1-AG3

Demand for fish from capture fisheries starts deceasing immediately if the aquafarming capacity grows with an average growth fraction of 6% per year (AG1). A contraction of about 24% by 2020 and 62% by 2040 is expected, compared to the BAU scenario. An average growth fraction of 4% per year (AG2) leads to a smoother decline in demand, as illustrated in figure 38. In this scenario the demand contracts by 2% by 2020 and 24% by 2040 respectively. The increase in demand from capture fisheries form 2030 in scenario AG1 and 2048 in AG2 is due to the formulation of the variable, which is based on the assumption that fish from aquaculture will not be used for the production of fish meal and fish oil. The equation of the variable is

MAX(Total Demand For Fish – aquafarming production rate , demand for fish from secondary processing)

Therefore the demand develops according to the demand from the secondary processing sector. This function implements a demand floor for capture fisheries and is indirectly indicating the dependency of aquaculture on capture fisheries, by assuming that farmed fish will not be used for the production of fish oil and fish meal.

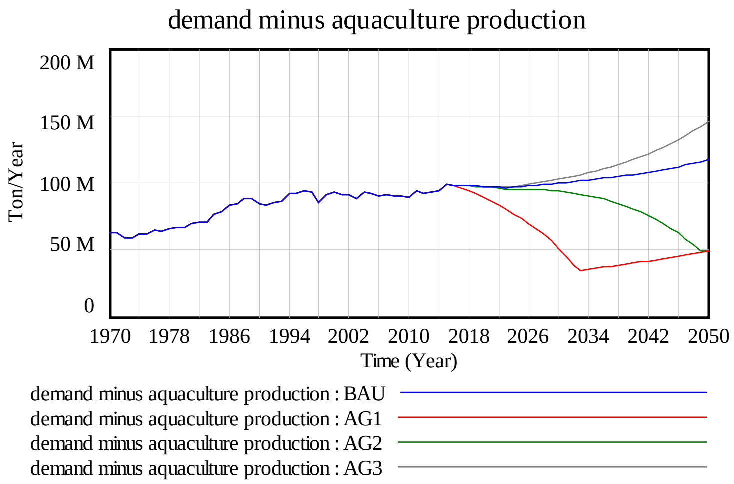

Figure 41: Demand from capture fisheries AG1-AG3

A lower growth rate than in the BAU will increase the demand for fish from capture fisheries above the BAU level. It is increasing gradually so that the demand is 1% higher by 2020, and around 24% higher than in the BAU scenario.

The aquaculture sector can be seen as the secondary production sector of the fish industry, which means that the more fish is produced by aquaculture, the less fish needs to be caught from the seas, and vice versa. In this simulation model this situation is represented until the MAX function that determines the demand from capture fisheries is activated and selects 'demand for fish from secondary processing' as the demand value from capture fisheries. Therefore any increase in aquaculture capacity is reducing the pressure on the natural resource stock.
The level of the fish stock in the scenario AG1 (6%) is around 18% higher by 2050 than in the BAU scenario, and the scenario AG2 (4%) yields and improvement of 6.1% above BAU. Assuming that the growth rate of aquaculture is slowing down (AG3) compared to the BAU scenario, this would reduce the fish stock by an additional 2.1% by 2050.

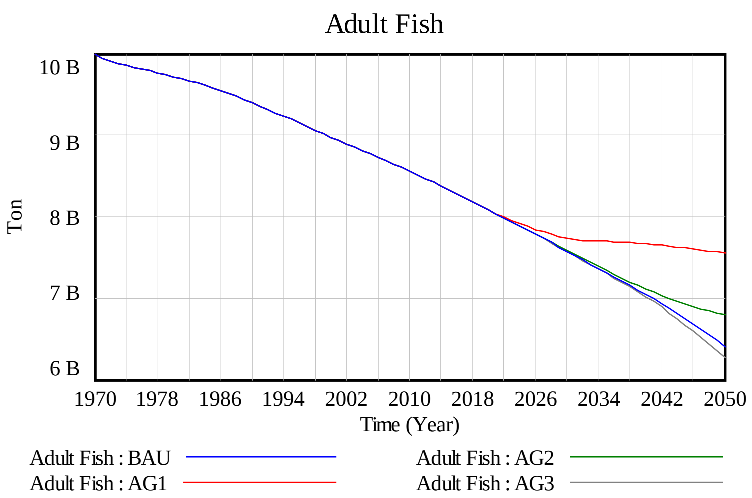

Figure 42: Fish stock level AG1-AG3

Indirect impacts

An increased supply from the aquaculture sector is decreasing the sales price of fish from capture fisheries by producing an oversupply, based on the assumption that there is one price mechanism for fish, no matter what source. Short term impacts until 2025 are small with 1.1% in AG1 and 0.2% in AG2, while prices in the AG1 scenario would be affected significantly by 2050 with a difference of 37.8% compared to the BAU values. However, in the scenarios AG2 and AG3 the changes in sales price for fish from capture fisheries by 2050 are small with a reduction in sales price of 1.4% in the scenario AG2 and an increased sales price of 2.7% in the scenario with a decreased aquaculture supply (AG3).

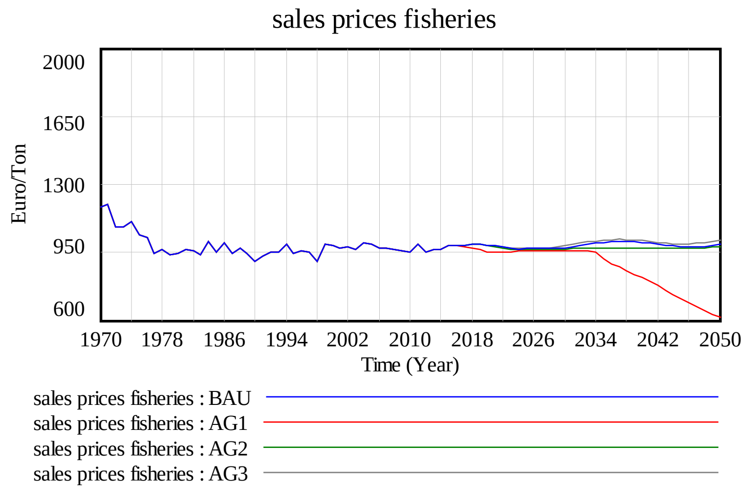

Figure 43: Sales price for fish from capture fisheries AG1-AG3

The decrease in demand from the capture fishery sector is increasing the operations costs of capture fisheries through an increase in idle capacity. This increase of operations costs combined with a reduced sales price causes the profitability of the capture fishery sector to decrease. In the long run the profitability of the sector would decrease by 44.6% and 16.1% in the scenarios AG1 and AG2 respectively. A lower growth in aquaculture, as simulated in AG3, would yield an improvement in profitability of 4.6% by 2050.

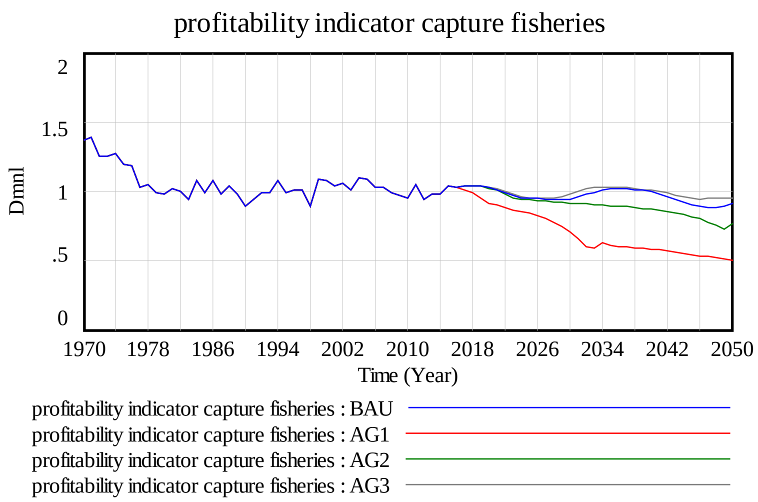

Figure 44: Profitability indicator capture fisheries AG1-AG3

A lower profitability in the scenarios AG1 and AG2, leads to less built capacity and therefore sector employment is lower than in the BAU scenario. By 2025, the indicated employment of the sector is 20.4% lower in AG1 and 1.5% lower in AG2, while the reductions in employment by 2040 are 59.9% and 16% respectively. If aquaculture growth is lower than in the BAU scenario, an increase of 15.6% in indicated employment can be expected by 2050.
The simulation outputs of the scenarios AG1 and AG2 indicate the same fractional reductions in indicated employment. The reason for this is that the demand by 2050 is the same for both scenarios as explained through the formulation of demand for fish from fisheries (demand minus aquaculture production).

Induced impacts

Further development of the aquaculture sector requires the space for building aquaculture capacity, support of policy makers, and the acceptance of society. Land and coastal regions need to be made available for transformation in order to make an increase in aquaculture capacity possible. This will require the application of an integrated approach, since society, especially in Western countries, are still averse to aquaculture facilities within or around habited areas.

Another crucial aspect is the establishment of a safe way for aquaculture that allows for damage control in case of diseases. Due to the high density in ponds and off shore cages, the risk of an infection and transmission of diseases from one fish to the whole population is high. It is important to have facilities in place that allow for isolating individuals and avoid diseases to spread to wild fish stocks. One recent example is the salmon borne ISAV virus, which is an influenza like infection in fish[16]. Next to infectivity, also the development of new fish borne diseases is accelerated in environments with a high population density.

The fact that aquaculture growth is partially dependent on capture fisheries raises the question whether it would be possible to produce fish in aquaculture without the dependence on fish based aquafeeds. Even though the fish-in-fish-out (FIFO) ratio has declined over the last decade, the aquaculture is still dependent on wild fish from the capture sector, which means that the depletion of wild fish stocks also endangers the future of the aquafarming sector.

[16] http://www.foodsafetynews.com/2016/01/most-feared-salmon-virus-has-arrived-in-bc-waters/

5.1.1 Policy recommendations for global fisheries

This section proposes several policy recommendations for the fishery sector. The proposed strategies will need to be adjusted to local circumstances, because the analysis of fisheries in this thesis has been conducted on a global scale.

It is recommended to integrate a decrease in catching capacity with an increase in aquaculture capacity up to a point where the fish stock is stabilized. The aim is to ensure the long term match between demand and supply, and to maximize profitability for capture fisheries through availability of wild fish. The development of alternative livelihoods for former fishermen in a familiar environment has the potential to gain stakeholder support, while reducing policy resistance. A major barrier for the reduction of fishing capacity is that capture fisheries are the livelihood for the fishermen, meaning without fisheries they cannot make a living. An employment in the aquaculture sector would need to be supported, which could be done by using some of the subsidies that are at the moment used to maintain the BAU scenario and pay for idle capacity. Making the demand for fish from capture fisheries a function of the demand from the aquaculture sector should be the aim in the long run. This would reduce the pressures on the natural resources and give the wild fish stocks the chance to recover.

Idle capacity and by-catch have been identified as two aspects of capture fisheries that harm the sectors profitability itself. Though idle capacity on a global scale cannot be avoided, especially in deep water fisheries where no specific national sovereignty is claimed, the introduction of capacity restrictions on a national, or even, local level is recommended. According to the simulation outputs, capacity reductions are a promising strategy to re-establish the profitability of the sector, even though the increased profitability comes at the cost of jobs. Enhancing the profitability allows to reinvest the subsidies on fishing capacity into the expansion of aquaculture or the protection of marine environments. Even though this strategy is recommendable, more research is needed to determine i) whether it would work under local circumstances, and if so ii) to the required reductions in specific regions or on country level.

More research is also needed regarding the aspect of by-catch. As comes forth from the analysis of the simulation results, even a 10% by-catch factor can have far reaching impacts depending on the scale on which this issue occurs. Though an inefficiency of 10% and 25% was simulated, these numbers are representative for the average of the whole industry. This further implies that quotas that are determined to catch a specific amount of one species are useful, but not sufficient to protect the resource base, because it is impossible to catch just one species. Stakeholder consultation and involvement is recommended in order to design useful by-catch mitigation strategies. This would at the same time signal that this is an issue of importance and not just an individual problem. Currently by-catch mitigation is more an individual responsibility than an imperative for the industry, and large trawlers basically discriminate solely through mesh size and dispose by-catch into the sea when sorting the fish, which creates a huge loss of biomass each year.

5.2 Scenarios in the aluminium model

To determine the changes in the system that are caused by implementing the following policy options, a list of outputs that the model generated for specific indicators for each scenario run will be provided. In this table the different outcomes will be compared to the BAU scenario and fractional changes will be determined. An overview of the following indicators will be provided:

1) **Changing recovery fractions (CRF): What are the effects of the amount of semi-fabricator and fabricator scrap on the demand for primary Aluminium?**

In the IAI's Global Mass Flow model a recovery fraction of 100% of internal scrap is assumed. This assumption has an effect on how the demand for primary aluminium develops, since secondary aluminium is the cheaper product and therefore consumed first. The amount of scrap depends on the utilization fractions of the semi fabricator and the fabricator sector and the total shipments to the respective sectors. In the BAU scenario all the internal scrap is recovered and accumulated in the stock of secondary aluminium. Due to the assumption that secondary aluminium is consumed first the amount of accumulated internal scrap has a direct influence on the amount of primary aluminium, and subsequently on the primary production capacity. To simulate a situation where not all the internal scrap is recovered, the amount of internal scrap collected will be multiplied by fraction that decreases the amount of collected internal scrap by 5% (CRF1) and 10% (CRF2) respectively over the whole simulation run.

2) **Change in utilization fractions (CUF): What total reduction in CO2 emissions can be expected if the energy intensity of the process decreases at a historical rate? What savings could be achieved in a hypothetical polluter pays case?**

This scenario evaluates an increase in efficiency in the processing of aluminium. For this purpose, all the utilization fractions that are used to calculate the internal scrap of the different sectors are increased by 5% (CUF1) and 10% (CUF2) respectively. This scenario examines the impacts that efficiency gains in the supply chain have on the industry as a whole. It is assumed that changes in the utilization fractions will have a direct effect on the total demand for aluminium on industry level, but also have indirect downstream effects on employment and CO2 emissions.

3) **CO2 efficiency (CO2E): Can a linear increase in energy efficiency (as took place historically) make up for the additional costs of rising electricity prices? What would be the required energy efficiency/necessary subsidies?**

Due to its high energy requirements this poses a threat for the competitiveness of the primary aluminium industry compared to substitute products, since higher prices will lead to higher operational costs and therewith lower margins. According to the Peak Oil news board[17] the costs of all fossil fuel sources are going to increase in the future.

The energy intensity of the primary aluminium production process have been decreasing from around 17,000 kWh per ton of aluminium in 1980 down to almost 14,000 kWh per ton in 2014, representing an average decrease of 0.5% p.a. The consumption of electricity has a direct influence on the amount of indirect CO2 emissions of the production process. In this scenario different efficiency gains will be simulated. Future reductions of i) BAU case, 0.5% p.a. , ii) 1% p.a., and iii) 2% p.a. are simulated and the effect on total life cycle CO2 emissions reported – the respective scenarios will be BAU, CO2E1 and CO2E2. These scenarios will show whether a continued reduction according to the historical BAU trend (0.5% p.a.) is sufficient to counteract the costs that would be caused by increasing energy prices. If not, it will be evaluated what efficiency gains in terms of energy intensity would be required to maintain the status quo regarding the payments for electricity consumption (CO2E3).

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17 http://peakoil.com/alternative-energy/trends-in-the-cost-of-energy

1) CRF1 and CRF2

In the scenarios CRF1 and CRF2 the effects of changes in the recovery fraction of internal scrap (semi fabrication and fabrication) is tested. This is to test the deviations that the systems' behaviour would have if collection rates deviate from the Global Mass Flow model of the IAI. Reductions in recovery rate of 5% and 10% respectively were tested, under the assumption that the recovery rate of internal scrap in the BAU is 100%. For this purpose, the variables "fabricator scrap collected" and "semi fabricator scrap collected" were multiplied with a fraction "CRF " with the value of 0.95 (CRF1) and 0.90 (CRF2).

Table 18 underneath presents the values for certain variables and their deviation when compared to the BAU scenario.

		Model outputs by scenario. Changes are differences relative to the BAU value.					
Name	**Scenario**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
primary production capacity million tons per year	**BAU**	**59.9**	**78.4**	**88.6**	**101.2**	**130.8**	**173.6**
	CRF1	62.7	82.4	93.3	107.0	140.3	184.3
	Δ CRF1	*4.7%*	*5.1%*	*5.3%*	*5.7%*	*7.2%*	*6.2%*
	CRF2	65.4	86.5	98.0	112.8	148.2	194.9
	Δ CRF2	*9.3%*	*10.3%*	*10.7%*	*11.5%*	*13.3%*	*12.3%*
demand for primary aluminium million tons per year	**BAU**	**63.1**	**81.5**	**89.3**	**101.9**	**132.3**	**172.8**
	CRF1	66.3	85.7	94.3	107.8	140.3	183.5
	Δ CRF1	*5.1%*	*5.1%*	*5.6%*	*5.8%*	*6.0%*	*6.2%*
	CRF2	69.5	89.8	99.4	113.7	148.3	194.2
	Δ CRF2	*10.1%*	*10.3%*	*11.2%*	*11.6%*	*12.1%*	*12.4%*
total aluminium recovery rate million tons per year	**BAU**	**84.0**	**109.4**	**131.3**	**156.2**	**214.6**	**292.7**
	CRF1	80.6	104.9	126.1	150.0	206.3	281.5
	Δ CRF1	*-4.1%*	*-4.1%*	*-4.0%*	*-4.0%*	*-3.9%*	*-3.8%*
	CRF2	77.2	100.4	120.9	143.8	198.0	270.4
	Δ CRF2	*-8.1%*	*-8.2%*	*-8.0%*	*-7.9%*	*-7.7%*	*-7.6%*
total indicated employment in million FTE per year	**BAU**	**0.62**	**0.80**	**0.94**	**1.09**	**1.46**	**1.96**
	CRF1	0.62	0.81	0.95	1.10	1.48	1.98
	Δ CRF1	*0.0%*	*0.9%*	*0.9%*	*1.0%*	*1.5%*	*1.0%*
	CRF2	0.62	0.82	0.96	1.12	1.50	2.00
	Δ CRF2	*0.6%*	*1.7%*	*1.8%*	*2.0%*	*2.5%*	*2.1%*
accumulated total life-cycle CO2 emissions gigaton per year	**BAU**	**10.9**	**13.9**	**17.7**	**22.0**	**32.4**	**45.9**
	CRF1	11.4	14.6	18.5	23.0	34.0	48.4
	Δ CRF1	*4.4%*	*4.5%*	*4.6%*	*4.6%*	*4.9%*	*5.3%*
	CRF2	11.9	15.2	19.3	24.1	35.6	50.8
	Δ CRF2	*8.8%*	*9.0%*	*9.2%*	*9.4%*	*10.0%*	*10.5%*
total electricity consumption aluminium production billion kWh per year	**BAU**	**886.3**	**1160.6**	**1312.5**	**1501.3**	**1943.5**	**2579.9**
	CRF1	926.0	1218.0	1379.9	1584.2	2078.4	2732.7
	Δ CRF1	*0.0*	*4.9%*	*5.1%*	*5.5%*	*6.9%*	*5.9%*
	CRF2	965.7	1275.5	1447.3	1667.2	2191.9	2885.3
	Δ CRF2	*0.0*	*9.9%*	*10.3%*	*11.1%*	*12.8%*	*11.8%*

Table 18 – Results of the changes in utilization rates scenarios

Direct impacts

Changes in the recovery fraction have a direct impact on the demand for primary aluminium. Through the reduction in recovered aluminium, the burden is shifted towards the primary production sector. Therefore the capacity adjustment loop causes production capacity to grow. It increases gradually compared to the BAU scenario, since the primary production sector needs to make up for the difference in recovered scrap. Figure 45 shows the primary production rate (blue line) and the total aluminium recovery rate (red line) of the BAU and the CRF2 scenario respectively. Those two outputs show that the gap between recovered rate and primary production rate in 2050 shrinks from roughly 120 million tons per year to 80 million tons per year.

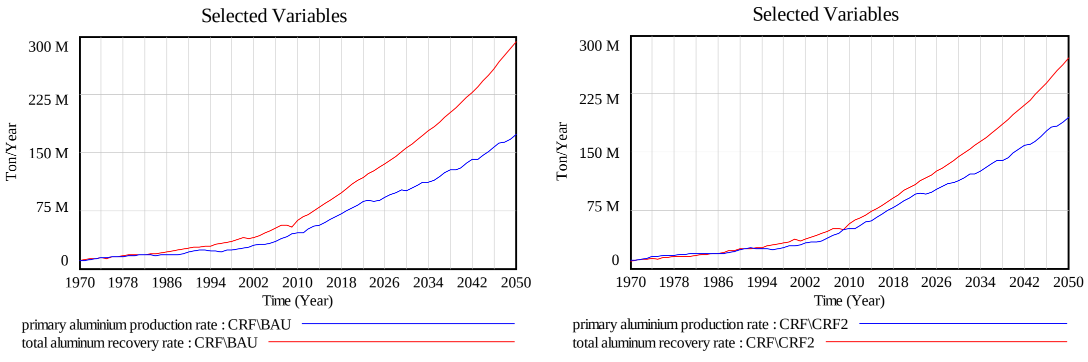

Figure 45: Comparison primary production to recovery rate BAU and CRF2

In the case of CRF1 the difference in demand for primary aluminium by 2050 is 6.2%, and 12.4% in the CRF2 scenario. Primary production capacity increases by 6.2% and 12.4% respectively, thus following the increasing trend in the demand for primary aluminium. In terms of quantity, the difference in demand and production capacity for primary aluminium by 2050 is approximately 10 million tons per year (CRF1) and 20 million tons per year (CRF2).
The difference in the total aluminium recovery rate, in 1970 5% (CRF1) and 10% (CRF2) lower than in the BAU, is decreasing over time and by 2050 the remaining difference is 3.8% and 7.5% respectively. This decrease is caused by the amount of old scrap which is recovered and recycled from the different sectors. Figure 46 illustrates the share of old aluminium scrap to internal aluminium scrap. The higher the level of accumulation of aluminium in society is, the more old scrap can be recovered. Furthermore the production of internal scrap is dependent on the rate at which primary aluminium is produced.

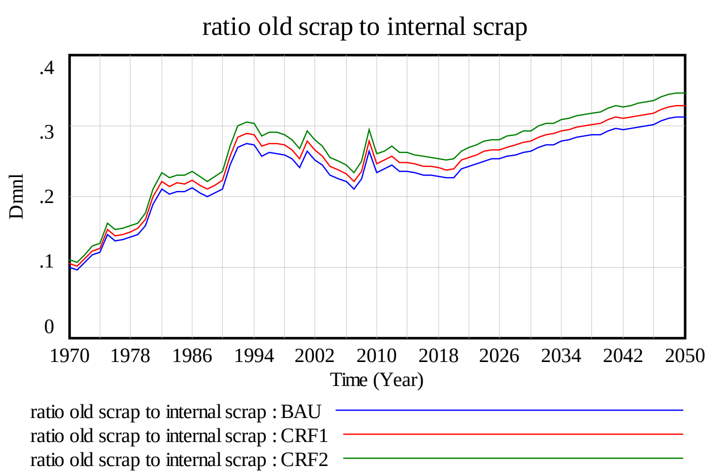

Figure 46: Ratio old scrap to internal scrap BAU and CRF1+2

The increase in the beginning of the graph is caused by the increasing amount of old scrap aluminium that is recovered from society. The decrease between 1994 and 2020 is caused by a steeper increase in primary aluminium production than before, which makes more internal scrap available. Once the production of primary aluminium is increasing at a steady pace, from 2020 onwards, the recovery rate from society is higher than the amount of scrap available from (semi-) fabrication.

Indirect impacts

The changes in demand for primary aluminium also have second order effects on employment and CO2 emissions of the aluminium industry. While the production output stays the same, the changes in employment are caused by the difference in indicated employment per type of capacity, and the increased level of primary aluminium production capacity. The shift towards primary production would create additional jobs due to a higher indicated employment per ton of aluminium in the primary production sector. The average employment per ton of primary aluminium is 0.0043 FTE per ton of aluminium produced, while the average employment in aluminium recycling is around 0.0023 FTE per ton of aluminium. By 2050, a 5% decrease in recovery (CRF1) would create an additional 20,000 jobs (1% above BAU), and the 10% decrease in CRF2 would create around 40,000 new jobs (2.1%) above BAU.

The increased amount of primary aluminium also increases the carbon footprint of the industry. CO2 emissions are increased by 5.3% in the CRF1 scenario, and by 10.5% in the CRF2 scenario. These increases are mainly caused by the increased energy consumption for the production of primary aluminium.

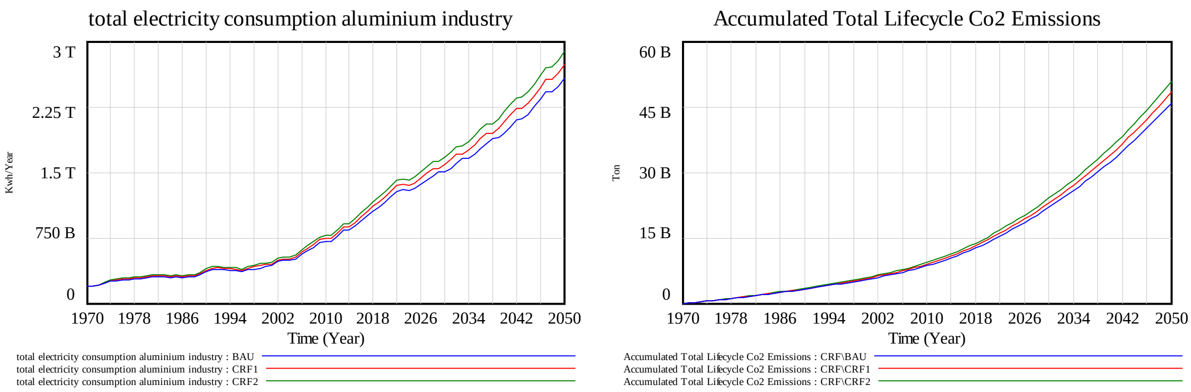

Figure 47: Electricity consumption and total CO_2 accumulation CRF1+2

Induced impacts

A reduction in the reduction in the amount of recovered aluminium means that a higher primary production is required to meet the demand for aluminium. In the long run this development would lead to a higher environmental impact than there otherwise would be, mainly caused through the electricity consumption and increased direct process emissions. This effect would work its way through the whole supply chain and amplify the environmental impact further by increasing the demand for alumina and ultimately the amount of bauxite to be mined.

An increase in primary production combined with an expected increase in energy prices is likely to increase the sales price of aluminium. This would make the market share of aluminium vulnerable to substitutes with comparable quality and lower prices. To evaluate this further, the structure of the price and demand would need to be modelled in more detail .

2) CUF1 through CUF4

In this scenario the utilization fractions of the semi fabrication and fabrication sector will be increased by 5% (CUF1) and 10% (CUF2), and decreased by 5% (CUF3) and 10% (CUF4) from the year 2015 onwards. The aim is to evaluate the effect of efficiency changes in the aluminium processing sectors on overall industry performance.

To obtain the desired simulation results, additional variables that allow increasing or decreasing the utilization rates (min 0; max 1) and a policy switch have been added to the structure of the model. The feedback to the demand for aluminium is introduced by calculating a ratio of the shipments of the BAU scenario (old utilization rate) and the shipments of the respective scenarios CUF1-4 (4 different utilization rates). Assuming that the demand for finished goods does not change, the changes in utilization rates have an effect on the total demand of aluminium. The effect on demand is calculated by doing a onetime adjustment in 2016 ('overnight changes in efficiency'), and afterwards multiplying the changes in demand with a conversion factor.

The change in demand for aluminium is calculated in the table underneath by comparing the respective demand values to the values of the BAU scenario.

Model outputs by scenario. Changes are differences relative to the BAU value.

Name	Scenario	2015	2020	2025	2030	2040	2050
primary production capacity	**BAU**	**60.6**	**78.3**	**90.9**	**103.7**	**133.9**	**175.5**
million tons per year	CUF1	60.6	74.8	90.2	102.2	131.7	172.9
	Δ CUF1	*0.0%*	*-4.5%*	*-0.8%*	*-1.4%*	*-1.6%*	*-1.5%*
	CUF2	60.6	74.4	89.6	101.3	130.2	171.2
	Δ CUF2	*0.0%*	*-5.0%*	*-1.4%*	*-2.3%*	*-2.7%*	*-2.5%*
	CUF3	60.6	86.6	91.7	105.8	136.8	179.3
	Δ CUF3	*0.0%*	*10.6%*	*0.8%*	*2.0%*	*2.2%*	*2.1%*
	CUF4	60.6	103.1	101.9	107.9	141.0	184.7
	Δ CUF4	*0.0%*	*31.7%*	*12.1%*	*4.0%*	*5.4%*	*5.2%*
demand for primary aluminium	**BAU**	**63.1**	**81.5**	**89.3**	**101.9**	**132.3**	**172.8**
million tons per year	CUF1	63.1	80.0	88.1	100.5	130.4	170.1
	Δ CUF1	*0.0%*	*-1.9%*	*-1.3%*	*-1.4%*	*-1.5%*	*-1.5%*
	CUF2	63.1	79.0	87.4	99.6	129.2	168.4
	Δ CUF2	*0.0%*	*-3.1%*	*-2.2%*	*-2.3%*	*-2.4%*	*-2.5%*
	CUF3	63.1	83.6	91.0	104.0	135.1	176.5
	Δ CUF3	*0.0%*	*2.6%*	*1.9%*	*2.0%*	*2.0%*	*2.2%*
	CUF4	63.1	86.5	93.6	106.9	139.0	181.9
	Δ CUF4	*0.0%*	*6.2%*	*4.7%*	*4.9%*	*5.0%*	*5.3%*
total aluminium recovery rate	**BAU**	**84.0**	**109.4**	**131.3**	**156.2**	**214.6**	**292.7**
million tons per year	CUF1	84.0	87.6	105.9	126.4	174.8	239.2
	Δ CUF1	*0.0%*	*-19.9%*	*-19.4%*	*-19.0%*	*-18.6%*	*-18.3%*
	CUF2	84.0	69.7	85.0	102.0	142.0	195.3
	Δ CUF2	*0.0%*	*-36.3%*	*-35.3%*	*-34.7%*	*-33.8%*	*-33.3%*
	CUF 3	84.0	136.3	162.8	192.9	264.0	358.9
	Δ CUF3	*0.0%*	*24.6%*	*24.0%*	*23.5%*	*23.0%*	*22.6%*
	CUF4	84.0	170.5	202.7	239.6	326.7	443.1
	Δ CUF4	*0.0%*	*55.9%*	*54.4%*	*53.4%*	*52.2%*	*51.4%*
total CO_2 emission rate	**BAU**	**685.8**	**888.5**	**1039.8**	**1198.2**	**1572.0**	**2083.4**
gigaton per year	CUF1	685.8	816.0	984.3	1127.8	1476.0	1956.5
	Δ CUF1	*0.0%*	*-8.2%*	*-5.3%*	*-5.9%*	*-6.1%*	*-6.1%*
	CUF2	685.8	777.7	938.9	1072.5	1400.1	1856.7
	Δ CUF2	*0.0%*	*-12.5%*	*-9.7%*	*-10.5%*	*-10.9%*	*-10.9%*
	CUF3	685.8	1012.5	1107.0	1287.3	1693.0	2243.9
	Δ CUF3	*0.0%*	*14.0%*	*6.5%*	*7.4%*	*7.7%*	*7.7%*
	CUF4	685.8	1221.2	1272.9	1396.0	1850.9	2453.6
	Δ CUF4	*0.0%*	*37.4%*	*22.4%*	*16.5%*	*17.7%*	*17.8%*

total indicated employment	**BAU**	**0.62**	**0.80**	**0.95**	**1.10**	**1.47**	**1.97**
in million FTE per year	CUF1	0.62	0.72	0.86	0.99	1.32	1.77
	Δ *CUF1*	*0.0%*	*-10.9%*	*-9.7%*	*-10.0%*	*-10.1%*	*-10.1%*
	CUF2	0.62	0.65	0.78	0.91	1.20	1.61
	Δ *CUF2*	*0.0%*	*-18.9%*	*-17.6%*	*-18.1%*	*-18.3%*	*-18.3%*
	CUF3	0.62	0.94	1.06	1.24	1.66	2.22
	Δ *CUF3*	0.0%	16.7%	12.0%	12.5%	12.6%	12.6%
	CUF4	0.62	1.13	1.25	1.42	1.90	2.54
	Δ *CUF4*	*0.0%*	*40.5%*	*31.4%*	*28.2%*	*28.9%*	*28.9%*

Table 19 – Results of the changes in utilization rates scenarios

Changing the utilization rates has effects on the primary aluminium production sector, recovery rates of internal scrap, total life cycle CO2 emissions and industry employment.

Direct impacts

Primary aluminium production capacity and demand for primary aluminium

Increasing or decreasing the utilization fractions has different implications for the production capacity of primary aluminium. With increased utilization fractions (CUF1+2) an immediate decrease of production capacity compared to the BAU value can be observed. The reason is that, assuming the changes in efficiency happen overnight, the demand for primary aluminium is reduced. This is because the fabrication sector needs overall less aluminium to produce the same output. While initial reductions for 2020 are between 4.5% (CUF1) and 5% (CUF2), the difference to the BAU scenario in 2050 is 1.5% and 2.5% respectively. The difference in production capacity is a reduction of 2.6 million ton per year in the CUF1 scenario, and 4.3 million ton per year in the CUF2. The red line in figure 45 represents the 5% efficiency increase, while the green line represents efficiency gains of 10%. It is visible that both runs score slightly lower than the BAU scenario (blue line).

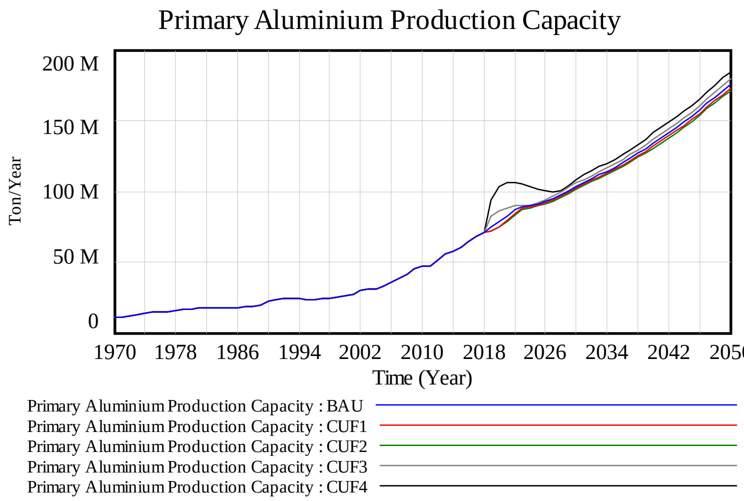

Figure 48: Primary aluminium production capacity CUF 1-4

The grey and the black line represent the two scenarios in which the utilization rates were decreased by 5% (CUF3) and by 10% (CUF4) respectively. In both scenarios an increase in primary production capacity can be observed. CUF3 shows temporarily 10.6% more primary production capacity compared to the BAU simulation run in 2020, and during the same period the CUF4 scenario shows a temporary increase of 31.7% above the BAU values. This represents an annual difference in capacity of 12.6 million tons in CUF3, and 38.7 million tons in CUF4. In the long run the primary production capacity is 2.1% (CUF3) and 5.2% (CUF4) higher by 2050.

This increase in capacity is caused by the peak in demand for primary aluminium around 2016, which is translated into desired capacity and ultimately built capacity. This peak is caused by the formulation of the model. The efficiency gains are implemented instantaneously, and total demand for aluminium is adjusted instantaneously as well. This correction of total demand creates the dip (CUF1 and CUF2) and the peaks (CUF3 and CUF4) in the demand for primary aluminium. In the case of CUF3, and especially CUF4, the sudden peak in demand for primary aluminium leads capacity to overshoot. In CUF3 the system returns to steady state behaviour around the year 2025, while it takes until 2028 in the CUF4 scenario.

Overall efficiency gains in the processing of aluminium of 5% and 10%, lead to a reduction of demand for primary aluminium of 1.5% and 2.5% by 2050 respectively. A decrease in processing efficiency of 5% and 10% results in an increase for primary aluminium of 2.1% and 5.2% respectively.

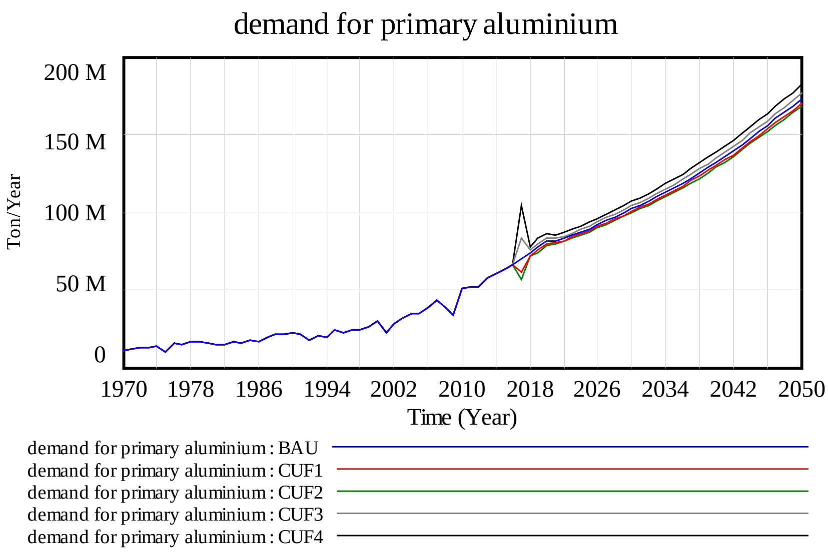

Figure 49: Demand for primary aluminium CUF 1-4

Recovery of aluminium

Figure 50 shows the total recovery rate of aluminium scrap for the BAU and CUF1 through CUF4. These changes are solely caused by changes in the amount of internal scrap generated. The efficiency gains in CUF1 and CUF2 decrease the amount of recovered scrap by around 18.3% and 33.3% respectively by 2050. The increased utilization rates of the processing sector leads to less internal scrap that is generated, which causes the aluminium recovery rate to decline. In the scenarios CUF3 and CUF4 the total aluminium recovery rate is increased by approximately 22.6% and 51.4% respectively, which is consistent with a higher demand for primary aluminium. More primary aluminium is needed due to a reduced input-output ratio of the processing sector.

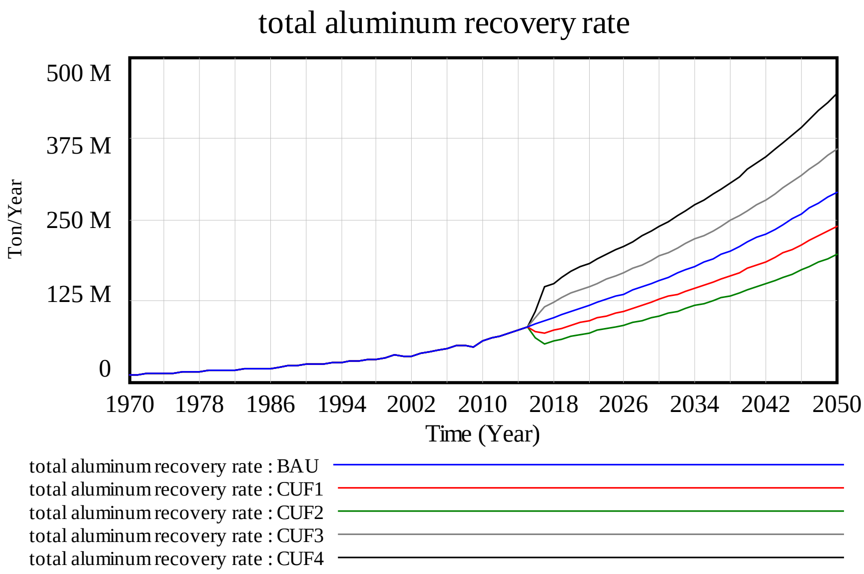

Figure 50: Aluminium recovery rate CUF1-4

Indirect impacts

Annual CO2 emissions and employment

The change in utilization fractions has an effect on the annual total lifecycle CO_2 emissions and the indicated employment of the aluminium sector. By 2020 CUF1 and CUF2 reduce the total CO_2 emissions by 8.2% and 12.5% respectively. This represents a reduction of 72.5 and 110.8 gigatons in annual emissions. In the long run the annual emission rate is reduced by 6.1% (126.9 gigatons per year) in the CUF1 scenario, and by 10.9% (226.7 gigatons per year) in the CUF2 scenario.

By 2020, the total annual CO_2 emissions are increased in the scenarios CUF3 (14%) and CUF4 (37.4%). The short term peak in CO_2 emissions is caused by the increasing production of primary aluminium which is peaking between 2016 and 2025 in CUF3 and 2016 and 2029 in CUF4 respectively. In the long run, a decrease in processing efficiency is increasing the annual CO_2 emission rate by 7.7% in the case of CUF3 and by 17.8% in the CUF4 scenario. Figure 51 shows the aluminium productions' total lifecycle CO_2 emission rate.

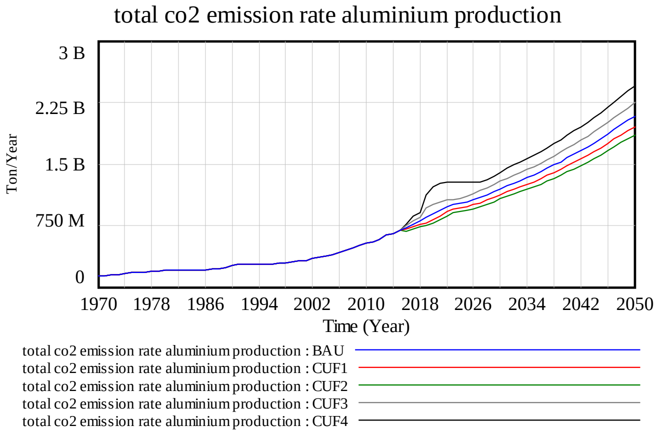

Figure 51: Total CO_2 emissions aluminium production CUF1-CUF4

Changes in the utilization fraction also have an effect on the indicated employment in the aluminium industry. While an increase in efficiency decreases the amount of full time employees by 10.1% (CUF1) and 18.3% (CUF2) respectively, a decrease in efficiency causes the total employment to increase by 12.6% (CUF3) and 28.9% (CUF4) compared to the BAU scenario. Figure 52 shows the indicated employment of all five scenarios.

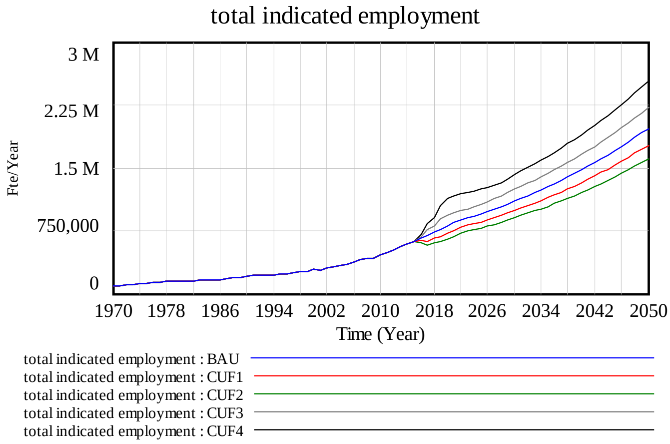

Figure 52: Total indicated direct employment aluminium industry CUF 1-CUF4

The changes in employment are mainly caused through the difference in internal scrap that is produced. Figure 50 shows the employment in the primary production sector and the recycling sector respectively. Furthermore it should be noted that the increase in employment comes at environmental cost. While a less efficient aluminium processing industry is creating more scrap, and therewith more employment in the secondary aluminium industry (recycling). This development has negative side effects on the environment. A decrease in efficiency causes an increased CO_2 emission rate caused by an increased production rate of primary aluminium in order to make up for the change in demand. Furthermore, the energy balance of the recycled aluminium will increase as well. During the recycling process additional energy is used to prepare the metal for reuse. This energy is added to the energy which is already bound within it from the primary production process. Internal scrap can also be regarded as unused primary aluminium. Recycling it adds an additional 5% of energy to the energy balance of the metal and therewith increases its life cycle impact. That way the footprint of the metal increases while part of it has not even been in use yet.

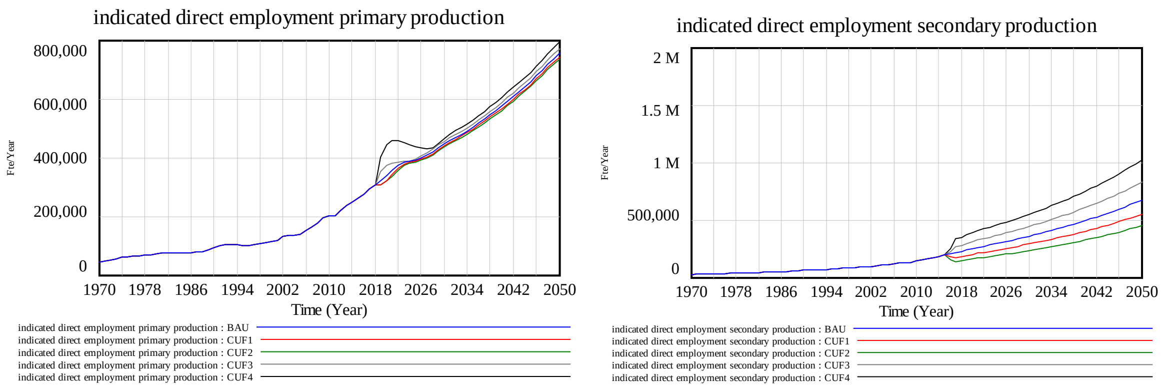

Figure 53: Indicated direct employment primary and secondary production CUF 1-4

3) Price: CO2E1 and CO2E2

Historical data on average global energy intensity of the electrolysis process is available until 2014. The annual reductions of 0.5% (BAU), 1% (CO2E1), and 2% (CO2E2) will take place from the year 2015 through 2050.

Note that an annual reduction of 2% would reduce the energy intensity to less than 7,000 kWh per ton produced. This is only around 1,000 kWh above the theoretical minimum energy intensity of 5,990 kWh per ton (Hall-Héroult carbon anode reduction) that is required to produce one ton of aluminium (DOE, 2007).

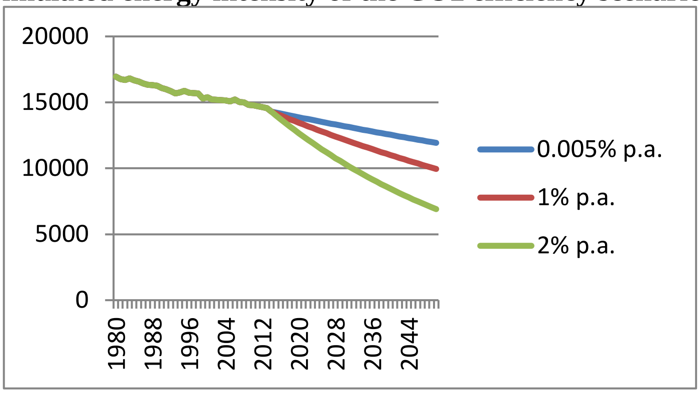

Figure 54: Simulated development of energy intensity BAU and CO2E1+2 (unit: kWh / ton)

Figure 54 shows the energy intensity for the production of one ton of primary aluminium in the respective scenarios. Table 20 shows the model outputs of the CO2 efficiency scenarios.

		Model outputs by scenario. Changes are differences relative to the BAU value.					
Name	**Scenario**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
energy consumption electrolysis billion kWh per year	**BAU**	**874.15**	**1,102.92**	**1,248.51**	**1,388.57**	**1,704.78**	**2,126.50**
	Co2E1	869.76	1,070.08	1,181.20	1,281.03	1,495.49	1,773.78
	Δ CO2E1	*-0.5%*	*-3.0%*	*-5.4%*	*-7.7%*	*-12.3%*	*-16.6%*
	Co2E2	860.97	1,006.84	1,056.39	1,088.96	1,148.54	1,230.76
	Δ CO2E2	*-1.5%*	*-8.7%*	*-15.4%*	*-21.6%*	*-32.6%*	*-42.1%*
total CO_2 emission rate gigaton per year	**BAU**	**683.7**	**872.2**	**1,005.6**	**1,142.2**	**1,457.3**	**1,880.2**
	Co2E1	681.6	856.4	973.1	1,090.2	1,356.2	1,709.8
	Δ CO2E1	*-0.3%*	*-1.8%*	*-3.2%*	*-4.5%*	*-6.9%*	*-9.1%*
	Co2E2	677.3	825.8	912.8	997.4	1,188.6	1,447.4
	Δ CO2E2	*-0.9%*	*-5.3%*	*-9.2%*	*-12.7%*	*-18.4%*	*-23.0%*
carbon tax payments billion Euro per year	**BAU**	**5.45**	**6.92**	**7.91**	**8.86**	**11.01**	**13.89**
	Co2E1	5.43	6.76	7.57	8.31	9.94	12.08
	Δ CO2E1	*-0.4%*	*-2.4%*	*-4.3%*	*-6.2%*	*-9.7%*	*-13.0%*
	Co2E2	5.39	6.44	6.93	7.33	8.17	9.31
	Δ CO2E2	*-1.2%*	*-7.0%*	*-12.4%*	*-17.2%*	*-25.8%*	*-33.0%*
electricity costs per ton of Aluminium billion Euro per year	**BAU**	**830.5**	**1,076.5**	**1,257.3**	**1,500.6**	**1,427.3**	**1,357.5**
	Co2E1	826.4	1,044.5	1,189.6	1,384.4	1,252.0	1,132.3
	Δ CO2E1	*-0.5%*	*-3.0%*	*-5.4%*	*-7.7%*	*-12.3%*	*-16.6%*
	Co2E2	818.0	982.8	1,063.9	1,176.8	961.6	785.7
	Δ CO2E2	*-1.5%*	*-8.7%*	*-15.4%*	*-21.6%*	*-32.6%*	*-42.1%*

Table 20 – Results of the energy efficiency scenarios

Direct impacts

Improvements in energy intensity by 1% (CO2E1) annual reduction would reduce the yearly electricity consumption by around 17%, and an annual reduction 2% (CO2E2) would reduce the electricity consumption by around 42.1% by the year 2050.

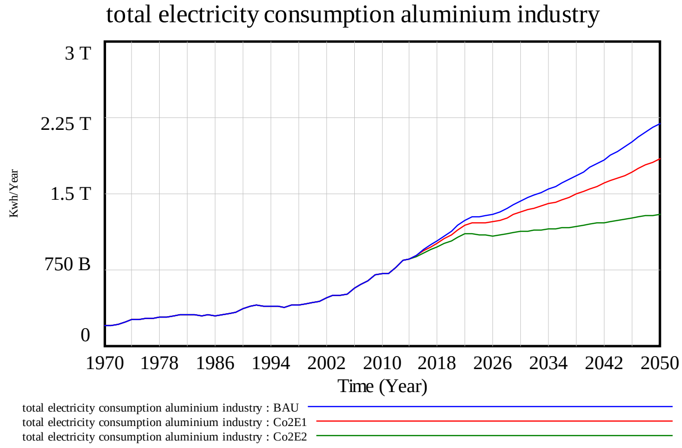

Figure 55: Total electricity consumption BAU and CO2E1+2

The average electricity costs per ton of aluminium are increasing through all three scenarios, but increased energy efficiency leads to an improvement over the BAU. Reductions by 2030 are 7.7% in scenario CO2E1 and 21.6% in CO2E2 respectively, yet even a 2% reduction in energy intensity is not sufficient to keep the electrolysis costs constant. The obtained trend on the development of energy prices reaches until 2030, and after that the values are kept constant. After 2030 the average electricity costs per ton of aluminium decrease due to further gains in energy efficiency while prices stay constant. Even though the costs per kWh increase, the respective percentages in which the costs are reduced are relative to the reduction in energy intensity.

Figure 56 shows the development of the average electricity costs per ton of aluminium in the three scenarios. It can be observed that the costs per ton are increasing in all scenarios. This means that none of the tested reductions in energy intensity is sufficient to avoid the total costs from increasing, even if prices stop increasing by 2030. The necessary reduction in energy intensity will be evaluated in the next section.

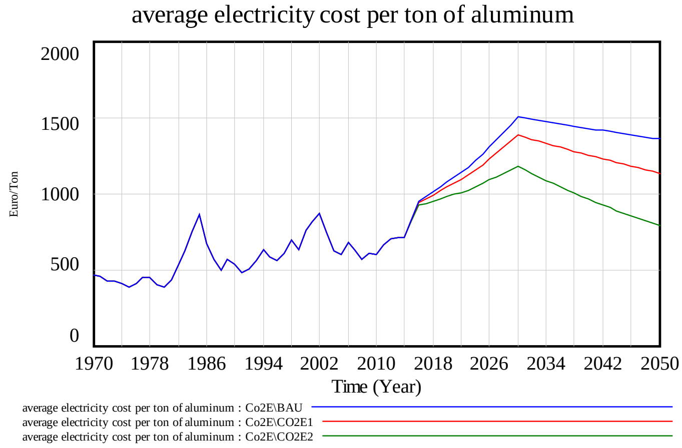

Figure 56: Average electricity costs per ton of aluminium BAU and CO2E1+2

Another direct effect of the reduction in energy intensity is the annual CO_2 emission rate. Improvements of energy intensity reduce the annual CO_2 emission rate by 4.7% (CO2E1) and 13% (CO2E2) by the year 2030, and 9.3% and 23.6% respectively by 2050.

Indirect impacts

According to the model output, the total reduction in annual CO_2 emissions compared to the BAU scenario would be 2.38 gigatons in the CO2E1, and 6.37 gigatons in the CO2E2 scenario. With an average energy intensity reduction of 1% p.a. (CO2E1) the total CO_2 emissions would be reduced by 170.4 megatons per year, which represents a 9.1% reduction compared to the BAU scenario by 2050. A 2% reduction per year (CO2E2) would yield a 23% reduction in annual CO_2 emissions by 2050, or a total reduction of 432.8 million tons. Figure 57 shows the total accumulated CO_2 emissions over the whole simulation period. From 2015 onwards, the effects of reduced electricity consumption and therewith a reduced CO_2 emissions become visible by the diversion of the three lines.

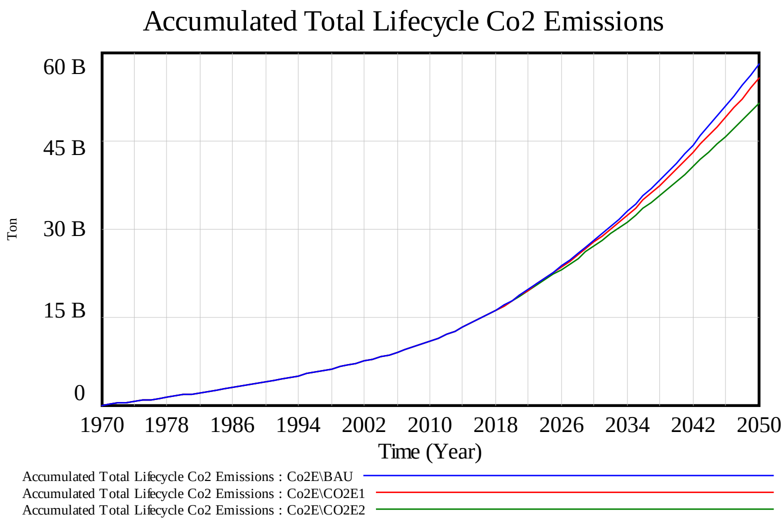

Figure 57: Accumulated CO_2 emissions aluminium industry BAU and CO2E1+2

The hypothetical carbon tax was calculated by multiplying a roughly estimated mean value of 10€ per ton of CO_2 (Co2e) emitted with the total lifecycle emissions of aluminium production. The carbon tax payments develop in a non-linear fashion compared to the reductions in energy intensity. This is because it is based on the total CO_2 emissions, and not just on the indirect CO_2 emission which are affected by the efficiency gains. The industry savings in the case of a carbon tax are 22.13 billion € (CO2E1) and 58.8 billion € (CO2E2), or around 12% and 33% respectively compared to BAU.

The hypothetical savings have an effect on the operational costs of the primary aluminium industry. A 1% annual reduction in energy intensity would reduce the extra costs of the industry by around 13%, while a 2% reduction would yield savings around 30% compared to the BAU scenario. This means that as soon as a global carbon tax system is introduced, the aluminium industry would benefit from being as energy efficient as possible. Figure 58 illustrates the development of the carbon tax payments in the BAU and CO2E1+2 scenarios.

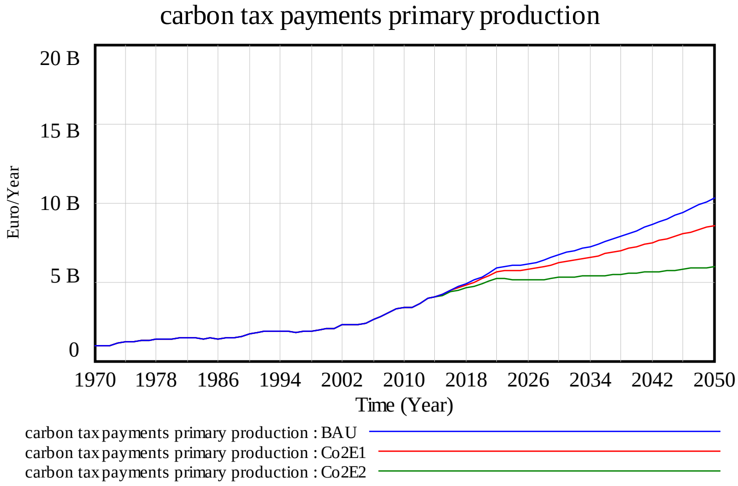

Figure 58: Carbon tax payments aluminium industry BAU and CO2E1+2

Induced impacts

Reductions in energy intensity are an imperative for the primary aluminium industry, for economical as environmental reasons alike. However, even a 2% reduction in energy intensity would not make up for the extra electricity costs in the case that electricity prices develop as forecasted. Increasing electricity costs are likely to reduce the operational surplus, and either cause aluminium prices to rise or force the most energy intense aluminium smelters out of business. This would have implications for industry employment and production quantities that have ultimately the potential to accelerate research and development for more affordable substitutes for aluminium. Another way to deal with the problem of energy costs is to move away from fossil fuels and to use energy from green energy sources.

From the recycling point of view, the development of energy prices is likely to shift the burden towards the secondary aluminium production loop. Possible developments could be that a higher price for aluminium accelerates the implementation of more efficient aluminium recycling programmes, or advanced aluminium recycling processes. It is also possible that this would foster the emergence of new business models with regard to the aluminium that is utilized in society, though this would be constrained to the major sectors as transportation, construction, machinery and cable, where different ownership concepts could be tested.

3.1) CO2E3: What would be the required reduction in energy intensity to keep electricity costs per ton of aluminium constant?

The forecasted energy prices from the Peak Oil news board increase at an average rate of approximately 4% per year. This implies that the average reduction in energy intensity would need to be 4% to keep the electricity costs per ton of primary aluminium constant.

To evaluate whether changes in energy intensity alone would be sufficient to make up for the rising prices in electricity, CO2E3 assumes a reduction of energy intensity in two steps:

i) a 10 year period with reductions in energy intensity of 5% per year between (2016-2025), and
ii) a 10 year period with a yearly reduction in energy intensity of 1% between (2026-2035).

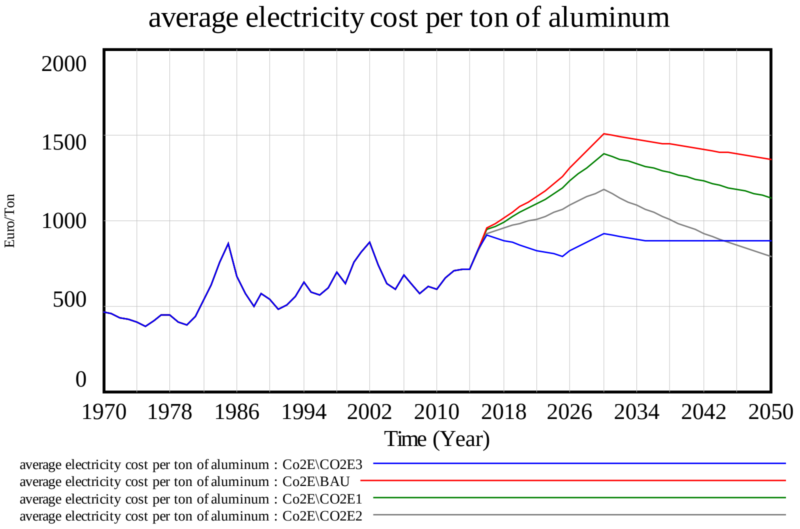

Figure 59: Average electricity costs per ton of aluminium

Figure 59 shows the simulation results of the 2-phase approach to increase energy efficiency (CO2E3 = blue line). It becomes visible that a 5% annual reduction in energy intensity enables the industry to reduce per ton electricity costs. However, after 2025, the electricity costs per ton start to increase during the period of 1% reductions in energy intensity. The informative value of these simulation results of this scenario is limited, since it is unclear whether an annual reduction in energy intensity is achievable. Furthermore, since a 4% increase in energy costs is assumed, it can be stated that a yearly decrease in energy intensity is required to make up for the higher prices.

Though the main reason is the amount of energy, it is also a question of the energy mix that is used, since coal and hydro electricity is relatively expensive compared to natural gas or nuclear energy prices. However, it is not said that a switch in energy source is possible, because availability of affordable energy is location bound.

4.2.1 Policy recommendations for the aluminium industry

This section proposes several policy recommendations for the aluminium sector. The proposed strategies will most probably need to be adjusted to national circumstances, since the analysis of the industry in this thesis has been conducted on a global scale.

The global aluminium industry is an industry with a large environmental footprint in terms of resource extraction, energy consumption, and emissions. Several, integrated measures need to be implemented in a coordinated fashion to ensure that increasing energy costs and possible emission taxes do not render the industry incapable of action. Instead of subsidizing electricity costs to keep the industry competitive, research to develop a new anode technology in order to achieve reductions in energy intensity should be incentivised and subsidized. With an average increase in electricity costs of 4% per year, a continuation of historical efficiency gains of 0.5% annually is not sufficient to ensure constant operations costs. Following the BAU trend in energy efficiency gains would, by 2050, result in 63% higher energy costs per ton of aluminium than in 2015. In addition, a decrease in the alumina yield of the bauxite ore are expected, which means that more inputs will be required to achieve the same amount of output.

The overall environmental impact can also be improved by making the processing sector more efficient. If the semi fabrication and fabrication sectors will enable the processing industry to produce the same output with less input, which reduces the overall demand for aluminium. Incentivizing efficiency gains in the processing sector should be combined with local and regional programmes that aim at increasing the old scrap collection rate. Social marketing campaigns that aim at informing the public to recycle as much aluminium as possible without much extra effort are likely to increase the collection rate of old scrap. This would help to maintain the employment rate in the aluminium recycling industry, which is likely to contract once the amount of collected internal scrap starts decreasing due to the achieved efficiency gains.

Indirect CO_2 emissions of the sector can be reduced by changing the energy source from which the industry procures its electricity for the electrolysis process. According to Peak Oil the prices for all fossil energy sources are going to increase in the future, while the price for wind energy is about to reach a long term equilibrium, and electricity prices for energy originating from photovoltaic are continuing to decrease until 2030 and beyond. While some plants are built near hydro-electricity plants to have access to cheap hydro-energy, other plants could build their own photovoltaic park or wind parks to gain a competitive advantage through cheaper energy prices, while at the same time reducing their CO_2 emissions. Further reductions in greenhouse gas emissions can also be achieved by upstream improvements in the efficiency of bauxite mining and especially alumina extraction processes.

Process innovation, at least in aluminium recycling, has the potential to reduce electricity consumption and CO2 emissions. A joint project between different institutions and the aluminium processing industry in South Africa, the SOLAM (solar melting of aluminium in a direct radiated rotary kiln) project[18], uses mirrors to concentrate solar energy to melt aluminium.
On industry level, the exchange of best practices and collaboration with research institution should be fostered to accelerate process innovations that reduce the environmental footprint of the industry. Break-troughs in developing new technologies should be incentivised by national governments and research foundations.

[18] http://www.nanowerk.com/news2/green/newsid=40472.php

5. Quality assessment of the simulation models

Simulation models that want to serve the purpose of policy analysis need to be validated thoroughly in order to gain the attention and the trust of decision makers. System dynamics models are causal-descriptive models, also referred to as “white-box” models, because they contain causal relationships between variables that need to be validated, opposed to “black-box” models, where correlation between two variables is assumed and the quality of the model is assessed by comparing the model output to the ‘real’ output data (Barlas, 1996).

This section describes the process of data collection analysis for the purpose of building the system dynamics simulation models prior and during the process. Subsequently, an overview over the model building process of the two models will provide insight in how the models have been constructed, and how both models benefited from a sequential, iterative modelling approach.

Next to the process of model construction, a table with the main variables for both models and their data sources will be given. Next to the sources, a qualitative assessment of the level of confidence in the variables was conducted, ranking them on a three point scale (low – medium – high). The qualitative assessment adds an additional assessment of the reliability of the data that is used in the models. One of the reasons is that highly aggregated data sets, and data sets that are difficult to measure (e.g. total global fish catch) have been used for the calibration of the model, but should be used being aware of the uncertainties involved.

In addition to the assessment mentioned above, several structural and behavioural validation tests, as propose by Barlas (1996) have been conducted*:

- Parameter confirmation test
- Dimensional consistency test
- Direct extreme condition testing
- Sensitivity test

*A description of the different tests is included in Appendix 1 – Overview and definitions of the applied validation methods

The results of the tests are reported for both models individually.

5.1 Data collection and analysis

A literature review and online research has been conducted on both sectors. RUQuest and Google Scholar were used as platforms to search articles for the literature review, where content analysis (Luna-Reyes & Anderson, 2003) served as method for data collection. Once a key article had been discovered, the snowball search method[19] was used to find additional information on important aspects of the systems. Regarding the literature review, the UNEP report "Towards a green economy: Pathways to sustainable development and poverty eradication" (2011) has been used as a starting point for this thesis.

Several sources were used to collect and compile the numerical database for the models. For the fisheries model, the FAO's homepage, next to independent empirical research papers, with its online publication provided a good overview over processes and system features. The FAO's software FishStatJ[20] was used as a main source to collect and aggregate data on historical fishery and aquaculture production rates. For the aluminium model, the publications on the IAI's homepage (http://www.world-aluminium.org/) served as a data pool for parameterising the simulation model. The draft version of the Global Mass Flow Model 2013-2014[21] created in Excel using iterative calculations was very helpful for orientation and calibration purposes of the stock and flow model.

The datasets obtained for both models were triangulated (Boeije, 2005) with different sources. Data triangulation was used to gain confidence in the correctness of parameters in the models and supported the qualitative evaluation process. Next to the data obtained from the FAO and the IAI, published research papers and reports published by other institutions were used to cross-reference and validate the obtained datasets.

5.2 Process of model construction

The process of model building was conducted iteratively as mentioned by several system dynamics modellers (e.g. Homer, 1996; Vennix, 1996; Sterman, 2000). An iteration is defined as "*a procedure in which repetition of a sequence of operations yields results successively closer to a desired result*" (Homer, 1996, p.1), whereby the desired results were two final simulation models for the purpose of answering the research questions. System dynamic models are typically built in several iterations, sequences of modelling and researching data, to increase the resolution of the final model and make it useful for problem analysis and decision support. Both models were constructed sector by sector following the literature on the topics.

The construction of the fishery model started with research on the causal relations of the system and the construction of the fish stock and the fishing capacity sectors. Once these sectors were built and a representative feedback structure was in place, research on processing was intensified and the processing sector was added. Then the wholesale and retail sectors were added based on simple supply chain structure elements (e.g. Sterman, 2000). Once the complete supply chain was built, the financial sectors of the respective supply chain elements were added and connected to them.

19 http://www.eur.nl/ub_informatievaardigheden/ul_instruction_oud/sfsi_me/searching/searching_by_following_up_references/snowball_method/

20 http://faostat.fao.org/site/629/default.aspx

21 http://www.world-aluminium.org/media/filer_public/2015/04/23/2013_2014draft.xlsx

Several feedback moments with the thesis supervisor increased the speed of modelling and the learning experience. After the model has been built, it was split up in different, interconnected modules to improve sector boundary analysis and visual appeal of the elements.

Once a basic structure on fisheries was constructed, the first version of the aluminium model was built, starting with research on the process and modelling a supply chain from bauxite to aluminium consumption. This structure was at first calibrated with historical data and once a reference mode was established, more variables were internalized. The aluminium model was built in modules from the start, based on the learning experience from the fishery model. The stock of aluminium in society was split up into different modules (i.e. construction, transportation, etc.), each with its own stock and flow structure built based on the collected data.

Building both models sequentially had the advantage that the experiences and insights from one modelling process could be transferred and applied in the next round of iterations for the other model. Figure 60 shows how the sequences and iterations between the models, whereby each "model" element of the figure contains several rounds of iterations (and supervisor feedback) in itself.

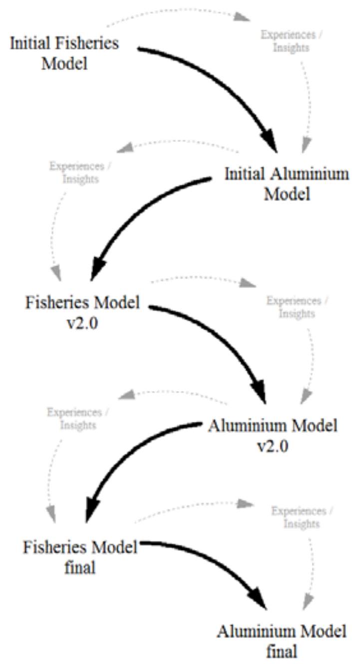

Figure 60: Iterations model building

5.3 Reproduction of historical behaviour

This section describes the calibration process for two simulation models. First a general description of how the models were calibrated is provided. A table with the different data sources, their use in the model and the goodness of fit (R^2) coefficient of the model behaviour respective to the data sources. The subsequent sections give insight over the accuracy of the model outputs and the data sources that were used to calibrate/simulate the model. This way, reproducibility of the models is possible by using the equations provided in the model description section and the data sources that are evaluated here.

5.3.1 Calibration of the fisheries model

In the process of calibrating the fisheries model it became clear that supply and demand had to be calibrated first, before being able to determine the other variables. The demand and the supply of fish were initially used as endogenous variables to ensure that the supply chain model produced reasonable behaviour. Demand for fish (consumption rate) still remains an exogenous input, driven by the forecasted population and the expected average per capita consumption of fish. The supply of fish is created endogenously by capture fisheries and aquaculture production. The fish stock was implemented and estimated. Estimations of the fish stock were made with the number of vessels and the historical catching rate, since there is no estimation of the global fish stock in terms of tons. Once the demand, the production and the capacity were showing reasonable behaviour, the remaining variables as size of processing capacity and the remaining supply chain were built and parameterized according to the collected data.

From former contributions it is known that several processes in supply chains are governed by negative feedback loops (as for example capacity adjustment), so during the process of model calibration it was made sure that these loops are in the model.

The following variables are used for the following purposes the fisheries model:

Name	Used for	Sources	Perceived accuracy
Catching rate	output	FishStatJ®[22] FAO (2008) FAO (2014)	Low
Vessels	calibration		
Weighted average processing efficiency	input	UNEP (2000) AIT (2007)	medium
Fraction of fish for human consumption	calibration	FAO (2008) FAO (2014) MSC[23]	high
Average per capita fish supply	input	FAO Green Facts[24]	medium
Demand for fish	calibration	FishStatJ®[25] FAO (2008) FAO (2014)	Medium
Population	input	World Bank[26]	high
By-catch rate	input	FAO (1994) Matusoka (2008)	low

22 http://www.fao.org/fishery/statistics/software/fishstatj/en
23 https://www.msc.org/healthy-oceans/the-oceans-today/fish-as-food
24 http://www.greenfacts.org/en/fisheries/l-2/06-fish-consumption.htm
25 http://www.fao.org/fishery/statistics/software/fishstatj/en
26 http://data.worldbank.org/indicator/SP.POP.TOTL

5.3.1.1 Demand for fish

The total demand for fish was modelled by using the 'reference population' which is the population data and future estimations form World Bank homepage[27], the per capita fish consumption, weighted average of production efficiency, and the historical growth rate of demand for fish[28]. The variables that are used to calculate the demand for fish are exogenous.

The consumption itself is calculated by multiplying the reference population with the per capita fish consumption. The weighted average is used to correct the consumption rate, since the concept of per capita consumption of the FAO is used, which calculates per capita consumption as total supply of fish divided by calculation, but does not account for production losses etc. Per capita consumption rates and future estimate from the FAO (1999) and the GreenFacts website[29] were used to calibrate the model.

The demand for fish is exogenous and used for model calibration purposes, meaning that the historical behaviour is of interest is the total fish supply that is produced by capture fisheries and aquaculture. Model outputs are referenced to the data that was provided by FishStatJ®. The production quantities of aquatic plants were corrected for in order to ensure a correct reference mode.

The total fish supply is the sum of aquaculture production and capture fishery production. With an R^2 value of .9768 the model output is very close to the historical behaviour in the real system. The R^2 value of the aquaculture production capacity is .999, since it is calculated solely by the historical growth rate that was determined from the FishStatJ® data set, meaning that the inaccuracy of the fish supply is caused by the catching rate of the capture fishery sector. Figure 61 shows the historical and simulated behaviour for the variable 'supply fisheries and aquaculture'. Reference data was available until 2015, though the full range of the simulation is shown to

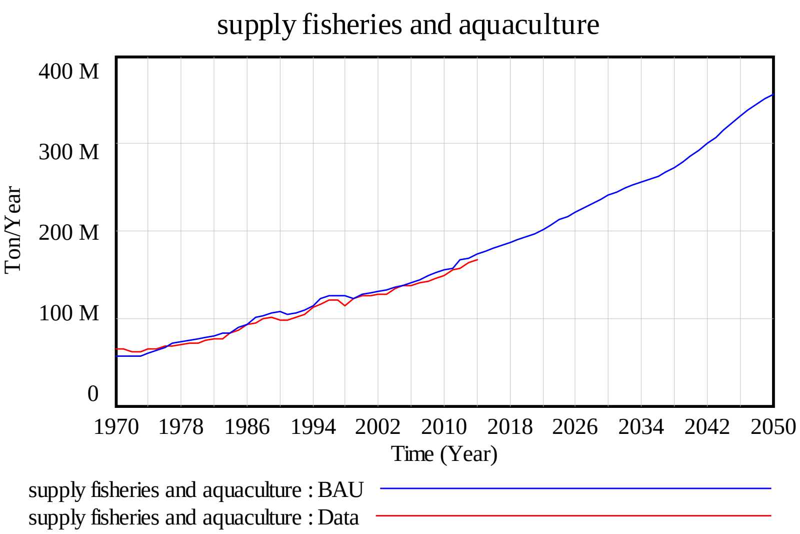

Figure 61: Total fish supply – BAU vs Data

27 http://data.worldbank.org/data-catalog/population-projection-tables

28 Derived from the data from FishStatJ

29 http://www.greenfacts.org/en/fisheries/l-2/06-fish-consumption.htm#0

5.3.1.2 Catching rate

The catching rate is a function of either capacity or demand for fish from capture fisheries, depending of which one is lower. In order to get the reference mode for the catching rate, the demand (consumption) of aquatic plants was excluded from the FishStatJ® data on fisheries production.

Correcting the demand for fish from capture fisheries is with an adjustment factor that accounts for capacity construction queues and future demand growth leads to a slightly higher catching rate from around 1990 on that it was in reality. Furthermore, as will be pointed out in section 3.2.1.4, covering the total catch with the catching capacity (number of vessels) is not realistic due to the fact that the stock only contains large vessels, and no definition of a certain capacity provided.

The R^2 value for the catching rate is .8383, which is adequate for the endogenous calculation and the purpose of analysing its effect on the fish stock. Furthermore, it has to be noted that the mean catching rate is deviating by 10.2% above the reference mode, but that the standard deviation is around 38% bigger than the reference catching rate. Regarding the standard deviation it can be noted that the values that are provided by FishStatJ® are reported values, which means that aspects like illegal, unreported and unregulated fishing are not included, and that by-catch and high-grading are not accounted for. Figure 62 illustrates how the simulated catching rate behaves compared to the reference mode catching rate.

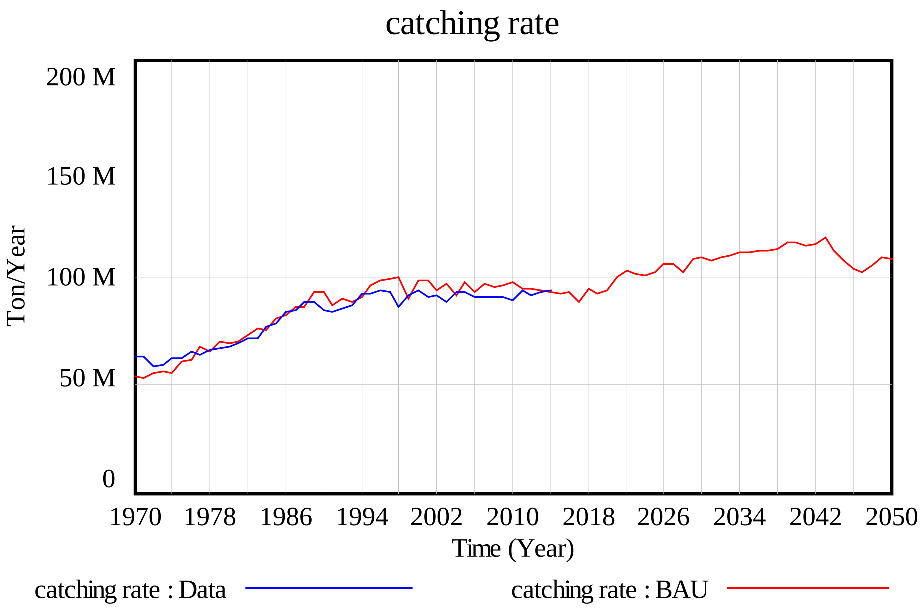

Figure 62: Catching rate capture fisheries – BAU vs Data

5.3.1.3 Per capita fish supply

The per capita fish supply is derived by dividing the supply from fisheries and aquaculture by the reference population to keep the same method as the FAO. The R^2 value of this variable in the base run scenario is .7922. The low R^2 value is mainly caused by the catching rate from the capture fisheries sector that has a R^2 value of .8383, and is therewith deviating quite strongly from the historical behaviour.

The strong deviation is partially caused by the uncertain number of vessels and the catching efficiency factor in the fish stock module of the model. The latter one accounting for the density effect and is an estimate that was implemented into the model to represent the increasing effort that the capture fishery sector needs to put into its operations to maintain the same level of output.
Initially the deviation is caused by a catching capacity which is slightly too low as that it could cover the demand for fish from capture fisheries. Latter deviations are caused by the demand for fish from capture fisheries. Two stocks, on as demand for fish from capture fisheries, and the number of vessels under construction are introducing a delay into the system that causes vessels and capacity to adjust slightly later than needed to reproduce the historical behaviour.

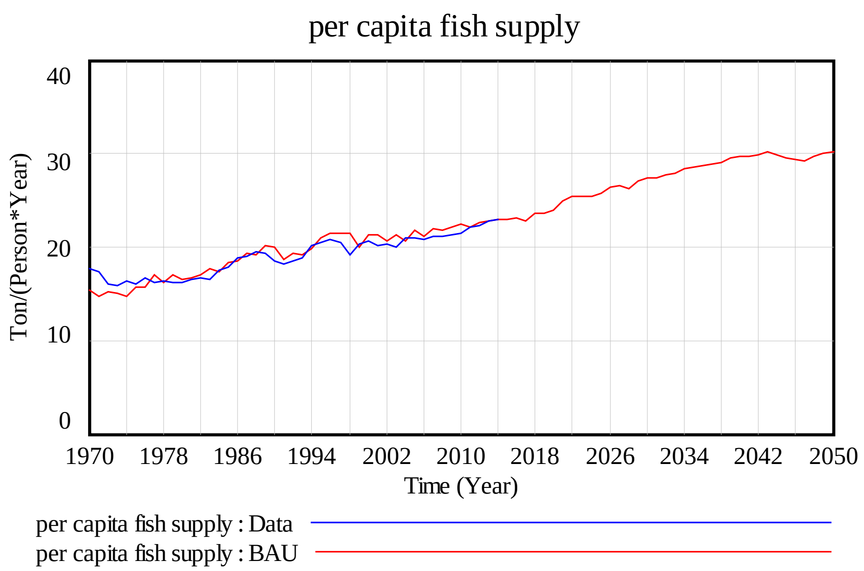

Figure 63: Per capita fish supply – BAU vs Data

5.3.1.4 Number of vessels

The number of vessels is a difficult variable to calibrate, since it was not possible to find aggregate statistics for this variable during the course of research for this study. The number that was used as a reference mode was taken from a graph that is presented in the limitations section further down.

In the simulation model the number of vessel is representative for those vessels that have a large capacity has been derived from a graph that was found on www.eatingjellyfish.com, in the article on the state of fisheries[30]. Exact values were not provided, meaning that the number of vessels in the model is not representative for the real number of vessels at sea, nor that it claims to be.

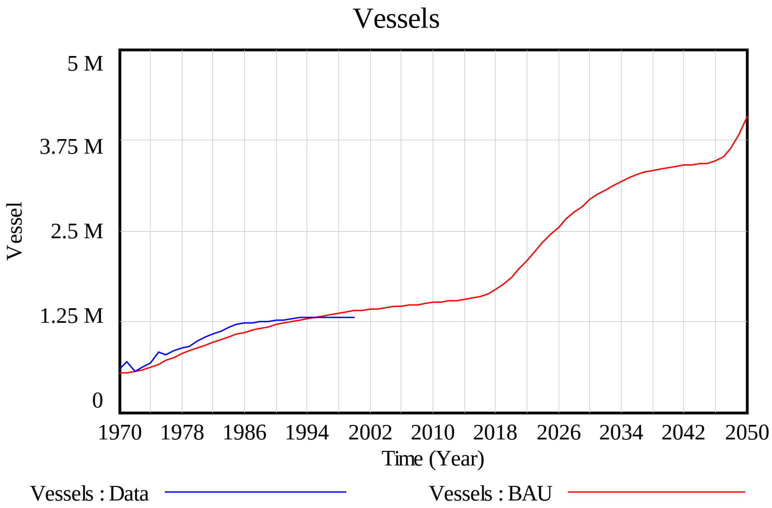

Figure 64: Number of vessels – BAU vs Data

The R^2 value of this variable is with .8842 relatively close to the historical development of large vessels. The behaviour of the stock of vessels is very dependent on the demand for fish from capture fisheries that is together with the catching rate and catch per vessel causing the capacity to adjust. It was calibrated jointly with the catching efficiency from the fish stock module so that the different values from the respective graph were reconstructed. However it can be questioned whether these values are correct, and why only one source was used to calibrate the number of vessels.

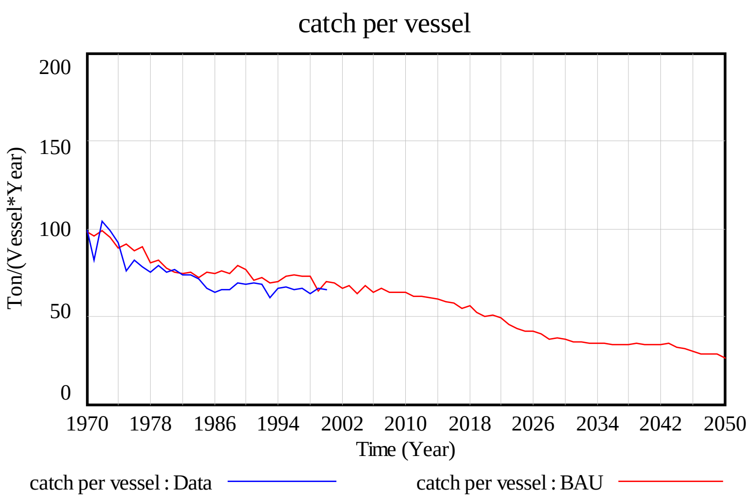

Figure 65: Catch per vessel – BAU vs Data

[30] http://eatingjellyfish.com/?m=201305

5.3.2 Calibration of the aluminium model

The aluminium model was calibrated based on the reference modes provided by the IAIs Global Mass Flow model. Once the supply chain has been modelled, reference modes were used in Vensim DSS® to calibrate the model so that it reproduces historical behaviour adequately. The driving force in the aluminium model is the demand for primary aluminium and the primary production capacity.

Once the capacity was calibrated and the recycling sector established, the parameters of the IAI were filled in and several variables parameterized according to the available data.

Name	Used for	Sources	Perceived accuracy
Primary production capacity	output	Global Mass Flow Model (2013) World Aluminium[31]	medium
Primary Aluminium	output	World Aluminium[32]	low
Primary production rate	output	Global Mass Flow Model (2013) World Aluminium[33] IAI (2010)	high
Demand for aluminium	calibration	IAI Global Mass Flow Model (2013)	medium
Aluminium in society	output	Global Mass Flow Model (2013) IAI (2009) IAI (2015)	medium
Aluminium recycling rate (old scrap)	output	Global Mass Flow Model (2013) IAI (2009) IAI (2015)	medium
Utilization rates semi processing and fabrication	input	Global Mass Flow Model (2013)	low
Amount of internal scrap	output	Global Mass Flow Model (2013)	medium
Fraction of aluminium consumed recycled	calibration	Global Mass Flow Model (2013) IAI (2009)	high
Energy intensity	input	World Aluminium[34]	high
Energy prices	input	Peak Oil news & message board[35]	low

[31] http://www.world-aluminium.org/publications/
[32] http://www.world-aluminium.org/publications/
[33] http://www.world-aluminium.org/publications/
[34] http://www.world-aluminium.org/statistics/primary-aluminium-smelting-energy-intensity/
[35] http://peakoil.com/alternative-energy/trends-in-the-cost-of-energy

5.3.2.1 Demand for aluminium

The demand in the aluminium model is calibrated via the historical growth rate of the demand. Historical growth fractions per year were calculated from the data in the IAIs' global mass flow model and included into the model via a table function. The demand for aluminium is driving the behaviour of the model in terms of how much aluminium is shipped into what sectors. This in turn determines the rates at which internal and old scrap are produced and collected, which is determining the availability of secondary aluminium. The R^2 value of .9843 is a good sign that the historical behaviour of demand is reproduced reliably in the model.

Figure 63 illustrates that reference mode (blue line) and simulated behaviour (red line) are showing the same behaviour, even though it is noticeable that the simulated behaviour ends up at a lower annual demand for aluminium than it was historically. The difference between reference mode and model output is approximately 7.5% by 2015, and roughly 8% by the year 2030. Values between 2015 and 2030 are based on the expected growth rate of the IAI, while values after 2030 are determined by the 'expected future growth rate', which is currently set as a continuation of the expected growth rate of the IAI.

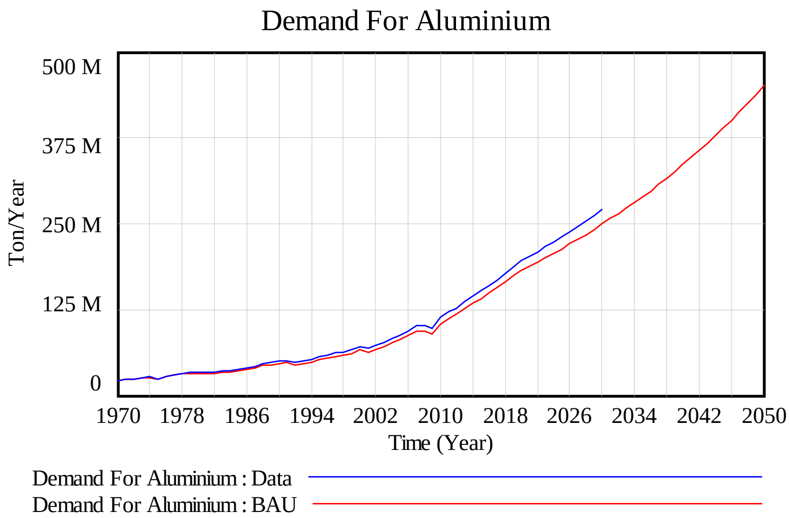

Figure 66: Demand for aluminium – BAU vs Data

5.3.2.2 Primary aluminium production capacity

The primary production capacity of the aluminium industry is calibrated through the demand for primary aluminium, the capacity in place and an adjustment factor for lead times and expected future demand. Production capacity is created in two steps, first as capacity under construction and then as production capacity. The R^2 value for the stock of primary production capacity is .9849, meaning that the simulated behaviour is close to the reference mode, which is also illustrated in Figure 67.

The values of the primary production capacity are slightly higher than indicated by the reference mode, the deviations by 2015 and 2030 are 4.5% and 3.2% respectively. Deviations in the primary production sector are caused through deficit in the recycling rate, and as a result a higher demand for primary aluminium as will be explained in the next sections.

As a lifetime for capacity a value of 40 years was chosen, even though it is assumed that capacity that is in place remains in place as long as the demand for primary aluminium is sufficient to keep that capacity running. Once the demand for primary aluminium decreases, primary capacity will decrease as well at the speed of the depreciation rate.

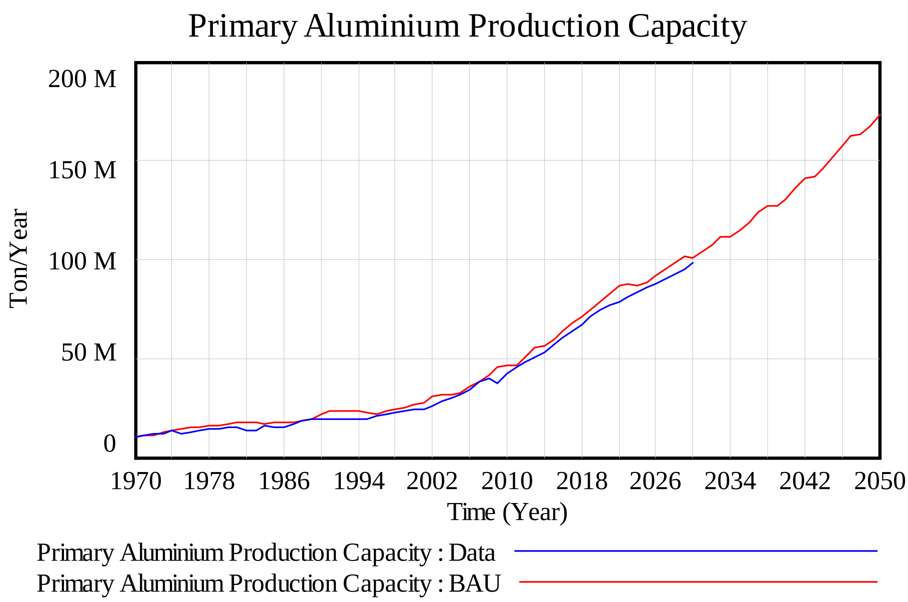

Figure 67: Primary aluminium production rate – BAU vs Data:

5.3.2.3 Aluminium recycling rate

The aluminium recycling rate is representing the amount of secondary aluminium that is produced by recycling old scrap that is collected in the different sectors of the industry. The R^2 value of the recycling rate is with .7209 low compared to the primary production capacity. In addition, the amount of aluminium that is produced from old scrap is significantly lower than the reference mode. By 2015 the simulated values deviate by 28.56%, or 7.14 million tons from the reference mode, while the deviation by 2030 is 19.7%.

In terms of structure, the recycling rate is the sum of the recovered old scrap from the eleven different sectors that is recycled with a weighted average recycling rate. The calibration of this variable thus took place by making sure that the rates of old scrap that flow out of society are as close to the IAIs' values as possible.

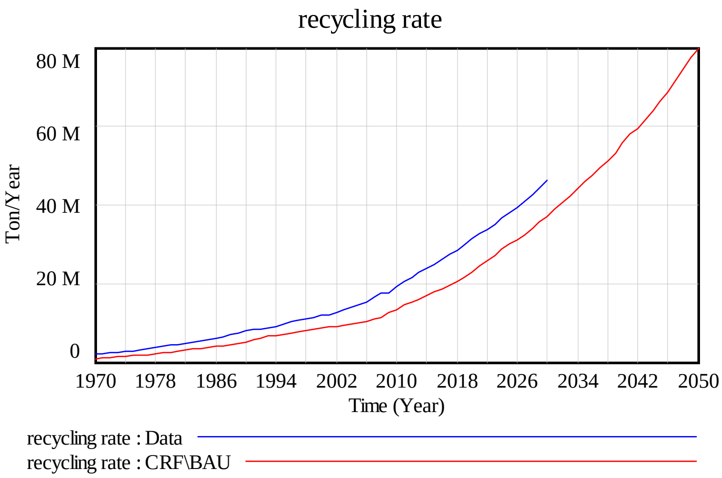

Figure 68: Recycling rate of old scrap aluminium – BAU vs Data

The difference between the reference mode and the simulated behaviour is caused by the formulation of the old scrap that is received from the construction sector. A pipeline delay was used, due to the assumption that once a building is constructed, the aluminium is bound in the building until it reaches the end of its lifetime. A very small outflow has been added to account for maintenance work in the buildings, but this number is not based in literature or on data. Due to the pipeline delay, the first outflows of old scrap from the construction sector occur in the year 1990, thus after the shortest delay time (life time of 20 years) after begin of the simulation in 1970. Figure xXX shows the reference recovery rate and simulation output of the old scrap recovery from the construction sector.

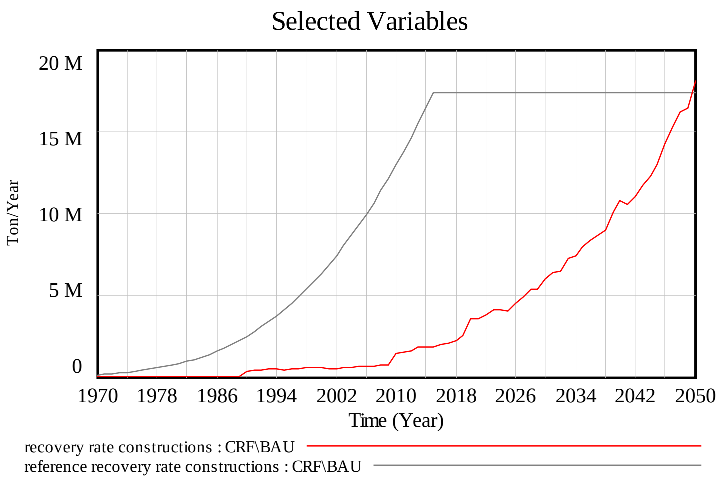

Figure 69: Recovery rate construction sector – BAU vs Data

A separate calculation was conducted to double check whether the low R^2 value of the recycling rate was caused by the difference in old scrap from constructions. To test whether the deviation is caused by the pipeline delay, the construction sectors recovery rate of 1990 was assumed to be the value at the beginning of the simulation, in 1970. Therefore the difference between the recovery rate in 1970 was deducted from the value in 1990, and the remaining quantity was added to the recycling rate in 1970 to see whether the increase would close the gap between the simulated recycling rate and the reference mode. The equation for the recycling rate in 1970 for this calculation would look like:

$$\text{Recycling rate}_{(t=1970)} = \text{Recycling rate}_{(t=1970)} - \text{Recovery rate const.}_{(t=1970)} + \text{Recovery rate const.}_{(t=1990)}$$

Calculations have been conducted from 1970 to 2015, since the reference mode data for this period is not based on predictions of future growth rates yet. Table XX summarizes the results of the separate calculation for chosen years (1970 – 2000 every ten years, then every five years). Values are in million tons of aluminium per year.

	1970	1980	1990	2000	2005	2010	2015
Reference	2.096	4.384	8.018	12.068	14.642	19.274	25.001
BAU	0.974	2.518	5.073	8.640	10.015	13.230	17.857
Δ *reference*	-53.5%	-42.6%	-36.7%	-28.4%	-31.6%	-31.4%	-28.6%
Control	1.304	3.047	6.163	11.619	13.419	17.808	22.049
Δ *reference*	-37.8%	-30.5%	-23.1%	-3.7%	-8.4%	-7.6%	-11.8%

The control shows that the values come closer to the reference mode than the simulation outputs. This supports the assumption that the deviations are caused by the scrap recovery rate of the construction sector. However, these numbers should be read with care, since the control numbers from 1970 to 1990 only contain the old scrap that flows out of the stocks of buildings with a life time of twenty years, but not those with forty or sixty years.

5.3.2.4 Aluminium in society

This section will summarize the R^2 values for the eleven different sectors that together represent the total amount of aluminium that is accumulated in society. Table 21 represents the R^2 values for the eleven sectors that are represented in the model.

Sector	R^2	Sector	R^2
Construction	.9797	Cans	.9339
Cars	.9427	Foil	.9737
Trucks	.9989	Consumer durables	.9710
Aerospace	.9606	Other electricals	.9698
Machinery	.9614	Other applications	.9767
Cable	.9464		
		Aluminium in society	**.9963**

Table 21 – R^2 values for the behaviour of the stocks composing aluminium in society

The R^2 values indicate how well the behaviour of the sectors fits with the reference mode of the respective sector. Based on the values it can be stated that the model represents the historical behaviour adequately. The variable “Aluminium in society” is the sum of all eleven stocks, and captures the total accumulation of aluminium in all sectors throughout the simulation run. An R^2 value of .9963 indicates that even if the behaviour of the eleven stocks is not represented perfectly, the total accumulation of aluminium in society develops according to the reference mode of the IAI Global Mass Flow model.

5.4 Validation tests

Two types of structure-behaviour validation tests were conducted for this thesis: sensitivity test and extreme condition test. The results of the analysis are described below.

5.4.1 Sensitivity test

During the sensitivity test, the capacity adjustment parameter of both models will be tested for accuracy and influence on the behaviour of the model. The sensitivity simulations were conducted under the same circumstances, thus the same parameter range and the same number of iterations.

5.4.1.1 Fisheries

In the BAU scenario the variable has a value of 1.075, which means that changes in demand are increased or decreased by 7.5%. For the sensitivity analysis, the range between 1 and 1.5 was simulated with 200 iterations. The following variables were used to see the effect of changes in the demand adjustment factor in the capture fisheries sector.

The simulation results of the BAU scenario in the fisheries lay mainly in the 75% confidence interval of the Monte Carlo simulation. The number of vessels is very sensitive regarding changes in the demand adjustment factor. With the values of vessels (Figure 70) and catching rate (Figure 71) being at the lower bound it can be stated that the chosen value is relatively close to the original value. The dominant factor for the construction of capacity is the demand for fish from fisheries. An increase in demand will increase capacity very fast, while a decrease takes more time since the decrease of capacity takes place via the depreciation rate.

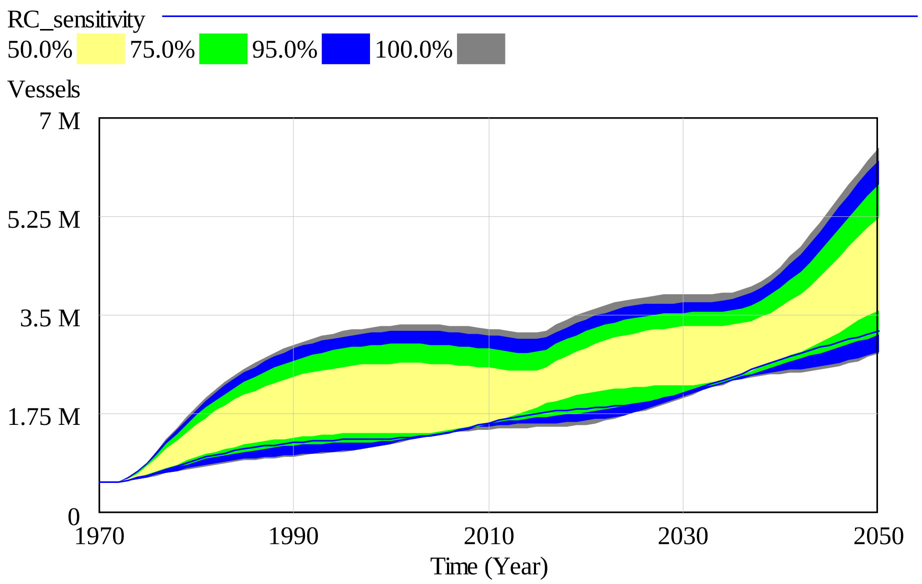

Figure 70 – Monte Carlo analysis capacity adjustment factor fisheries: number of vessels

Furthermore, even if the spread for the values of the catching rate between 1970 and 2015 is quite broad, the spread for the values after 2015 is getting smaller. This indicates that the balancing loop that is introduced by the catching efficiency (the density effect) is gaining dominance after 2015 and reduces the size of the confidence intervals. This indicates that both, stock and capacity are dominant in the historical part of the simulation, while the future values are dominated by the fish stock.

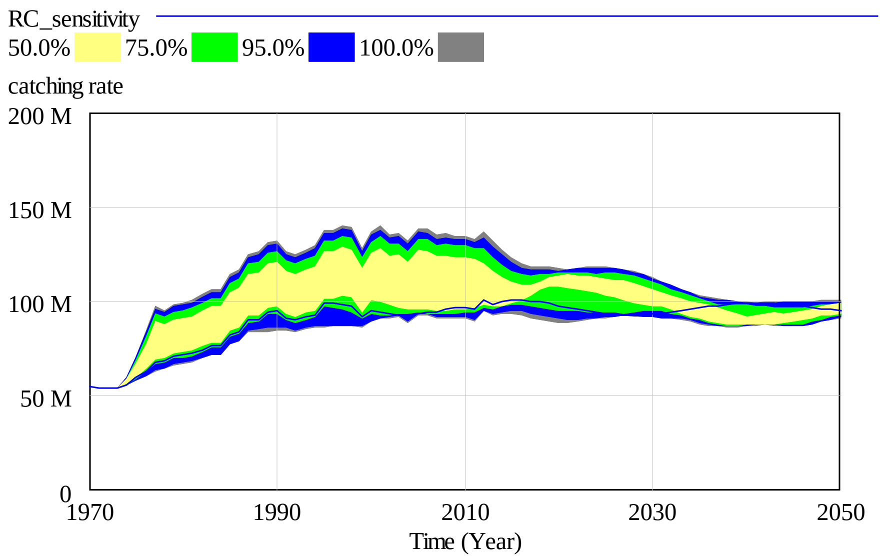

Figure 71 – Monte Carlo analysis capacity adjustment factor fisheries: catching rate

5.4.1.1 Aluminium

In the BAU scenario the supply adjustment variable has a value of 1.1, which means that changes in capacity are adjusted by 10%. For the sensitivity analysis, the same range (between 1 and 1.5) was simulated with 200 iterations. The variables of interest in this scenario were the total aluminium production capacity and the total price for aluminium.

The primary production capacity is within the lower 75% confidence interval, with a wide spread upwards, indicating that the chosen value of 1.1 is close to the actual value that the industry is using to adjust its capacity. Higher values in primary production capacity would be cause if higher adjustment values would be used, though this would produce a situation of overcapacity.

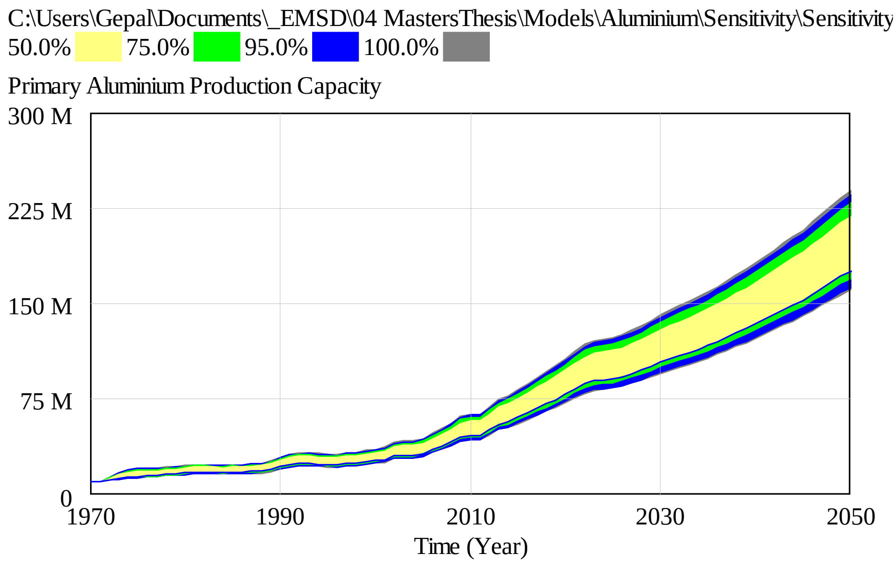

Figure 72 – Monte Carlo analysis capacity adjustment factor aluminium: primary production capacity

The simulated price of aluminium is at the upper 75% confidence interval of the sensitivity analysis. The variable itself has a wide spread, which is partially caused by the cost curve that is used to calculate the price for aluminium. However, due to a lack of data a cost curve of 2010 was used, which means that prices from 2010 into the future are still based on the maximum value of the cost curve. They thus do not consider changes in the cost structure of the industry, which is one of the limitations of the model as explained later in the limitations section.

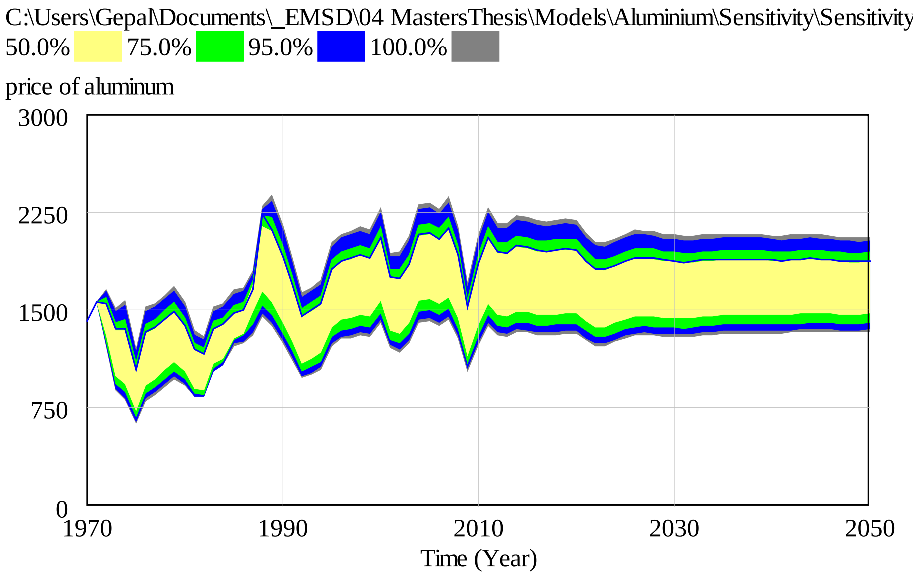

Figure 73 – Monte Carlo analysis capacity adjustment factor fisheries: price for aluminium

5.4.2 Extreme condition tests

This section will briefly describe the structure-behaviour test “extreme condition testing”. A variable will be set to zero and the behaviour of several variables of interest will be observed and described.

5.4.2.1 Fisheries

Testing for zero demand

Figure 74 show the behaviour of the main variables in the BAU scenario and the “demand = 0 in 2015” scenario. The stocks of vessels, aquafarming capacity and processing capacity are decreasing, since no replacement of the depreciated capacity takes place. The stock of vessels, which is increasing in the BAU scenario is decreasing over time in the zero demand scenario, since no capacity adjustment is needed to satisfy demand. The same is true for aquafarming capacity, which is depreciating because the fish supply is not needed any longer. Processing capacity is decreasing as well, since the change in processing capacity is supply driven. Catching rate drops to zero as soon as the demand drops to zero, which is consistent with its formulation, though not realistic as many people are dependent on fisheries as a nutrition source. The fish stock starts recovering as soon as the catching rate drops to zero.

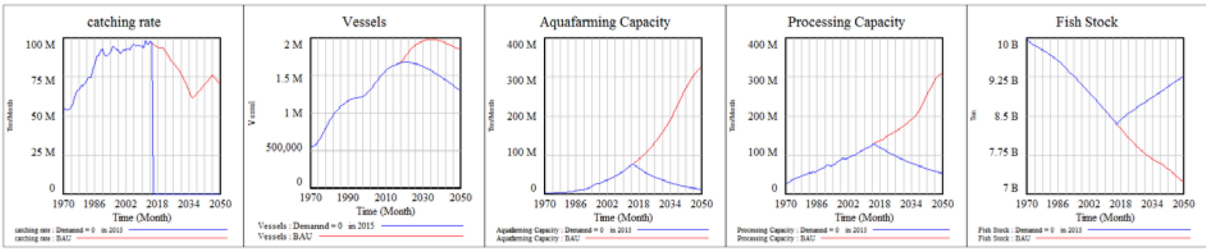

Figure 74: Selected variables for extreme condition test fisheries – BAU vs Zero demand

5.4.2.2 Aluminium

In the aluminium model the demand for aluminium was set to zero in the year 2015. Figure 75 underneath represent the model behaviour in the BAU scenario and the zero demand scenario.

The primary aluminium production capacity starts decreasing immediately, respective to its depreciation rate, since smelters start going out of business. The total CO2 emission rate aluminium production instantaneously drops to zero. No aluminium production means no demand for alumina, thus no demand for bauxite either, but also that there is no demand for anodes or electricity for the electrolysis process. In summary, the emissions drop to zero because all of the CO2 emitting steps in the production chain are demand driven, which means that no demand for aluminium will lead to an instantaneous stop of aluminium related emissions. The demand for primary aluminium, which is defined as total demand less secondary consumption, instantaneously drops to zero as well, since there is no demand for aluminium at all. The last variable that was examined was the fraction recycled aluminium, which is representing the amount of recycled old scrap compared to the total consumption. This ratio drops to zero as well because if there is no consumption of aluminium this ratio will stay zero.

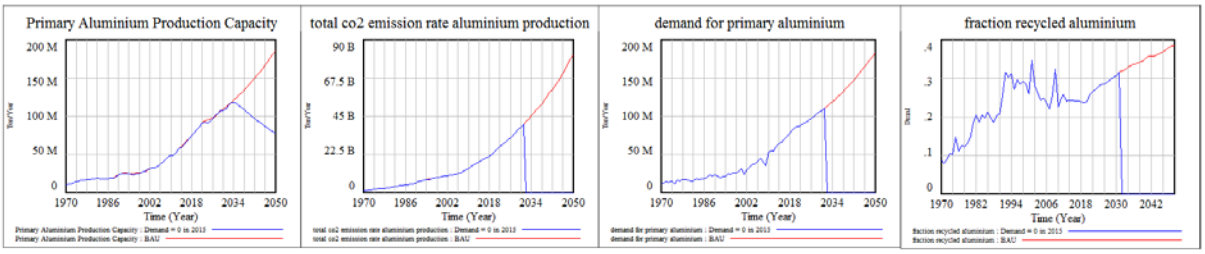

Figure 75: Selected variables for extreme condition test aluminium – BAU vs Zero demand

6. Limitations

Both models that serve as a base for scenario analysis in this thesis have their limitations. A model is always a simplification of reality and therefore never a hundred percent accurate. As pointed out above both models are on a global scale. However, customization for adjusting them to a national context is possible. The high level of aggregation asked for simplifications in many regards which necessarily limits the representativeness of the model. The limitations of both models will be described individually.

6.1 Limitations of the fisheries model

The first limitation of the fisheries model is the number of vessels and the fishing capacity. Detailed information about fleet size and capacity are not available on a global scale. As a point of departure the following graph was used to deduct the initial number of vessels and for calibration purposes. Information about the exact capacity of the vessels was not mentioned, neither their sizes. The comparison of those numbers to a more detailed compilation on the FAO's homepage[36] raises awareness that more research is needed to collect exact data on vessels and their respective capacity. The numbers in use are thus putting a constraint on the representativeness of the resulting numbers from the simulation runs model, but since they are important for the models behaviour it is difficult to determine the extent of this limitation.

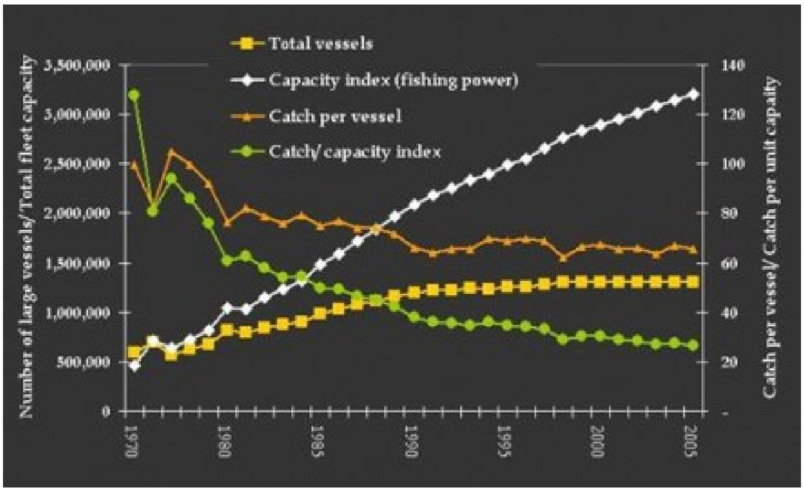

Figure 76: Graph used to deduct initial number of vessels and catch per vessel[37]

The estimation of the fish stock which was necessary due to the unavailability of data on the global quantity of fish is a second major limitation of the model. Data on numbers of fish stocks and their respective degree of exploitation are available (Froese et al., 2010), while quantities, or even estimations of how much fish there still is are lacking. A range of possible initial fish stocks needs to be tested to avoid jumping to conclusions and to embrace uncertainty instead of neglecting it.

Another limitation of the fisheries model is that it does not distinguish between different types of fish, as for example white fish and oily fish (UNEP, 2000). With the difference in type of fish comes a difference in utility, as oily fish is for example used for canned fish, but white fish for fish fillets. The reason why this difference was not made is the scope of the model. Even though the classification is

[36] www.fao.org/docrep/008/y6982e/y6982e00.htm#Contents
[37] Reference to the World Bank homepage: http://eatingjellyfish.com/?p=3743

important to keep in mind, the model was build to examine the underlying feedback structure and to test strategies that can improve the long run performance of the sector. Discrimination of the types of fish would have led to a model twice the size, since two different fish stocks were needed, different processing and transportation chains. The decision to not model different types of fish was taken because it would add additional complexity and uncertainty to the model, while not adding additional value in terms of answering the research questions.

Next to the type of fish seasonality is not included in the model. Seasonality has an impact on the catching rate of certain fish since some species are migrating, or prohibited to be caught for reproduction purposes. Since the time step of the model is in years the inclusion of seasonality would have been mere speculation, and added more uncertainty to the model that cannot be validated. Therefore the decision was made to exclude seasonality from this model. It should be included once the model is adapted for a specific country or area.

For some arguments, the feedback between the primary and the secondary processing chain was mentioned, as for example using fish by-catch and leftovers for the production of fish meal and fish oil that takes place according to the IFFO[38]. This feedback was not included in the simulation models though it could have an impact on the demand for fish for secondary processing. The demand for fish from secondary processing is for now based on historical numbers, but for further iterations it is highly recommendable to examine the connections between the primary and secondary fish processing sectors.

The level of aggregation is putting several limitations of the validity of the model. The model is mainly parameterized with average numbers (e.g. UNEP, 2000) in terms of efficiency and technology, but some numbers were taken from reports referring to a certain geographical area. Using these specific numbers reduces the validity of the simulations results when running a simulation for the global scale.

6.2 Limitations of the aluminium model

The orientation on the reference modes of the Global Mass Flow model of the IAI regarding the parameterization of the aluminium model can be seen as one of the main limitation of the model. Though the numbers correspond with other reports of the IAI, the model is already a simplification that contains certain assumptions. These assumptions were not made explicit in the IAI’s model, and no empirical sources for the validation of the data were listed, meaning that a the validity of the resulting numbers, if in line with the reference modes, confirm the assumptions of the IAI, which do not necessarily need to be in line with the real data. However, since the IAI is the main global institution doing research in and providing data on the aluminium sector, it is assumed that the data in use is derived from industry surveys and empirical research.

A second limitation is that the fractions that distribute the shipments of the aluminium into the different sectors are fixed after 2030, keeping in mind that the fractions from 2013 through 2030 are already representing the IAI’s expectations on how the industry will develop. The same limitation applies to the fractions that are used to distribute the aluminium shipments to the construction sector among the different geographical areas; those fractions are constant after 2013. Though indications about future development of the fractions could be derived based from the trends in the different sectors, fractions were kept constant to evaluate the strength of the respective feedback loops, and to avoid adding more data to the model that cannot be validated. Furthermore, for the purpose of this study, the aggregate development of the demand for aluminium is the driving force for the production of aluminium, and not its distribution among the different sectors, The distribution among the sectors

[38] http://www.iffo.net/fishmeal-and-fish-oil-production

has an influence on the recycling rate due to the differences in recyclability of old scrap and the recovered quantities among the sectors, which will not be examined in this model.
Not considering transportation costs for bauxite that is shipped from the mining site to alumina refining sites is another limitation of the model. Transportation causes emissions and costs money, both aspects that should be represented in the model. Even though transportation modes and distances were provided in the IAI's life cycle analysis (2013), they were not included into the model because they are not representative for the whole industry. This implies that the 'total life cycle emission flows' in the model omit the emissions that are caused by transportation.
The calculation of the price for aluminium is another strong limitation of the model. The price is calculated based on a producer cost curve of the year 2010. This means that price calculations after 2010 do not take a change in cost structure into account. There was not enough time or coherent information to produce a more comprehensive cost curve within the remaining time to finish the thesis. Furthermore, the price in the model should partially be driven by the demand-supply ratio and an elasticity factor, which can be changed in future iterations.
Another aspect that is not represented in the model is that there are different types of primary aluminium alloys and different types of aluminium scrap. Different types of primary aluminium, would add more complexity if different qualities or types should be considered. The aim was to investigate and analyze the macro behaviour of the industry, and develop a blueprint that can serve as a base for customization. The structure can be cloned and used for the analysis of different aluminium types. Another aspect that is out of the boundaries of the model, but comes with different types and coatings of aluminium is the recyclability of these blends, and the quality of the recycled produce. Some types of aluminium, either additives or coatings, make the recycling process more labour intense, lead to a lower quality of the recycled produce due to residuals, or both.

6.3 Lessons learned personally from modelling endeavour:

Writing while doing

During the modelling process, I did a lot of research to inform the process of building the model, but without writing down notes or adding sources to the model. After I had to start writing after 2.5 months of building two relatively big stock and flow structures it was difficult to find a starting point, and to put down the red line of my thesis in simple words due to the rich amount of information that I accumulated during this time. My future approach will be to start taking notes and writing small segments while building the model, thus a sequentially iterative approach of modelling and reporting. In addition, I will start documenting the model while building it, thus adding sources in the comment boxes, and adding small descriptions as soon as a building block of a model is finished.

"You have to go big before you can go small."

This advice came from my supervisor Andrea Bassi. I assumed that I knew what he was talking about when he gave me that advice, but after using around 60 variables to arrive at an average production efficiency I realized that I didn't get it right away. It is difficult to keep the same level of aggregation and to just use the necessary amount of variables. After realizing that, and for the remaining modelling of my thesis models, I went back to pen and paper modelling to evaluate how much structure is really needed. This helped a lot in terms of orientation of the modelling and keeping the focus on the issue that I want to model.

Detail versus no detail

This lesson is related to the reflection above. It is not important to build a detailed model, but it is important to build a model that contains all the crucial elements of influence to the reference mode under evaluation (which does not necessarily need to go hand in hand). When doing initial research on fisheries and by-catch I started modelling the fish stock and tried to add by-catch and IUU to the model before even having modelled the capture fishing capacity. Doing too much research into detailed problems that occur somewhere in the system under evaluation, but are not key to the problem at hand, is very interesting, but i) not a very efficient way of time management to a project, and ii) can misguide or derail the modelling project. Therefore a combination of the above two paragraphs should help to keep the perspective on the bigger picture, while not adding too much structure in the beginning. An additional advantage of this approach is that feedback loops remain visible, and the model is easier to communicate to the audience and other third parties.

On the work itself and personal preferences

This project helped me a lot to figure out my preferences and personal needs regarding a future profession that I want to do some day. Communication is very important to me, as I figured out when I was locking myself up for a week or two to build a model without much task related communication. This is on the one hand due to the task itself, which is challenging every time again, but on the other hand also about the workflow. After calls with my supervisor I was very motivated and enthusiast, not only because of the help, but also because talking about the issue at hand also helps keeping the red line and gives fresh wind to the modelling endeavour. On a broader level of reflection I have to state that I like working on tasks that have an impact in a real life situations, which made it difficult sometimes to keep the focus on the thesis – the work I was doing is very interesting and adds more detail to the scientific body of system dynamics applied to green economy questions and natural capital valuation, but I think that a direct stakeholder would have reinforced the motivation to work on the thesis.

Working attitude - content

I picked this project on the recommendation of Andrea Bassi to work on something that I consider as ‘not my strong suit’, and to gain experiences in the field of green economy and supply chain modelling as well. While doing research for the masters’ thesis I learned a lot about different concepts that are used to define for example per capita fish consumption or fraction of recycled aluminium used. Furthermore I learned a lot more about the fishery and aluminium sector in general, and about problems regarding externalities as well as the implementation of different solutions.

Working attitude - process

Looking back, I have realized a lot of things for and about myself when it comes to working under a large degree of freedom. Working with that degree of freedom forced me to learn to set my own deadlines, since no client was pushing and it was solely my responsibility to finish the project. What I realized is that I like exploring certain questions, or systems, since I am interested in many things, but that an ‘official deadline’ makes it easier for me to plan my work and get it done.

In addition this was the first real system dynamics modelling project that I conducted by myself, meaning that I learned a lot about how I should arrange modelling and research to make the process efficient for myself, and, thanks to Andrea Bassi, progressed on my skills of building system dynamics models, though I desire to progress further and apply it on a professional level as well.

Last but not least I learned how important it is to really have one final model, and also to really think the policies through before simulating them. During the scenario analysis I often had to go back to the structure, adjust it and then run the analysis again. This made the work with the models a continuous debugging process, which was a very time consuming, but also interesting exercise to do, since I will try to minimize that extra effort in the future.

7. Results

This section will answer the two research questions based on the conducted analysis with the simulation models. First it will be described how the dynamics that underlie the BAU scenario are related to, or directly cause the inefficiencies of the two sectors. Thereafter the areas of the two sectors that are vulnerable to sustainable development will be identified, and some promising paths into the future will be pointed out. The last part of the section will describe similarities and differences in terms of the underlying structure of the two models.

7.1 How does the BAU harm the profitability of the two sectors?

This section contains the feedback loops and aspects of the two systems that have been identified as being, at least partially, responsible for causing detrimental behaviour, and thereby undermining the profitability of the sectors.

7.1.1 Fisheries

In the case of the fisheries, the underlying feedbacks that govern the behaviour undermine the sectors profitability in several ways. The first feedback loop that causes negative consequences is the capacity adjustment loop of the capture fisheries. Uncoordinated construction of capacity has led and is likely to lead the sector to overshoot on capacity and to cause the situation of the lock-in (economic pressures) to use the available capacity. Capacity is used in multiple fisheries, which increases the pressures on the fish stocks by having more capacity than required to catch at the maximum sustainable yield. By building capacity, people are either drawn into the sector for work or buy in vessels themselves. This makes capture fisheries their livelihood and thereby causes a social lock-in in terms of employment as well. That causes situation of overcapacity that needs to catch fish to earn the desired returns, it is not possible to remove capacity from a policy point of view, because of the employment it provides.

The second feedback process that harms the fisheries profitability is caused by the combination of the capacity adjustment loop, the density effect (catching efficiency loop), and the regeneration loop of the fish stock. The exploitation at quantities that are considered to be the MSY has led to situations where fish stocks collapsed, which means that the catching efficiency is decreasing – the effect of a lower fish density. Technological progress and the expansion of capacity have aided the fisheries to maintain the current level of catch, while increasing the pressures on the fish stocks at the same time. By overexploiting fish stocks, their respective regeneration rate is decreasing, because less fish is left to reproduce what accelerates the depletion of the stocks with each season. The consequence of lower regeneration rates is less adult fish that can be caught. That causes fishermen to put more effort into their fishing activities, thus decreasing the stocks even further.

The regeneration loop of the fish stock is the third process that is affecting the profitability of the sector, though not directly manageable by humans but affected through by-catch. The analysis of the IoCF scenarios shows that an inefficiency of 10% (IoCF1) already leads to by-catch quantities of 9.7 million tons of fish per year. Though there is a shift towards using by-catch for the production of secondary fish products, most of it is still thrown back into the sea, because it is more profitable for fishermen to catch and sell the target species. It is worth mentioning that a by-catch fraction of 10% is at best slightly below the average for marine capture fisheries. In his paper on the utilization of by-catch from marine fisheries, Clucas (1997) shows that in the period between 1980 and 1991 by-catch fractions for North Sea Haddock and North Sea Whiting were around 5% and 25% respectively, and that some shrimp fisheries have an average disposal rate of 85%. Therefore the loss of unused biomass is likely to be much higher than in the simulated scenarios.

Regarding aquaculture production, the dependency on fish from marine capture fisheries for the production of feed compounds (though only mentioned but not implemented in the model), can be regarded as an additional driver that increases the pressure on capture fisheries. By maintaining, and depending on the process of decoupling possibly increasing demand from the secondary processing industry, which procures its fish from marine capture fisheries, aquaculture growth has the potential to accelerate the exploitation of natural fish stocks.

7.1.2 Aluminium industry

Inefficiencies in the aluminium industry are mainly related to the increase of demand for primary aluminium, because of its environmental footprint. The first feedback process that is of influence on the sectors profitability is related to the recycling of aluminium. According to the IAI, it is assumed that all the internal scrap is collected and recycled. Opposed to this, the collection rate of old scrap is still low in some sectors of aluminium foil (32%), but also consumer durables (56%), and other electrical (56%). The overall average collection rate of old scrap in all sectors is 66%, though sectors with a low recovery fraction as foil only may have a small share in the overall availability of old scrap. Aluminium recycling is an imperative for the future of the sector. Therefore the strength of the secondary production loop is determining the amount of primary aluminium that will be required in the long run.

The two balancing loops that are representing the aluminium processing sector in the model used for this thesis haven an overall impact on the sectors performance by affecting the total demand for aluminium. Assuming an average utilization rate of 67% in the semi fabrication sector (IAI, 2015) this means that, to produce an amount of 10 million tons of aluminium, an aggregate demand of roughly 15 million tons needs to be satisfied. Five million tons of this quantity will be returned as internal scrap, and then recycled. When shipped to the processing sector for the second time, these five million tons of aluminium will have an energy balance of 105%. Thus the amount of energy used during primary production plus 5% that are added during the recycling process. The efficiency of especially the semi processing sector thus has a significant impact on the total demand for aluminium.

At the same time the processing efficiency is also determining the quantity of aluminium that is available for recycling. Making the processing sector more efficient reduces the amount of internal scrap and thereby weakens the balancing loop that has been established by the aluminium recycling sector.

Based on these insights it is not only a matter of feedback dominance. Only an increase in the recovery of old scrap aluminium would strengthen the secondary production loop, while avoiding negative effects. Some loops like the availability of budget to do research into new technologies that improve energy efficiency, and factors that drive the total demand for aluminium are not included in the model. Adding those aspects to the model would give more insight whether there is sufficient investment into new technologies, or whether the industry is relying on the subsidies from the state for its competitiveness and future viability.

7.2 Sustainable development as threat for the future profitability

In both sectors an integrated approach to sustainable development is needed. The reduction of primary capacity is desirable in both sectors, since it has the bigger environmental footprint in terms of emissions and resource input. However, only in the fisheries sector a reduction of primary capacity could re-establish the profitability of the sector. A reduction of primary capacity in the aluminium sector is not possible as long as the demand for aluminium is still growing.

In the fisheries sector sustainable development could threaten profitability in several ways. One threat would be a reduction in the allowed catching quantity if too strict policy instruments in terms of quotas are imposed. Reducing the TAC would increase the pressure on the fisheries in terms of capacity utilization and could possibly accelerate the ongoing “race for fish”. However, policy makers should be cautious and implement strategies that avoid an increase in the number of vessels, or the fishing capacity in general. Furthermore, a capacity reduction should take place in a way that combines aquaculture growth with a reduction of fishing capacity, and opportunities to employ former fishermen in the secondary sector should be sought.

Even though by-catch is an issue of importance that need attention, regulation and supervision, policies should be developed with care and in collaboration with the fishermen. By-catch quantities and species differ between fisheries and geographical areas, and experienced fishermen know best how to abate those. Many fishermen take steps to abate by-catch themselves. However this behaviour should be supported and encouraged by policy makers. Best practices should be exchanged, standardized and implemented fast within the respective fisheries that they origin from.

The aluminium sector is more vulnerable to sustainable development strategies, since improvements can mainly be achieved by technological developments in terms of process efficiency. Resistance can be expected because of the fact that producers are competing by matching their operations costs to the prices that are determined by the LME. The implementation of a carbon tax, as already be analysed by Yudken & Bassi (2009, 2010) could pose a threat especially for primary producers, but also the recycling sector. An immediate implementation without rebates and allowances for a certain period of time would yield negative consequences in both sectors. Other policies as for example environmental protection programmes in areas where bauxite ore with high yields are located would force the sector to use ore with lower yields and thereby increase the environmental footprint by increasing the amount of inputs for the same quantity of output.

The primary aluminium industry is very vulnerable to any increase in input costs, due to the way that the price is formed in the industry. Strategies that aim at making the sector more sustainable would be detrimental if they are not accounting for the time it needs to develop new technologies, or the lead times to upgrade the existing facilities. Even though the viability of the sectors is maintained by subsidies, policy makers should focus on incentivising the development of more efficient technologies, while phasing out the energy subsidies. Efficiency gains would help to avoid shifting the burden on society, which is happening at the moment by using tax payer money to keep the industry alive.

7.3 Similarities and differences of the two models

At first glance, renewable and non-renewable resources are generally regarded as distinct taxonomies. The classification of the resources takes place based on whether the resource is reproducing itself. One of the objectives of this research is to examine the genuine structures of one renewable and one non-renewable resource sector in order to broaden our understanding of the underlying structure of these sectors, and to gain insight into the functions that certain feedback loops have in these systems. The aim is to evaluate whether these systems have structural similarities, with feedback processes that fulfil the same function in the two respective sectors.

7.3.1 Similarities

(i) The production of outputs of the secondary sector in both systems is dependent on a healthy primary production sector.

The production module in both sectors have a similar structure in the sense that there is a dependency on natural capital (wild fish/bauxite), and a secondary production sector (aquaculture/recycling). This reduces the dependency on primary resource consumption and therewith the pressure on the environment. Primary production in both cases is depending on the availability of natural capital to produce output. In both models the primary sector is driven by a reinforcing loop that causes demand to grow. In the case of fisheries it is the main driver is population growth, which is not modelled explicitly, but can be easily implemented by using a stock for population and a certain growth fraction. In the aluminium mode the growth in demand is caused by the development and application of aluminium in certain sectors of society. Predictions of the IAI assume that it will continue to grow at 3% annually what indicates a reinforcing loop as well. These reinforcing loops are causing the production systems to grow and to produce the amount of output that is required to satisfy the demand. The adjustment to higher demand thus takes place through balancing loops that cause capacity to adjust and thereby supply to meet demand.
The secondary production of both sectors is depending on the availability of the primary resource. Thus aluminium cannot be recycled without the availability of scrap aluminium (internal and old), and fish cannot be produced without fish based aquafeeds. Even though research into alternative feed compounds for aquaculture is ongoing, it was up to date not possible to breed fish completely without feeding at least some wild fish. In terms of structure this indicates that growth takes place through a balancing, goal-seeking process. This process involves one or several loops, and causes the secondary production systems to grow until its potential is reached. The potential in both cases is depending on the primary production sector.

(ii) *The primary production of renewable and non-renewable resources is more intensive in terms of capital and inputs than the secondary production.*

Another similarity is that the primary sector in both resource systems has a bigger environmental impact than the secondary production sector. Environmental pressures of the primary aluminium industry are mainly attributed to the mining of bauxite and the consumption of energy and fossil fuels. The environmental externalities of the capture fishery sector are the destruction of fertile biomass and the marine environment. The functioning of primary production capacity for aluminium is dependent on several reinforcing (demand) and balancing (supply) loops that ensure the alumina supply to meet the demand for primary aluminium. The capture fishery sector is dependent on vessels, facilities to unload and transport the fish from vessels into containers on land, and on the shipbuilding industry to build the vessels. The secondary industry is relying on the availability of the primary resource, and a lower degree of fixed capital is necessary for proper functioning. This indicates that both primary sectors are more labour intensive than the secondary sectors. As a consequence, greening primary production in both systems will come with a larger loss of jobs than greening the secondary production would.

(iii) *Secondary production systems in renewable as non-renewable supply chains have the potential to erode their own resource base when offering same quality products as primary production systems for lower prices.*

In both cases the output of the secondary sector is cheaper than the output of the primary sector. The prices for these products start to increase as soon as input costs are increasing. This is due to the capital and labour intensity of the primary production, and in both cases caused by massive operations in terms of fixed capital and logistics. Both models are assuming that the products from secondary production are consumed first. In the case of fisheries because it is assumed that fish from aquaculture is solely bred for being eaten and in the aluminium sector because secondary aluminium is cheaper. This introduces a balancing loop that satisfies as much demand as there is supply form the secondary sector, and thereby reduces the demand for the primary produce. Supply from the secondary sector directly affects the balancing loop that determines the desired capacity in the primary production sectors. The long term consequence of a strong secondary production is a reduction in primary production capacity. Since the secondary sectors depend on input that originates from the primary sector (internal & old scrap / aquafeeds). The availability of input introduces a maximum production level for the secondary sector. Therefore, a reduction of primary production capacity will reduce the resource base of the secondary production sector and thus its potential to function in the long run.

(iv) Efficiency gains within the supply chain reduce upstream demand and therewith increase environmental performance while reducing employment.

As seen in the aluminium case, an increase in the utilization fractions of semi-fabrication and fabrication result in a lower total demand in aluminium. This causes (primary) production capacity to grow at a lower rate than in the BAU scenario. At the same time a higher efficiency reduces the total amount of recovered internal scrap. This affects both, the (balancing) capacity adjustment loop and the recycling loop, another balancing loop that contributes to demand satisfaction. Since emissions are a function of production quantity, the resulting, lower level of production therefore improves the environmental performance of the sector. As a consequence, a reduction in the level of capacity reduces the number of available jobs in both sectors compared to the BAU scenario. However, in the case of fisheries a capacity reduction could yield an increase in profitability of the capture fisheries sector, and a reduction in primary production of aluminium would probably increase the prices and thereby re-establish profitability as well (when for now neglecting the probability of increasing energy prices). Further analysis is needed to confirm this statement about the identified similarity of non-renewable and renewable resource systems, and their effects in terms of profitability and employment.

7.3.2 Differences

(i) *Price forming in the renewable resource system is to a larger degree supply driven than in a non renewable resource system, where prices are determined by third parties.*

Price forming in both sectors takes place in different manners. In the case of fisheries the demand-supply balance determines the price per ton of produce, thus price forming is depending on the relationship between demand and supply. The forming of the price(s) in the model depends on several demand (reinforcing) and supply (balancing) loops within the system. Opposed to the fishery sector, producers in the aluminium industry compete based on operations costs. The price of aluminium is determined by the London Metal Exchange, and producers need to meet the price in order to avoid negative returns. The product is sold in a commodity market and producers are competing based on costs. These dynamics are, were not included in the model that was constructed for this study. The cost curve is used to determine the price for aluminium. This does not mean that prices are independent of demand and supply. It indicates that not only demand and supply are determining the price, but that other external forces are involved in the price forming as well (cf. Nappi, 2013).
In the fishery sector, aquaculture supply has been more expensive until 2002 (cq. FAO fish price index). Since 2006, fish supply originating from capture fisheries is more expensive than the farmed one, which is related to several different factors. It can partially be attributed to an overexploitation of global fish stocks and increased input costs for equal catching quantities. Another reason is the increased aquaculture production and the development of more efficient production practices. In the case of aluminium, secondary aluminium is approximately 30% cheaper, even though the quality of primary and secondary aluminium often is undistinguishable.

(ii) *Conservation is a viable option for renewable resources, while it can pose a constraint on non-renewable supply chains.*

Conservation strategies have the potential to lead to improvements in environmental performance in the supply chains of renewable resources. The future prospects in the BAU scenario of capture fisheries are that the capture fishing sector is likely to stagnate or decline. This is why many countries are regulating their coastal zone fisheries in order to avoid a collapse of the stocks. The future of the aluminium industry however is very depending on the future demand for aluminium and the availability of high quality bauxite ore, since new capacity is costly and energy costs are likely to increase in the future[39]. Improvements in environmental performance can solely be achieved by process innovation and efficiency gains in terms of input-output ratios and emission rates. Environmental conservation in the case of fisheries protects the habitat of the fish stocks and therewith provides them with a safe environment to reproduce, which in the long term beneficial for the health of the resource. Conservation strategies would protect the reproduction loop of the fish stocks by protecting the fish stock itself. In the case of aluminium it would pose a barrier for the primary aluminium production, because a limit on the availability of the resource would be introduced that limits the demand satisfaction loops of bauxite production. Furthermore it would change the structure of the bauxite mining activity to a balancing loop by introducing a maximum amount that can be mined.
Therefore conservation strategies would in both cases affect the adjustment loops of the industries. While it restricts access to fishing grounds and therewith limits the availability of fish, less vessels will be constructed/used in that certain area. However, long term beneficial effects could be expected from the implementation of a conservation strategy. Land conservation could pose a threat for the expansion

[39] http://peakoil.com/alternative-energy/trends-in-the-cost-of-energy

of the aquaculture sector. More protected areas could lead to a situation where land becomes unavailable, or unaffordable, for fish farmers, which would cause aquaculture growth to stagnate. In the case of aluminium the limited availability of bauxite would lead to an adjustment of primary capacity to the available bauxite quantity, and force the industry to either use bauxite with lower yields, or strengthen its secondary production sector which is not depending on natural capital in form of bauxite.

(iii) Investment decisions in non-renewable resource systems are accounting for capacity under construction, while investment decisions in renewable resource systems are mainly based on profitability of the sector.

Another difference is the capacity adjustment process in for both primary production systems. The global fish stocks are a resource of the commons that has seen an increase in regulation through the last three decades. Since fish has been thought of being available in abundance, an increased need for regulation was perceived when the first negative side effects of unregulated fishing was affecting a large amount of people, as the depletion of the cod stock in Canada. Non-renewable resources often have an owner, either a national government or a private entity that has control over the resource. Therefore laws and contracts determine the access to the resource and the construction of capacity. The planning for production of primary aluminium is taking aspects as future demand, and capacity under construction into account before starting to build a new smelter. Fisheries mainly focus on the profitability of the sector and the availability of quotas, but not on the number of fishing vessels under construction when ordering a vessel. In terms of model structure this means that the capacity adjustment process in a non-renewable supply chain accounts for capacity under construction, while renewable supply chains do not. Therefore the strength of the capacity adjustment loop is different, and the non-renewable system is more likely to overshoot, compared to the non-renewable one.

(iv) In the examined non-renewable supply chain materials flow in a circular fashion, while the materials in the renewable supply chain are used in a linear way.

Another difference between the two supply chains is that aluminium is used in a circular fashion, due to its recyclability, while the supply chain of fish is ending with its consumption. Fish is a good for consumption, and ways to “close the loop” are out of question due to hygienic reasons. Ergo, even though a regeneration of fish takes place, the structure of this supply chain is a linear one. It starts in the ocean/pond, and ends with human consumption. Of course this is not true for all renewable resources, e.g. the supply chain of wood (e.g. paper) can have a circular structure as well, where paper is disposed and then recycled. However, the main difference between the two might also be in the mental model of people. It might be is easier to throw away food, paper or other consumer durables that are based on renewable resources, than it is if they are made from non-renewable resources. That difference might also be related to the difference in lifetime (perceived difference) or the robustness of the product, but further research is needed to gain insight into the underlying aspects that are causing this behaviour.

8. Discussion

In the literature it is often pointed out that there is no silver bullet to solve problems that are related to the triple bottom line of sustainable development. However, there are tools that allow for detailed analysis of the causal relations, and help to design integrated approaches that have the potential to create synergetic effects that a single solution could not achieve. The ultimate aim of this analysis is to explore the dynamics of two different sectors to assess whether similarities can be found for the formulation of sustainability.

The analysis of the different scenarios illustrated that strategies that aim at improving a certain aspect of a system are insufficient to achieve results on economic, environmental, and social scale. And that even though the models were simulating the globally aggregated behaviour of two major industries, meaning that a lot of details that come with a more detailed aggregation level are excluded from the models.

Some of the assumptions are unrealistic, as for example a continuous 6% growth of the aquaculture sector for the next 35 years. Compared to the World Banks' projections in the report "Fish to 2030" the growth rates for the aquaculture sector are too high, and values by 2030 are 60% higher than in the report (cf. WorldBank, 2013, p. 56). This means that the expected aquaculture growth rate is assumed to be well below 3-4% annually.

But even if the probability of the specific scenario is low it provides insight into the dynamics of the system. When looking at the different scenarios of the fisheries sector it is remarkable that none of the implemented strategies, as for example the reductions in capacity, led to a situation in which the fish stocks were able to recover. One possible explanation is that the chosen value for the reproduction fraction of adult fish is too low and therefore insufficient to represent the BAU reliably. Another explanation could be that the fish stocks are already depleted to a degree that the simulated capacity reductions of 5% and 10% under the actual MSY would not be sufficient to abate the negative consequences. UNEP (2011) states that the "current fishing capacity is between 1.5 and 2.5 times the level needed" (2011, p. 95) which indicates that there is overcapacity and that catch takes place at unsustainable levels when this capacity is used. Fleet reductions up to 2.4 million vessels are proposed, which would leave around 1.6 million vessels to remain in marine fisheries. Based on the simulation results of this study, this number is still too high to avoid a depletion of the fish stocks. This is under the assumption that the capacity value is correct. Another difficulty is that the state of the marine life stocks is very difficult to assess, but many signs indicate that we are on the road of overexploiting marine resources. This means extraction takes place at a rate that regeneration might take a long time, or not occur anymore (cf. Froese et al., 2012).

In the same line it should be questioned, whether the practice to use by-catch as input for fish meal and fish oil production is a solution, or only fighting the symptoms, but not the root of the problem (cf. Clucas, 1997). On the one hand is using by-catch for secondary production much better than simply throwing it back into the sea to die. On the other hand the marine fisheries should try to be more aligned to the functioning of the ecosystem, instead of aligning themselves to their own inefficiencies and calling it best practice. Furthermore, the numbers that are published by Clucas (1997) on the by-catch quantity should raise more red flags. By catch rates between 5% and 25% in the North Sea, and discard rates up to 98% in certain shrimp fisheries are far above the simulated scenarios. From the analysis it became clear that by-catch has significant impacts on stock levels and regeneration rates. Therefore the rates that are mentioned in the literature bear the question how long these unsustainable practices continue? The fish stock in the model is sensitive towards human activities, and especially negative externalities, and food-chain effects are not even considered in this model.

The demand for fish from capture fisheries should mainly be a function of aquaculture production. The amount of fish from capture fisheries should compensate for the share of demand that cannot be covered by aquaculture production. In addition, it provides the required amount of fish that is needed to produce the compounds for the aquaculture sector.

The same issue can be pointed out when looking at the subsidies for electricity that flow into the aluminium sector. Public payments to (semi-) private entities shift the burden onto society, since subsidies are tax payer money, while at the same time maintaining the status quo of a system that has a large environmental footprint. The industry should consider that it would benefit from improvements in energy efficiency. According to a study of The Australian Institute (Turton, 2002, p. 19), an average amount of 8.5$ per megawatt hour, or a total of 210 million dollars in annual subsidies for low-priced energy are paid to the Australian aluminium smelting industry alone. And these costs are still at a minimum estimate, which means that the real numbers are probably much higher. By doing so, governments are supporting the inertia which is inherent in large industries. That allows those industries to make profits by using a business model that would not carry itself in the long run. According to a joint-study between the Fraunhofer ISI and ECOFYS (ECOFYS, 2015) energy prices above 5 Eurocents per kilowatt-hour were not competitive in the year 2013. The electricity prices that were used for the simulations reach the value of 5cts in the year 2004, and 7cts in the year 2016. Assuming the values are correct, this means that the aluminium industry is struggling to maintain its viability since at least 3 years when solely looking from an energy perspective. A successful example of the application of a new best practice is needed to motivate other players to move as well.

With an electricity share of between 30% and 50% of total costs, gains in energy efficiency would contribute to maintaining the viability of the industry. Viability, and therewith competitiveness, is not only depending on the availability of cheap energy, but also on procurement prices of raw materials. Vertical integration can make a difference due to the availability of cheaper raw materials (ECOFYS, 2015).

9. Conclusions

This study examined the supply chain structure of two different types of resources, namely renewable and non-renewable, with the aim to develop an understanding of key feedback loops that are driving the behaviour of the systems. Two simulation models were built in order to simulate different strategies that foster sustainable development in the two respective systems, and to evaluate whether the type of strategy that is efficient in the one system has comparable effects in the other.

Though renewable and non-renewable resource systems can be seen as two distinct categories, similarities in their underlying structure have been identified. First of all it is stated that the functioning of the secondary sectors depends on a healthy primary production sector. Therefore, based on the output of the primary, and requirements of the secondary sector, a cap is introduced that is the maximum possible production quantity for the secondary sector. The adjustment of the secondary production capacity takes place through a goal seeking process, with the maximum value as goal. The second similarity is that the labour and capital intensity, as well as environmental impact of primary production sector, is higher than that of secondary production sectors. Increases in primary production will thus increase the pressures on the environment. Based on the scenario analysis of the fisheries, increases in marine capture capacities are likely to undermine the profitability of the sector even further. In terms of greening an industry, this means that a loss of jobs is almost unavoidable in the short run. As a third aspect, it has been pointed out that a secondary production sector has the potential to undermine its own viability by harming the viability of the primary production system by selling same quality products at a lower price. It was argued that the secondary production sectors in both systems are depending on the primary sectors input. Due to lower capacity requirements, the secondary sectors are able to sell at lower prices. If the secondary production loop gains dominance in terms of demand satisfaction, while still being dependent on primary production, it might undermine the future potential of the secondary production system. For this to happen the output of the secondary production sector would need to reach a critical quantity to undermine its primary sector in terms of quantity.

Next to similarities, some differences have been identified as well. The first main difference between renewable and non renewable supply chains is the price forming. While price forming in fisheries take place through the demand and supply ratio, aluminium producers trade products that are priced in commodity markets. For the latter on this indicates that competitiveness means to keep operation costs below the sales price in order to stay profitable. Price forming in the fisheries sector is this more dependent on the feedback processes in the system than it is in the aluminium sector. In the aluminium sector prices are partially determined by external influences and therefore less dependent on the supply chain dynamics. Based on the literature review it was found that promising strategies for a renewable supply chain, as for example the protection of the resource base from overexploitation (conservation) would put a constraint on production systems that extract and process non-renewable resources. Technological improvements have the highest potential to improve the environmental impact of non-renewable production systems. Another feasible alternative is the reduction of upstream emissions in order to reduce the total life cycle emissions of a product. The structure of the capacity adjustment loops was identified as a third difference between renewable and non-renewable supply chains. While investment decisions in the aluminium sectors are accounting for both, capacity in place and capacity under construction, capacity adjustment in the fishery sector is driven by the profitability of the sector, and more recently by the availability of quotas. Therefore, the capacity in the fishery sector is more likely to overshoot, which is confirmed when considering the documented development of capacity in both sectors.

However, this study only covers two systems, fisheries (renewable) and aluminium (non-renewable). Differences in terms of feedback structure are likely to differ not only between, but also within different resource types. Therefore more research is needed to develop several archetypes of existing production systems, while accounting for the type or resource they process. Aspects that deserve attention are the attributes of the product, whether it is a consumer good or a commodity, the degree of circularity regarding the use of a resource, and also the environmental pressures that come with the different production sectors and possible strategies to abate those. According to the author, the identification of new systems' archetypes has the potential to blur the lines between the concepts of renewability and non-renewability. In addition, it would enhance our understanding of the complexity and interrelationships within and across sectors, and thereby foster the development of integrated strategies to abate negative effects while fostering positive ones.

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Appendix 1 – Overview and definitions of the applied validation methods

Type of test	Name	Activities involved	Application
Direct structure test	Structure confirmation	Comparing model equations with the relationships that exist in the real system (Forrester & Senge, 1980; in Barlas, 1996)	Theoretical
	Parameter confirmation	Evaluating the constant parameters against empirical knowledge, "both conceptually and numerically" (Forrester & Senge, 1980; in Barlas, 1996, p. 190)	Theoretical
	Dimensional consistency	This test evaluates whether the dimensions of the right hand equal the dimensions of the left hand of the equation, meaning that inconsistencies are discovered by direct comparison (Senge, 1979).	Theoretical / Software
Structure-oriented behaviour tests	Direct extreme condition testing	The validity of the model is assessed by parametrizing the model with extreme conditions and comparing the results with real world knowledge or formed expectations about the behaviour of the model. (Forrester & Senge, 1980; in Barlas, 1996)	Theoretical / Simulation
	Sensitivity test	This test serves to identify the sensitive parameters within the models' structure, and to evaluate whether the sensitivity in the model corresponds to the sensitivity of the real system (Barlas, 1996).	Simulation
Behaviour pattern test	Pattern prediction test	The behavioural pattern created by the simulation model is statistically compared to the behavioural patterns of the real system with the purpose of i) evaluating whether the simulation model is able to reproduce historical behaviour patterns adequately, to ii) build confidence in the accuracy of the model (Barlas, 1996).	Simulation & Theoretical