NTNU – Trondheim
Norwegian University of
Science and Technology

Feed alternatives and phosphorus efficiency of the Norwegian fisheries and aquaculture system

Magnus Inderberg Vestrum

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Supervisor: Daniel Beat Müller, IVM
Co-supervisor: Franciska S. Steinhoff, IVM

Norwegian University of Science and Technology
Department of Hydraulic and Environmental Engineering

Abstract

With the worlds reserves of rock phosphate expected to be depleted within 50-100 years, the mapping of the flows of phosphorus in the world is crucial. The Norwegian fisheries and aquaculture industry is one of the largest industries in Norway, and is predicted to grow significantly the coming decades. This opens up to many challenges and opportunities regarding sustainability and efficient use of the available resources. In this thesis a material flow analysis (MFA) is utilized in order to investigate the current flows of P in the Norwegian fisheries and aquaculture industry with consumption and waste management.

Using the total amount of landed fish (2 578 663 tons) in 2011 it was found that the total input of P from the Norwegian fisheries were found to 10 075 tons. Of this 6 757 tons were in fish sold as food products and 2 573 tons in fish and fish scrap used for fishmeal production. In addition a total of 696 tons of P from the marine fisheries were used in other industries. From the total production of farmed fish (1 142 892 tons) it was estimated that the total P content of the feed used was 15 240. Of this 5 394 tons were from import of animal feed components, and 8 121 tons were imported vegetable feed components. Of the total input to the aquaculture it was found that only 4 576 tons were retained in the farmed fish, and that 10 334 tons were lost due to sloppy feeding, excretion and faeces. As a significant amount of the P in fish is located in the bones, 1 825 tons were located in fish scrap which were used by other industries. Thus only 2 751 tons were to be found in the farmed fish sold as food products and together with marine fish the total export of P in fish was found to be 7 732 tons.

According to predictions the landing of marine fish in Norway is expected to be 4 million tons in 2050, and the total production of aquaculture 5 million tons. Using these predictions it was found that this would lead to a total of 15 629 tons of P in landed catch, and 19 987 tons in produced animals from the aquaculture industry. As a consequence of the increased production in aquaculture it was found that the total emissions would be a total of 45 132 tons P.

In addition a number of scenario analysis were performed in order to investigate the potential for alternative feed sources in the aquaculture industry. It was found that with a high degree of fileting of marine and farmed fish, this fish scrap could significantly reduce the dependency upon imported feed components in the aquaculture industry.

Sammendrag

Med utgangspunkt i at verdens reserver av mineralsk fosfat er beregnet å være brukt opp innen 50-100 år, er kartleggingen av flyten av fosfor i verden meget viktig. Den norske fiskeri- og havbruksnæringen er en av de største industriene i Norge, og er forventet å vokse betydelig de kommende årene. Dette åpner for mange utfordringer og muligheter hva angår bærekraft og effektiv bruk av de tilgjengelige ressursene. I denne oppgaven blir en material flyt analyse benyttet for å undersøke den nåværende flyten av fosfor i den norske fiskeri- og havbruksnæringen.

Med utgangspunkt i den total mengden fangst (2 578 663 tonn) i 2011 ble det funnet at den totale tilførselen av P fra norske fiskerier var 10 075 tonn. Av disse var 6 757 tonn i fisk til konsum og 2 573 tonn i fisk og fiskeavfall brukt til produksjon av fiskemel. I tillegg ble 696 tonn av fiskeavfall brukt av andre industrier. Av den totale produksjonen av oppdrettet fisk i 2011 (1 142 892 tonn) ble det beregnet at den totale tilførselen av fosfor i fôr var 15 240 tonn. Av disse tonnene var 5 394 tonn importert i form av fôrbestanddeler av animalsk opprinnelse, og 8 121 tonn var importerte fôrbestanddeler av vegetabilsk opprinnelse. Av den totale tilførselen av fosfor til norsk oppdrett ble det funnet at kun 4 576 tonn ble tatt opp og beholdt av fisken, og at 10 334 tonn gikk tapt som en følge av fôringssvinn, ekskresjon og avføring. Siden en majoritet av fosforet i fisken er i bein, ble det funnet at 1 825 tonn P var i slakteavfallet som videre ble utnyttet av andre industrier. Dermed var den totale mengden av fosfor i oppdrettsfisk solgt som mat kun 2 751 tonn, noe som ga en total eksport av fosfor på 7 732 tonn.

Forutsigelser for 2050 anslår den totale fangsten til å bli 4 millioner tonn og den totale produksjonen av oppdrettsfisk 5 millioner tonn. Ved å benytte disse forutsigelsene ble det beregnet at dette ville medføre en samlet tilførsel av fosfor som fangst på 15 629 tonn, og 19 987 tonn som produsert oppdrettsfisk. Som en konsekvens av den økte produksjonen i havbruksnæringen ble det beregnet at den totale mengden utslipp av fosfor ville bli 45 132 tonn.

I tillegg ble det gjennomført en analyse av flere scenarioer for å undersøke potensialet for alternative fôrressurser i havbruksnæringen. Det ble funnet at med en høy grad av slakteavfall fra fiskeriene og havbruksnæringen, kunne dette fiskeavfallet drastisk redusere avhengigheten av importerte fôrmidler til havbruksnæringen.

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1 Introduction

As a limited resource, it is vital to investigate and map out the phosphorus flows in the world today. This could work as an incentive to improve technology and reduce any unnecessary losses of P. In this study the flows of phosphorus in the Norwegian fisheries and aquaculture industry will be investigated, with a scaled-up system also taking the consumption and waste management of the fish and food products into account. In addition a number of scenarios will be analysed in order to estimate the P flows according to future projections of the Norwegian fisheries and aquaculture, and how flows with a current low efficiency can be improved.

1.1 The role of phosphorus in a modern world

Since its initial discovery in 1669 by the German alchemist H. Brandt the role of phosphorus in the world has been mapped and the understanding of its importance for life has been shown to be massive. Being a key element in both DNA and RNA, which hold and translate all genetic information in an organism, and also essential for the energy transport in all organisms, the importance of P to life on earth, can hardly be underestimated.(European Fertilizer Manufacturers Association 2000; Smil 2000; Cordell et al. 2009)

The discovery of phosphorus led to an extensive mapping of its abundance and characteristics, and a simplified illustration of the flows of P in the world can be found in Figure 1. The long term, and main, cycle of phosphorus is a time consuming and complex cycle. Phosphorus naturally occurring in soil (or as a result of human activities) can be transported by soil erosion, mineralization, weathering or runoff transfer to aquatic systems such as rivers, lakes or oceans. When in an aquatic environment the phosphorus will take part in the secondary water-based cycle before it will sink to the ocean floor and into the sediments. From the ocean floor the phosphorus can piggyback on the tectonic uplift and after 10^7 to 10^8 (marked with red in Figure 1) years the P-containing rocks are exposed to denudation, spreading the P to soils where it partake in the secondary land-based cycle before the cycle is closed and the P once again goes into water bodies (Smil 2000).

In contrast to the primary cycle, the two secondary cycles, that is land- and water-based, have a significantly shorter cycling, just 10^{-2} to 10^{0} years. These cycles are driven by the uptake of P from the soil by plants or algae, and the return of P to the soil when plant litter and other biomass are decomposed. The cycle between plants and soil can be seen marked in green in Figure 1. With the utilization of these cycles, humans have therefore used organic matter like manure or other waste to increase the output of crops in centuries.

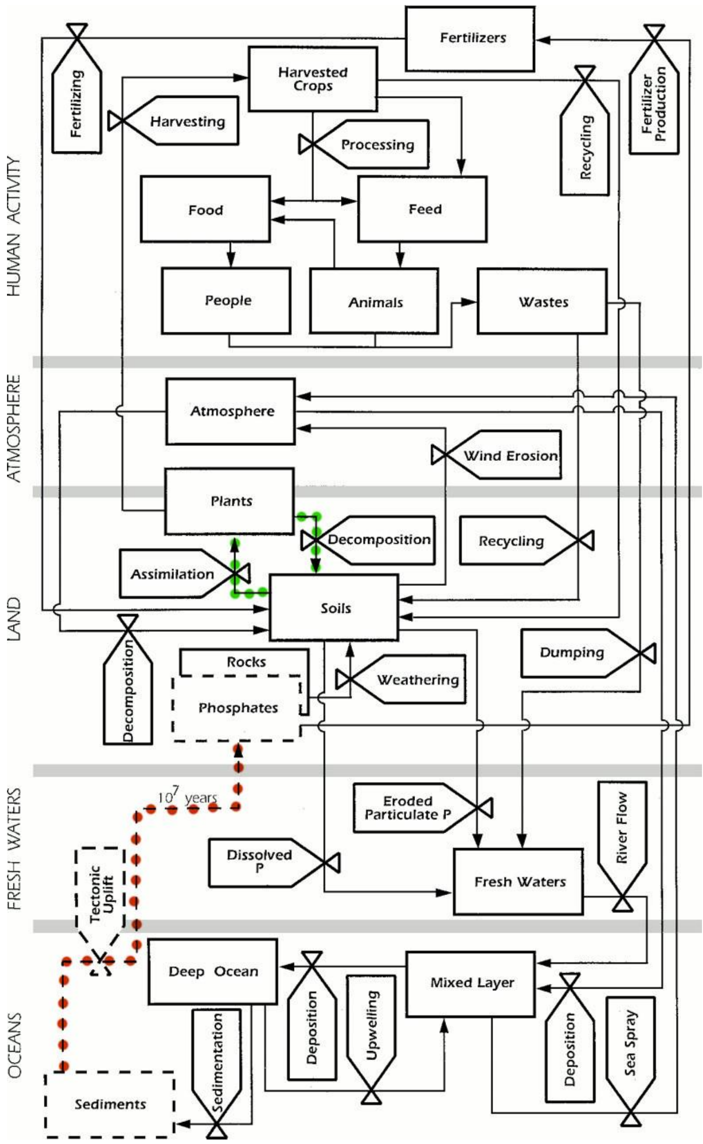

Figure 1: Global P cycle, adapted from Smil (2000)**. Red dots in the lower left corner indicate the sedimentation, tectonic uplift and forming of phosphate rock. Green dots represent the land- based cycling of P between plants and soils.**

1.1.1 A limited resource

From the very beginning of crop production, the addition of manure and other organic matter, like human excreta to the fields, have been essential in order to get good results on the crops. The recurring famines in Europe in the 17th and 18th century as a result of soil degradation, forced the discovery of additional phosphorus sources in addition to the traditional supplements. In England this need was covered by importing large amounts of bones from other European countries, which were used as fertilizers(Cordell et al. 2009), as bones contain large amounts of P in the form of hydroxyapatite (Smil 2000), and all over Europe fertilizer factories were established around cities producing fertilizers from different organic waste. (Cordell et al. 2009)

With the discovery of the phosphorus-rich guano, bird droppings deposited over millennia, and phosphate rock, the use of organic matter as a source for P was replaced. However, being a limited resource, the guano fields were depleted by the end of the 19th century, and with it the focus shifted towards the mining of phosphate rock. This was seen as an infinite resource, and having a higher concentration of P than manure (Smil 2000), the demand for mineral fertilizers grew rapidly. With the co-occurring introduction of water closets in cities, meaning that the P rich waste was discarded into water bodies and not returned as fertilizer to the agriculture. This lead to an outcry from intellectuals, amongst them Victor Hugo, who's writing were cited by Cordell et al. (2009):

"*Science, after having long groped about, now knows that the most fecundating and the most efficacious of fertilizers is human manure. The Chinese, let us confess it to our shame, knew it before us. Not a Chinese peasant – it is Eckberg who says this – goes to town without bringing back with him, at the two extremities of his bamboo pole, two full buckets of what we designate as filth. Thanks to human dung, the earth in China is still as young as in the days of Abraham. Chinese wheat yields a hundredfold of the seed. There is no guano comparable in fertility with the detritus of a capital. A great city is the most mighty of dung-makers. Certain success would attend the experiment of employing the city to manure the plain. If our gold is manure, our manure, on the other hand, is gold*"

With the increased use of artificial fertilizers based on mineral phosphorus, the amount of food produced increased and saved millions of people from starvation (Cordell et al. 2009). Today the consumption of artificial fertilizers with P in the agricultural sector amounts to around 15 Mt every year (in 2010/11 a total of 8 901 tons of P fertilizer was used in Norway, in addition to the 12 000 tons of P from manure (SSB 2012i)) and the demand for food on a global scale is dependent on the use of mineral fertilizers. Thus the world is effectively addicted to phosphate rock (Cordell et al. 2009; Smil 2000).

Considering modern day food production and its dependence on regular inputs of artificial fertilizers derived from phosphate rock mining, assessing the situation of the global reservoirs of phosphate rock is critical. On a global basis, 30 countries are extracting phosphate rock, however, the distribution of the amounts mined are skewed and the top 12 producing countries extract more than 95% of the total production. Furthermore the 3 top producers, the United States, China and Morocco produce 66% of the total, and the US alone 33%. Recently China, in order to secure domestic needs, imposed a high export tariff on phosphate, which effectively prevents any export. Import of phosphate from Morocco is also politically sensitive as much of the phosphate mined can be found in currently occupied Western Sahara, and as a result many countries, Norway included, have boycotted imports from Morocco in later years (Smil 2000; Cordell et al. 2009; European Fertilizer Manufacturers Association 2000).

In addition to the abovementioned factors the quality of mined phosphorus is decreasing, having decreased from 15% P in the early 1970s to 13% P in 1996, meaning that more rock have to be mined in order to meet the demand for mineral based artificial fertilizers (Cordell et al. 2009; Smil 2000).

With the estimated population growth up to 2050 and the resulting increase in food production, the global demand for phosphorus is expected to increase by 50-100% within 2050. Taking into account that many studies have shown that the current global reservoirs will be depleted within 50-100 years, finding new sources of phosphorus will become increasingly important (Smil 2000; Cordell et al. 2009).

1.2 The importance of fisheries

The predicted increase in food production will occur in all areas of the world and the marine environment will most likely be extremely important. Today it is estimated that a total of 1 billion people rely on fish as an important and essential part of their diet (Chen 2008), and given the expected population increase there is reason to expect this number to grow.

In Norway the marine fisheries are one of the most important industries and in 2011 a total of 2 578 663 tons of different marine species were landed in Norway (SSB 2013c; The Norwegian Directorate of Fisheries 2012), and this is predicted to grow to 4 million tons within 2050. As marine fisheries are based on the catch of a natural resource, the growth in the fisheries will have to be based around a well-regulated harvest of the resources and this will lead to the development .

Given the expected increase in the demand for fish and fish products, it is widely accepted that one will have to look to other production methods in order to be able to secure a steady supply of food. One such production method could be the farming of fish and other marine organisms, which is an industry that has grown significantly the last decades. Assumed to grow to 4 million tons in 2050 (Olafsen et al. 2012)

1.3 Aquaculture as a food resource

Since the 1950s rearing of fish in cages has become an increasingly important food source with a total global production of about 80 million tons in 2010 (FAO Fisheries and Aquaculture Department 2012). This growth can be illustrated by the increase of fish produced in the Nordic countries. Between 1974 and 1994 the total production of farmed fish in the Nordic countries increased from 15 800 tons to approximately 250 000 tons (Islam 2005), and in 2010 Norway alone produced 939 575 tons of Atlantic salmon, increasing to 1 065 975 tons in 2011 (see Appendix a for details) (SSB 2012a), and the growth experienced can clearly be seen in Figure 2.

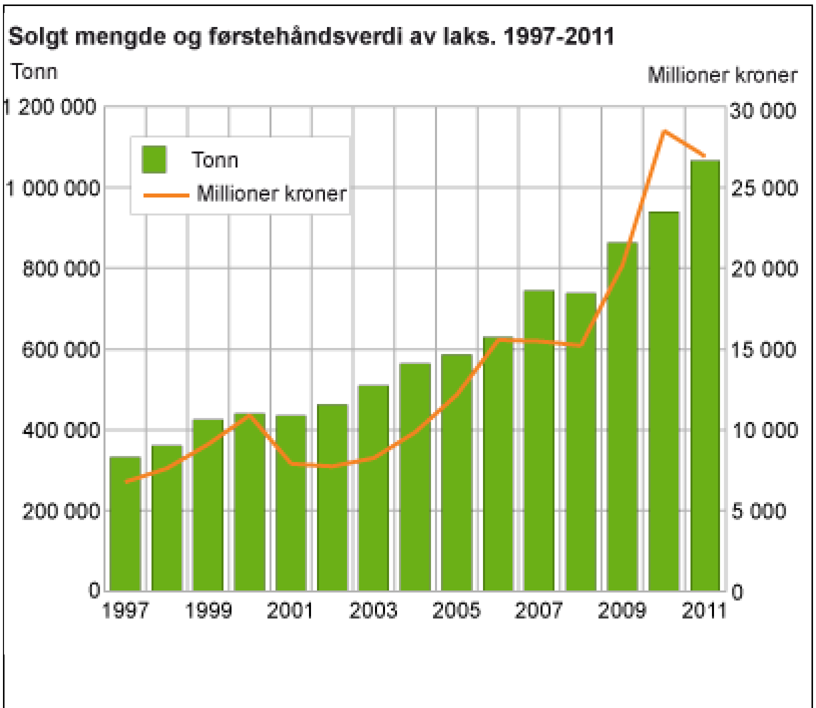

Figure 2: Total amount sold salmon, round weight, and landed value in the period 1997-2011(SSB 2012c)

The production of salmon in Norway in 2011 accounted more than 93 % of the total production of farmed fish in Norway for the given year (1 142 892 tons) (SSB 2012c; SSB 2012a), and the landed value was reported to be 27 billion NOK (SSB 2012c). In comparison the catch of fish and crustaceans by Norwegian vessels the same year can be seen in Figure 3, and was reported to be 2.3 million tons with a landed value of 15.9 billion NOK. This made fish the third biggest export article in Norway after oil and gas, and metals, accounting 5.7% of the total Norwegian export (SSB 2012g).

Taking into account that the total amount of meat produced in Norway the same year was reported to be about 325 000 tons (SSB 2012j), it is clear that the sheer amounts produced make the aquaculture sector an important food producer.

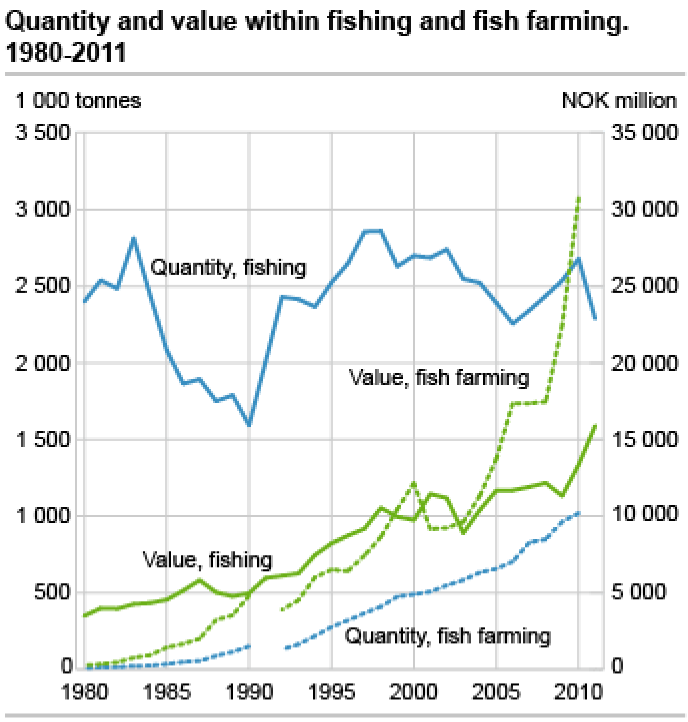

Figure 3: Quantity and value within fishing and fish farming. 1980 - 2011 (SSB 2012g)

With the world population reaching 7 billion in 2012 and an expected population of 9.3 billion in 2050 (United Nations, Department of Economic and Social Affairs, Population Division 2011), food production will have to increase significantly to ensure food for everybody. In order to keep up with the population growth and assumed increased consumption, it is estimated that the food production will have to increase by 70% within 2050. As an effect of climate change and limited fresh water it is doubtful whether this increase can be ensured by agricultural means only (Olafsen et al. 2012). The role of aquaculture as a food source in the future can therefore become increasingly important. Aquaculture in Norway has experienced an average annual growth of 10% the last 20 years and given the same rate of growth the Norwegian production would be more than 40 million tons in 2050. The growth rate is, however, not expected to continue at the same rate and in 2012 a report by Olafsen et al. estimated that the Norwegian aquaculture industry will produce about 5 million tons by 2050.

1.3.1 Aquaculture as a threat

In 2011 SSB reported that a total of 387 000 farmed salmon escaped from production facilities and the Directorate of fisheries in Norway reported a total of 405 000 escaped salmon. An increase from 2010 when 215 000 salmon were reported to have escaped. These numbers are based on reports from the fish farmers, and thus there is some uncertainties regarding these numbers (Fiskeridirektoratet 2011; Fiskeridirektoratet 2012b; SSB 2012c).

Taking into account that the total stock of wild Atlantic salmon was estimated to be 3.5 million in 2008 (Hindar et al. 2011), and that it has been shown that escaped farmed salmon cause a significant threat to the indigenous salmon by lowering fitness and reducing growth rates of wild populations (Nislow et al. 2011), it is clear that the farming of salmon causes is a significant threat to wild salmon populations.

1.4 Phosphorus in fisheries and aquaculture

As phosphorus is an essential nutrient to all life, it is also important for the farming of fish. Phosphorus deficiency in fish has been shown to cause significant physical reactions in the fish. Such signs of phosphorus deficiency include poor growth, poor feed efficiency and poor bone mineralization (Lall 1991).

In fish most of the phosphorus is bound up in the bones of the fish (86%-88%), where it exists as calcium phosphate and hydroxyapatite. The remainder of P in fish is found in cells and extracellular fluids in the form of different proteins, phospholipids and ions and total P content of a whole fish is estimated to be approximately 0.4-0.5% of the round weight. As the phosphate concentration in aquatic environments is low, the main source to phosphorus for fish is the food consumed and this is also the case for the fish modelled in this thesis (Lall 1991).

For aquaculture, feed entails feed particles consisting of a number of different compounds, of which fishmeal and fish oil are some of the most important ingredients (Bellona 2009). The fishmeal and oil is produced using mainly fish on a low trophic level (Tacon & Metian 2009), and fish offal generated by the landed catch. Two of the deciding factors for the continued growth of aquaculture are the sustainable harvest of fish for feed production, and the development of new feed types with a smaller total content of fish components (Naylor & Hardy 2009).

Due to the nature of population dynamics in fish stocks, the sustainable harvest of fish for feed production is essential for a prolonged use of this resource. This means that the amount of fish harvested on an annual basis can not be higher than the ability of the natural population to replenish the lost biomass with new individuals. In the modern history of fisheries there are many examples of unsustainable harvest of the natural resources, such as the collapse in the Norwegian herring fishery due to overfishing in the 70's (Store Norske Leksikon 2013) and the well-known collapse in the cod fishery at the Grand Banks outside Newfoundland.

The importance of avoiding such collapses in the future is obvious, both from an economical and environmental perspective, and for the aquaculture an unsustainable harvest can be fatal. This could be illustrated with the decline in the anchovy fisheries in Peru which, due to the weather system El Niño saw a decline in 1997. Due to the importance of this fishery for the global production of fishmeal and oil the prices for these products soared. This led to an increased awareness of the issue, and much research was done in order to replace parts of the fish components in the feed with vegetable components (NIFES 2013).

Even though the development of feed for aquaculture has led to a decrease in the dependence of fish per kg of feed output, the total amount of fish produced has grown significantly, both domestically and globally, the last decades. In 2006 it was estimated that the total consumption of small pelagic fish for feed production was 16.6 million tons on a global scale, using more than 68% and 88% of the global production of fishmeal and oil, respectively (Tacon & Metian 2008; Tacon & Metian 2009). Given the large amounts of feed, and thus fish, used in aquaculture, it would be beneficial from both an economic and environmental point of view to ensure that the feed fed is as efficient as possible.

For salmon it is estimated that the required P content in feed is about 0.6% bioavailable phosphorus. With a P content in feed of 1%-1.5%, and a total P content in live salmon between 0.4%-0.5% it would seem that there is a surplus of P in the feed. However, as can be seen in Lall (1991) the bioavailability for salmon of phosphorus in different feedstuffs fluctuates from 0% availability in phytate to 95% in sodium phosphate. Furthermore, of the feed eaten, it is estimated that only about 36% of the total phosphorus eaten is retained in the fish, 10% is excreted as dissolved waste, and the remaining 54% is excreted as solid waste in faeces (Bergheim & Braaten 2007; Lall 1991).

As this is a significant loss of a valuable nutrient, it would be beneficial, both economically and environmentally, to improve the composition of fish feed, so as to increase the ratio of highly bioavailable P from the feedstuffs, and at the same time reducing the total input of P by such an improvement (Bergheim & Braaten 2007; Lall 1991). In addition it would be an equally large gain both environmentally and economically if feeding strategies were to be improved in such a fashion as to reduce the amount of feed that is lost as a result of sloppy feeding (CY Cho & DP Bureau 2001).

1.4.1 And the continuation of the cycle

When the phosphorus is lost to the system due to excess feed, faeces, or excretion, it effectively enters the surrounding ecosystem, and it is estimated that 73% of the total addition of phosphorus to coastal waters in Norway was a result of aquaculture (Selvik et al. 2010). In 2009 it was modelled that 10 470 tons of P added to Norwegian coastal water originated from aquaculture; this accounted more than 76% of the total addition of phosphorus to coastal waters in Norway (Borgvang & T Tjomsland 2001; Selvik et al. 2010). As most of the excess feed is assumed to be eaten by wild fish living near the farming sites, it does not have a direct influence on the surrounding areas to the farms by actuating eutrophication. The faeces, mainly consisting of poorly bioavailable P quickly drops into the sediments where it once again will piggyback on the tectonic uplift and become available as phosphate rock in approximately 10 million years (Figure 1)(Lall 1991; Islam 2005; Smil 2000).

The dissolved P resulting from excretion is highly bioavailable, and will quickly be taken up by other organisms, such as algae. This excessive amount of phosphorus can affect the environment through eutrophication. In general this means that with the excessive amounts of phosphorus made available, a large blooming of algae can occur (Lall 1991). As this colossal amount of new biomass over time dies and is decomposed, oxygen is used by decomposers, which can strangle other organisms requiring oxygen, and the excess of nutrition will eventually choke the entire system.

Given the characteristics described above, the amount of P released from aquaculture in Norway could be a significant threat to the marine ecosystem. However, with current rules and regulations regarding the location of fish farms in Norway, eutrophication of marine waters is not a considerable problem, as the water has a rapid turnover rate, and the nutrients are quickly dispersed over large areas. In areas where the water is not changed at a high enough rate this can however, be a significant problem(Aure & Stigebrandt 1990).

As the known reserves of phosphate rock used for producing artificial fertilizers are expected to be emptied within 50-100 years, reuse and recirculation of phosphorus in different systems around the world is gaining attention. In aquaculture the amount of useful (bioavailable) P in the feed is essential to the growth of the fish. The focus on bioavailability of the P has caused the total amount of P in the feed to decrease, but it has been shown that the share of P that is not utilized by the fish, and thus released back to the environment is still high. This is both a problem due to the effects excessive amounts of P can have on the environment, but also a potential source for reducing the demand of artificial fertilizers produced from phosphate rock.

1.4.2 Alternative feed sources and composition of fish feed

As described in Chapter 1.4, the development of feed to aquaculture the last decades has been focused on reducing the dependency on natural fish stocks by replacing fish components in the feed with vegetable oils and protein. As can be seen in Figure 4, this has led to a significant reduction in the fishmeal and oil content in the fish feed. However, as the aquaculture industry is expected to grow significantly the coming decades (Olafsen et al. 2012), and the global production of fishmeal and oil is more or less stable (Chamberlain 2011), it is vital to look to other sources for feed.

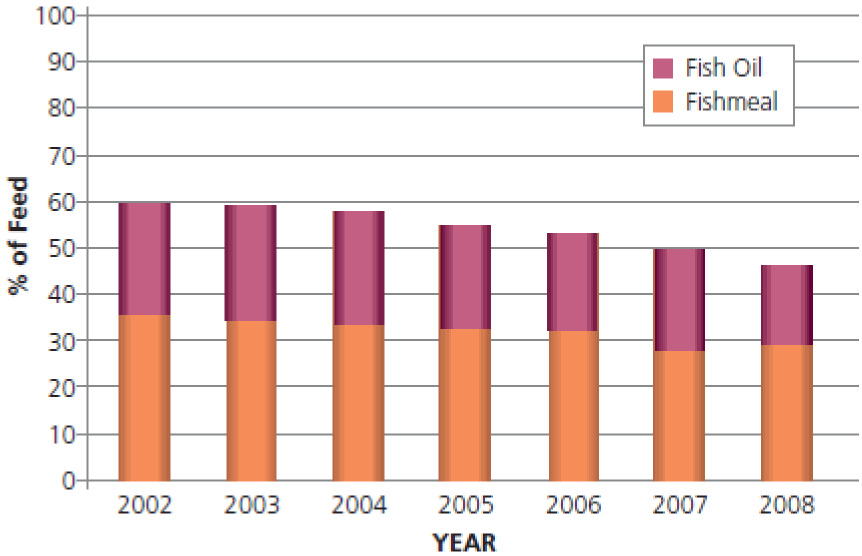

Figure 4: Use of fishmeal and oil in fish feeds produced by EWOS in the period of 2002-2008; showing a decreasing trend for the total use of fishmeal. Courtesy of EWOS (2010)

One of the limiting factors when developing new fish feed is the content of important fatty acids such as Omega-3 and Omega-6 fatty acids. These are essential for fatty fish such as salmon, and as the fish cannot synthesize them itself, it is dependent on a good access to them through the feed. As a result of this it is difficult to produce fish feed based solely on vegetable components, as Omega-3 is currently available through marine resources (Thorarinsdottir et al. 2011). Furthermore the bioavailability of phosphorus in vegetable feed components is reduced compared to components of fish (Lall 1991).

In the report by Thorarinsdottir et al. (2011) the focus was on local raw materials as a method of increasing sustainability and decreasing costs for the Nordic aquaculture industry. With this in mind it was found that a number of different raw materials could prove useful as feed components as they are rich in Omega-3 fatty acids and/or good sources for protein, lipids and other important substances. Some of the more interesting findings were the potential of micro- and macro algae as these are rich in Omega-3 fatty acids. Furthermore they remove nutrients from the water, and could thereby be used as a means of reducing the amount of P lost from aquaculture. Meal made from mussels is also rich in Omega-3, and in addition protein, but as the dry matter content of mussels is as low as 6-8%, a sustainable production of mussels for meal production could prove difficult. However, as they are filter feeders they also take up nutrients from the water masses, and could reduce any stress due to excessive amounts of P released from fish farming sites if reared in close vicinity (Thorarinsdottir et al. 2011).

A local raw material that would increase the sustainability of the aquaculture industry is the fish scrap generated both from the marine fisheries and the aquaculture. A large share of this is currently utilized for different products, and especially as feed components for poultry and pigs (Thorarinsdottir et al. 2011). As a result of the increased awareness regarding the use of waste from slaughter after the mad-cow disease "epidemic", rules laid out by the European Parliament (2008) restrict the use of fish scrap from aquaculture as a raw material for fish farming. If this resource could be utilized as a raw material for fish farming, this could help increase the efficiency of the aquaculture industry significantly. This means that with a generally higher level of utilization of fish scrap from fisheries and aquaculture, and reduced amounts used in agriculture, the fish scrap could prove a significant resource for the aquaculture industry (Thorarinsdottir et al. 2011; RUBIN 2012; RUBIN 2011).

1.5 Literature review

1.5.1 Modeling of effluents from aquaculture

The Fish-PrFEQ software developed by Cho & Bureau in 1998 is based on bioenergetic models with the aim of estimating production, feeding rations ad waste output from aquaculture. It has been used in many different studies regarding waste output in aquaculture around the world.

The MOM model (Monitoring – Ongrowing fish farms – Modelling) as described by Stigebrandt in 1999 is a general model dealing with fish metabolism and growth and with the main application focused on deriving aspects regarding water quality in and around fish farms. This model is currently being used as an environmental management tool for Norwegian aquaculture (Azevedo et al. 2011).

In a study performed by Islam in 2005 the total amount of phosphorus lost to the environment per ton fish produced was estimated to be 25kg for a hypothetical net cage system. In his study he used a feed conversion ratio of 2.5, a P content of the feed of 1.4%, an estimated loss of excess feed of 20% and a loss of P through excretion and faeces to 50%.

In a study from 2007 by Bergheim & Braaten a P content of the feed was based on an average value for the P content in feed throughout the salmons different life stages, and was thus set to be 1.05%. A loss of feed as a result of sloppy feeding (excess feed) was estimated to be 9%, giving a total FCR of 1.15. For the loss of P as a result of faeces and excretion, they assumed that 54% and 10%, respectively, of the total P intake was lost, meaning that 36% of the P in the feed eaten was taken up by the fish, and that 33% of the P of the total feed input to the system was taken up by the fish. This concluded with a total of 6kg P lost as particulate matter and 2 kg lost as dissolved waste per ton salmon produced.

Azevedo et al. (2008) used the Fish-PrFEQ tool to perform a mass balance on nutrient loadings from a rainbow trout farm and comparing them with nutrient measurements using water quality monitoring. Per ton fish produced 5.3 kg P as particulate waste was found, and 3.4 kg P as dissolved waste was found. When comparing the results from the mass balance model with the results from the water quality monitoring, it was found that the results from the monitoring were not reflective of the waste production estimated using the mass balance.

1.5.2 Treatment of effluents from aquaculture

In their study on removal of suspended solids from a land based aquaculture facility Cripps & Bergheim (2000) found that the suspended solids typically contained 30-84% of the total phosphorus in the waste water from the facility. A number of different treatment methods were evaluated, including a drum filter which was reported to remove 21-86% of the total P. This large discrepancy relied on the concentration of the effluents, thus requiring an efficient pre-treatment in order to increase the concentration of the waste water.

In a series of studies on alum, synthetic polymers and other substances, it was found that many of these had a high potential as treatment technologies for aquaculture waste, with high removal rates for phosphorus and other substances in the waste. In 2003 Ebeling et al. performed trials using alum and ferric chloride as coagulation-flocculation aids in order to remove suspended solids and phosphorus from aquaculture effluents. They found that both alum and ferric chloride showed excellent performance regarding the removal of suspended solids, and removed 89% and 93% of the orthophosphate, respectively. In 2005 Ebeling et al. used synthetic polymers as flocculation aids, resulting in a total removal of reactive P of 92%-95%. In an evaluation of the performance of an inclined belt filter with alum and synthetic polymers as coagulation and flocculation aids, it was found that the use of alum would remove 96% of the reactive phosphorus, but only 82% of solids, whilst polymers only removed 40% of the reactive P and 96% of the suspended solids. When these two methods were combined it was found that the removal efficiency for suspended solids and reactive phosphorus was 95% and 80%, respectively (Ebeling et al. 2006). In a similar study Rishel & Ebeling (2006) also using a combination of alum residuals and synthetic polymers a removal rate of 92%-99% was experienced for reactive P, and 98% of the total P.

Using alum residuals as a mean of removing phosphorus from aquaculture processing water Mortula & Gagnon (2007) found a removal rate of 94%-99% of the total phosphorus in the processing water compared to the pre-treatment content.

Whilst synthetic polymers are efficient at flocculating small particles together, it does not efficiently remove P. Alum, on the other hand, is efficient at sequestering phosphorus by chemical precipitation and coagulation of fine solids through charge neutralization (Rishel & Ebeling 2006). In addition to removing most of the P in the processing water; the use of alum residuals is a cost efficient method as the alum is a waste residual from a drinking water treatment plant (Mortula & Gagnon 2007).

In a report by KLIF from 2010 they reported that by using micro sieves treatment on sludge from aquaculture, a total of 85% of the suspended particles in the sludge was removed. This accounted for 50-65% of the total phosphorus content in the sludge. Furthermore it was reported that a system named biofish, using swirl separators and biofiltration was able to remove a total of 90.5% of the P in the sludge.

Even though many of the treatment methods evaluated show great potential for removing phosphorus from aquaculture waste, the economic viability of the implementation of these techniques are often questionable. This is because the technology is expensive and often not capable of utilization at large fish farming facilities (Mortula & Gagnon 2007).

1.6 Aim of the thesis

The goal of this thesis is to examine the flows of phosphorus in the Norwegian fisheries- and aquaculture industry in order to produce an estimate of P involved in the system of Norwegian fish industry. The chosen tool for this analysis is a Material Flow Analysis (MFA), which is further explained in Chapter 2.2. More specifically the goal is to investigate the amounts of P currently not utilized and could be recovered with a higher degree of recycling and change in production routines. With such a change in practice the recycled P could potentially be made available as a resource for different industries.

The scope can be summarized with the following main questions.

The project aims at answering the following **questions**:

1. How can we characterize the current Norwegian fisheries and aquaculture industry system in terms of feed inputs and phosphorus emissions?

2. What are the main opportunities, barriers, and open questions concerning the use and recycling of P in the Norwegian fisheries and aquaculture industry? What fraction of the feed demand could be substituted from alternative domestic (or imported) sources? What are potential alternative domestic feed sources (e.g., use of biomass waste as feed)?

3. What are the implications of alternative feed sources for the phosphorus cycle of the Norwegian fisheries and aquaculture industry system?

2 Methodology

This study investigates the current state of Norwegian fish industry, being fisheries and aquaculture, and also the consumption and waste management of products originating from the fish industry.

Furthermore, the thesis aim at modeling different scenarios for the system based on predictions made for production in 2050. The purpose of the scenario modeling is to illustrate the potential difference between the current status regarding phosphorus use and management in the Norwegian fish industry, and what this possibly could be using improved technology and recycling techniques throughout the system.

2.1 What is Material Flow Analysis

In order to model and estimate the amounts of phosphorus at play in the fish industry sector a Material Flow Analysis (MFA) will be used. From Brunner & Rechberger's (2004) handbook of Material Flow Analysis, MFA is defined as a method that allows for a systematic assessment of the flows and stocks of a given material or substance within a system that is defined by space and time. Taking the law of the conservation of matter into account, and respecting it, the results of an MFA model can be assessed by a material balance of all inputs, stocks, and outputs of the system.

2.2 System definition

From Brunner & Rechberger (2004) the following definition of a system is given: "*A system is defined by a group of elements, the interaction between these elements, and the boundaries between these and other elements in space or time. It is a group of physical components connected or related in such a manner as to form and/or act as an entire unit.*" Further they define the difference between an open and a closed system, where the open system interacts with the environment and have imports and/or exports of materials or energy or both, whilst the closed system is completely isolated from the surroundings, thus preventing imports/exports of materials or energy across the system boundary (Brunner & Rechberger 2004).

Even though the system usually defines a specific geographical area where the different processes can be found, it can also define a more abstract area. This is usually done when MFA is applied to a more specific part of an economy where it will be impractical to define a geographical area. Such a system could be the waste-management system of a county (Brunner & Rechberger 2004).

With the definitions of Brunner & Rechberger, the Norwegian fish industry can be defined as an open system as it is dependent on both exports and imports (import/export of fish, feed, other products necessary for the industry, etc.) with a temporal boundary of one year (2011 and 2050 modelled) modelled as a quasi-stationary system. Furthermore, even though the system boundary covers all of Norway, it is an abstract area. This is because the system only considers one part of the Norwegian P cycle, namely the fish industry with consumption and waste treatment, and not other important areas as agriculture and other industries; this can be illustrated by the process "Other food production" as it shows the P from fish going to other systems e.g. the Norwegian agriculture.

An important aspect of the system boundary is the exclusion of the marine fisheries as a process on its own. This choice was based on the assumption of potentially significant gaps in data regarding the dumping of fish and fish waste from industrial vessels, significant amounts of fish being directly exported and fish caught in other Economic Zones or International waters. It was therefore decided that the marine fisheries would be represented with an import flow and process illustrating the amount of fish actually landed in Norway, regardless of the origin or nationality of the vessels.

As can be seen in Figure 5 the system is further separated into three subsystems: the *Aquatic P cycle*, the *Trade and Consumption P cycle* and the *Waste Processing P cycle*, and also one standalone process (*Other use of fish* process), which illustrates the amount of P originating from fish used in other areas of the Norwegian P metabolism. This was done in order to increase the transparency of the flows between the different main subsystems in the system.

As a basic rule in the system all aquatic animals, except mammals which are not taken into consideration, is denoted as fish and fish products, and this include other species from the animal kingdom, such as molluscs unless otherwise stated.

2.2.1 The Aquatic P cycle

The *Aquatic P cycle* subsystem can be considered the main subsystem of the Norwegian Fish Industry system as this is where the main production of fish and fish products is located, and is also where the majority of inputs and outputs are located. The input to the subsystem is given by three phosphorus flows, being the marine fish landed in Norway (going to the *Marine Fish Landing* process); imported meal, feed, and fish for meal production (going to the *Feed Market* process); and any other feed stuff, such as vegetables, necessary for producing fish feed which also goes to the *Feed Market* process.

An important part of the subsystem is the process *Feed Market*, which was modelled in order to increase the transparency of the system and reduce potential "noise" due to the great amount of flows in the system.

The fish landed in Norway is separated according to the use of the fish in the *Marine Fish Landing* process. The usage areas for the landed fish are fish to consumption (to the *Market* process in the *Trade and Consumption Subsystem)*, fish and fish scrap to meal and oil production, and fish used for production of feed (other than fish feed). In addition a significant flow is the fish scrap which goes to the *Fish scrap sorting* process in the *Waste Treatment Subsystem*. The fish used for meal and oil production goes through the *Feed Market* process, which then goes to the *Fishmeal (and Oil) Production* process with additional imported fish. It is then returned to the *Feed market* as meal and transferred to the *Feed production* process with additional imported meal and other feed stuff. In addition a certain amount of fish for feed production and meal is exported instead of being used for domestic feed production. The feed produced is mainly used in the *Aquaculture* process, but a small amount is also exported, going through the feed market. A small amount of meal not meant for feed or human consumption is also imported and from the feed market it goes to the *Other Use of Fish* process, located outside the three subsystems. The majority of the P input to the *Aquaculture* process is from domestically produced feed, but a small amount is also imported feed, going through the feed market.

Due to different circumstances, e.g. sloppy feeding, not all the feed used in *Aquaculture* is eaten by the fish. The feed that is not lost is eaten by the fish (which is located in the *Farmed Animals* process), which in turn discharge a share of the total P eaten via excretion and faeces. The P in excretion and faeces is then returned to the aquaculture process, where it, together with the lost feed, escapes the system as waste from fish. In this report the P lost as a result of excretion and faeces (defecation) is modelled as two different flows due to the nature of the phosphorus lost as a result of the two processes and the different effect it can have on ecosystems. Dissolved inorganic P (DIP) is lost through excretion and particulate organic P (POP) is lost through faeces (and feed loss). This separation is important as DIP is readily available to be taken up by phytoplankton and macroalgae, whilst POP sink and may accumulate in the sediments (Wang et al. 2012; Bergheim & Braaten 2007). A certain amount of fish die during farming, and these are then taken out of the *Aquaculture* process and goes to the *Fish Waste Sorting* process in the *Waste Treatment subsystem*. The last flow from the aquaculture process is illustrating the P in fish that escapes or is lost due to other reasons; this flow is modelled to leave the system.

In the *Farmed Animals* process there is a negative stock change. This is due to the farming of shellfish (mainly mussels). Being filter feeders, the farmed shellfish does not require feed input the same way as the farmed fish, as they simply take up the nutrition needed from the water masses. The flow of animals for slaughter from the fish process to the slaughter process therefore contains the total amount of P contained in both the farmed fish and the farmed shellfish.

The last process in the Aquatic subsystem is the *Fresh Water Fisheries*. This process does not have an input and the P in fish caught and going to the *Market* process (in the *Trade and Consumption Subsystem*) therefore correlates with a negative stock change in the *Fresh Water Fisheries* process.

2.2.2 The Trade and Consumption P cycle

As the *Aquatic P cycle* is responsible for the main part of production of fish in the system, the *Trade and Consumption P cycle* is responsible for the trade of fish for consumption and the consumption of this fish. The input of phosphorus to the subsystem is given by four flows, namely the farmed animals (fish and shellfish) to the *Slaughter* process; the fresh water fish to the *Market* process; the marine fish for consumption to the *Market* process and the imported fish and fish products to the *Market* process.

Similar to the *Aquatic subsystem*, this system was modelled with a market process in order to increase transparency and reduce noise due to an excessive amount of flows.

The *Slaughter* process has one input from the *Farmed Animals* process, and two outputs with the P contained in slaughter waste going to the *Fish Waste Sorting* process and P in slaughtered fish and shellfish going to the *Market* process. In addition to the slaughtered fish and shellfish from the *Slaughter* process, the *Market* has, as mentioned above, an input from the *Fresh Water Fisheries*, the *Marine Fish Landing* process, and imported fish and fish products. The majority of the P input to the *Market* process is exported as fish and fish products, but a significant amount also goes to the *Retailer* process in order to be sold to consumers. From the *Retailer* process the P in waste produced in this process goes to the *SWT (and WWT)* (Solid Waste Treatment and Waste Water Treatment) process in the *Waste Treatment subsystem*, whilst the P in food fish and fish products purchased goes to the *Consumption* process.

The *Consumption* process represents the P in fish and fish products consumed in Norway annually. As the majority of the products are consumed, the consumed P was modelled as a positive stock change in the *Consumption* process. The part that is not consumed goes to the *SWT (and WWT)* process as wet organic waste.

In addition to the *Retailer* process one could also choose to include a process for the wholesale of fish products. In this system, this process was not included as most fresh fish usually goes directly from producer to retailers (Hanssen & Schakenda 2011b; Hanssen & Schakenda 2011a).

2.2.3 The Waste Processing P cycle

The *Waste Processing P cycle* as a subsystem has, as described previously, five inputs. These are the two solid waste flows from the *Trade and Consumption subsystem*; the slaughter waste from the *Slaughter* process; the dead fish from the *Aquaculture* process and the fish scrap from the *Marine fish landing* process.

The two inputs to the *SWT (and WWT)* process is wet organic waste from the *Consumption* process and the *Retailer* process, and the input of P is modelled as a positive stock change as this process has no outputs. Norway has a ban on landfilling of wet organic waste (WOW), and thus this is not landfilled as WOW but rather as ashes after energy recovery or other rest resources after waste treatment (Ministry of the Environment 2004; Miljøstatus i Norge 2013). The *SWT (and WWT)* process include P in both solid waste (wet organic waste) and any P originating from fish in the waste water. The *Fish Waste Sorting* process is the receptor for the remaining three processes, which then is sent to the standalone *Other Use of Fish* process.

2.2.4 Other use of fish

The last process in the system is the *Other Use of Fish* process. As previously mentioned this process was modelled in order to illustrate the amount of P originating from fish that is used in other areas of the Norwegian P metabolism. These areas include (but are not limited to) agriculture, where it is used extensively in feed, and different chemical industries. The three inputs to this process is the fish scrap from the *Fish Waste Sorting* process; the fish used for other feed (than fish feed) from the *Marine Fish Landing* process; and the imported meal not meant for feed or human consumption from the *Feed Market* process. The *Other Use of Fish* process has one export flow indicating the transfer of the P originating from fish from the P cycle for the Norwegian fish industry to other parts of the Norwegian (and potentially international) P metabolism.

2.2.5 The system for the Norwegian fisheries and aquaculture industry

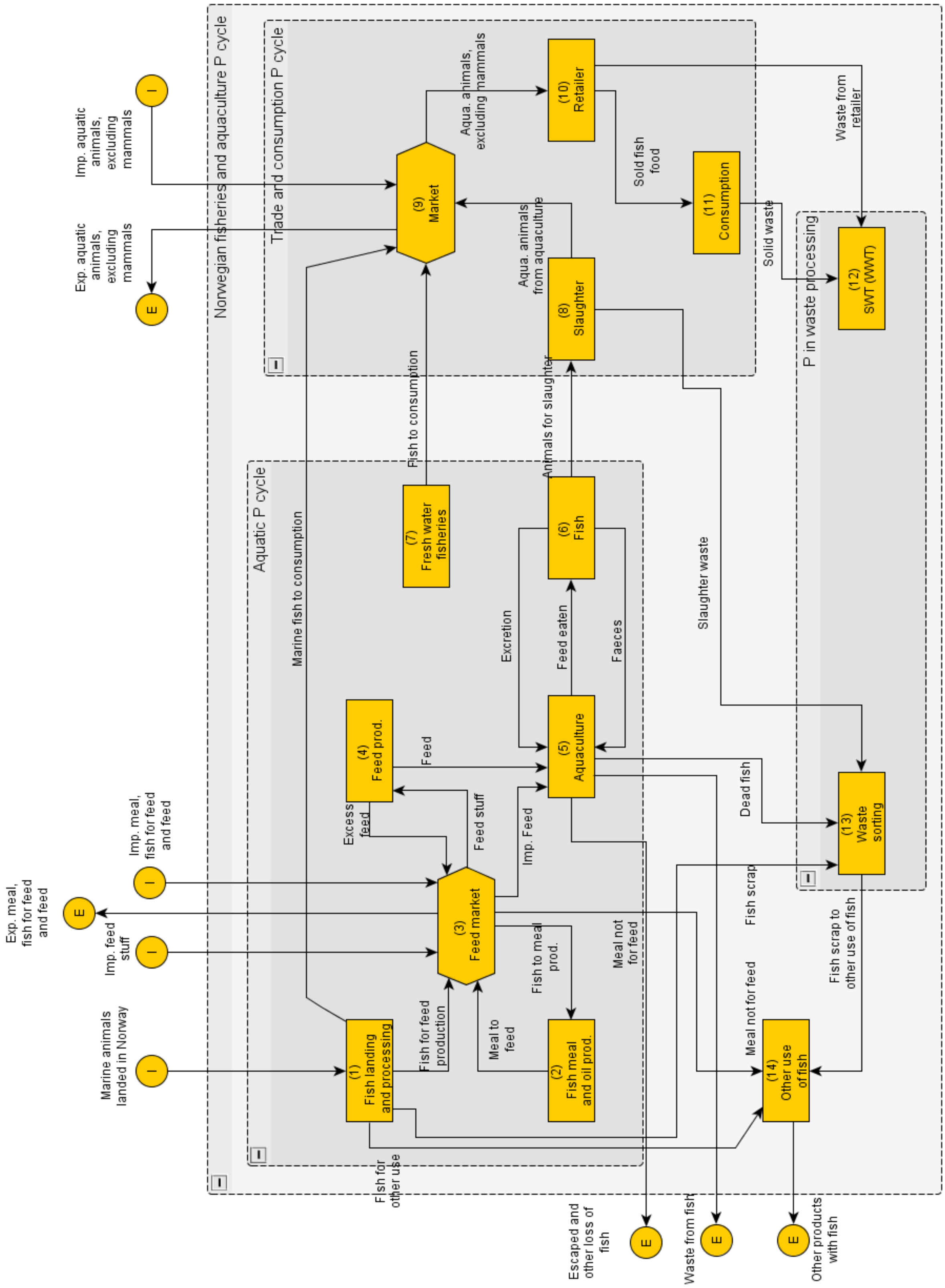

Figure 5: The P cycle for the Norwegian fisheries and aquaculture industry with consumption and waste management. In Table 1 the flows are denoted with the respective flow numbers F#. Description of the different flows and processes can be found in chapter 2.2

Table 1: The flows of the Norwegian fisheries and aquaculture P cycle with the flow number F#. It is important to note that the flow number (F#) does not follow the flows from start to end.

Flow name	From process #	To process #	F#
Marine animals landed in Norway	0	1	**F32**
Marine fish to consumption	1	9	**F15**
Fish for feed production	1	3	**F1**
Fish scrap	1	13	**F31**
Fish for "other" use	1	14	**F13**
Meal to feed	2	3	**F2**
Imp. Meal, fish for feed and feed	0	3	**F26**
Imp. feed stuff, not fish	0	3	**F24**
Exp. Meal, fish for feed and feed	3	0	**F25**
Fish to meal production	3	2	**F3**
Feed stuff for feed production	3	4	**F4**
Imp Fish feed to aquaculture	3	5	**F7**
Meal not for feed or food	3	14	**F33**
Excess fish feed	4	3	**F5**
Fish feed	4	5	**F6**
Waste from aquaculture	5	0	**F30**
Escaped and other loss of fish from aquacult.	5	0	**F29**
Feed eaten	5	6	**F14**
Dead fish	5	13	**F12**
Excretion	6	5	**F22**
Faeces	6	5	**F23**
Animals for slaughter	6	8	**F17**
Fresh water fish to consumption	7	9	**F16**
Aqua. Animals from aquaculture	8	9	**F18**
Slaughter waste	8	13	**F11**
Imp. Aquatic animals, excluding mammals	0	9	**F28**
Exp. Aquatic animals, excluding mammals	9	0	**F27**
Aquatic animals, excluding mammals to retailer	9	10	**F8**
Sold fish food (food products)	10	11	**F9**
Waste from retailer	10	12	**F19**
Solid waste from consumer	11	12	**F10**
Fish scrap to other use of fish	13	14	**F20**
Other products with fish	14	0	**F21**
Net stock accumulation #6	-	-	**-**
Net stock accumulation #7	-	-	**-**
Net stock accumulation #11	-	-	**-**
Net stock accumulation #12	-	-	**-**

2.3 Model development

The development of the model is the most crucial part of the study performed, and in the following section the different steps towards developing the model is described.

2.3.1 Development of processes and parameters

As much of the analysis is based on public data from Statistics Norway and the Norwegian Directorate of Fisheries special measures had to be taken into account in order to produce an estimate of the P values that would regard the different species concerned. This meant that an average P content was estimated for different product groups, and product categories. The parameters denoting P content for the different product categories appear to be identical, and one could most likely reduce the number of parameters. However, due to the significant amount of data, and the importance of updating large data sets as new information surfaced, it was decided that this was the best way to perform the independent analysis of the different data sets obtained.

One of the most important parameters for the entire system is the phosphorus content of fish. As reported by Lall (1991) the total P content of fish is between 0.4% and 0.5%. As this is a physiological factor and hence not a parameter that we can manipulate, this is a key parameter that the system have to balance itself against. In this report the P content in fish was decided to be 0.4% as this was the initial value used when developing the model. It was also found to be the P content in salmon when doing back calculation on other studies assessing the nutrient flows in aquaculture (Bergheim & Braaten 2007).

An average P content for whole shellfish (with the shell) was estimated to be 0.25%. This was based on data for farmed oysters from Newell & Mann (2012) as other, and potentially better, data could not be obtained.

These two P contents (fish and shellfish) are the basis for all recalculation of P content for the different flows in the system given the composition of the flows (amount fish/shellfish).

2.3.1.1 Development of processes and parameters for the Aquatic subsystem

From Statistics Norway and The Norwegian Directorate of Fisheries (2012) the total amount of marine fish landed in Norway in 2011 was found to be a total of 2 578 663 tons. Using the use categories from SSB (2013b) for the different species landed, the catch was separated into three categories: Fish to consumption; fish to meal and oil production; and fish to other feed and use. The amount to the three categories was 2 051 470 tons, 509 289 tons and 17 904 tons, respectively. In addition data from RUBIN (2011) showed that of the total amount of fish landed a total of 350 000 tons of fish scrap was used as a resource for different products. Of the 350 000 tons of fish scrap, 49.22% was used for fish meal and oil production, and the remainder to the fish waste sorting. It was assumed that this fish scrap originated from the share of the landed catch meant for consumption, as the production of meal and oil, and other usage areas, generally use the entire fish, leaving little scrap (FAO Fishery Industries Division 1986). As the landed catch included a variety of species, an average P content of the total landing was estimated to be 0.39%. This estimation was based on the assumption of a P content in different fish of 0.4% and a P content of different shellfish of 0.25%, meaning that little of the total landed catch was shellfish. Further it was calculated that for the fish going to consumption an average P content of 0.4% was calculated. For the fish going to the production of meal and oil an average P content of 0.37% was calculated, whilst the fish scrap used in meal and oil was estimated to have a P content of 0.4%. This estimation was based on uncertainties and lack of data regarding the composition of this fish scrap, and therefore calculated using the main P contents of fish and shellfish (0.4% and 0.25%). The fish used for other feed and products was found to contain a majority of different shellfish and the P content was calculated to be 0.27%. (Appendices n, o and p)

The amount of fish meal imported to Norway was calculated from the national trade statistics (SSB 2013d) indicating a total amount of 230 047 tons of fish meal, of which 39.2% of the fish meal was estimated to originate from pacific countries, and was thereby classified as Pacific type fish meal. This was essential as the P content of different fish meal types varies, and this can be seen in Table 2. This meant that the average total P content of the fish meal was balanced against the different P contents, giving an average P content of imported fish meal of 2.17%. In addition a minuscule amount of meal (5.5 tons) was imported which was not meant for either consumption or feed production; given the originating countries of this meal it was estimated that the P content would be equal to the domestically produced meal of 1.67% (which is explained further on).

In addition to the import of meal, fish for feed production and fish feed were also imported. It was assumed that the fish for feed production (feed fish/misc. in Appendix d) was used for meal production. This assumption was based on the fish species in the category and the details on the different trade flows from The Norwegian Customs Office (2011). The total amount of fish for meal production imported to Norway was 18 197 tons and the P content was chosen to be represented by the standard P of 0.4% due to lack of other good data on this. The total amount of fish feed imported in 2011 was found to be 30 383 tons, and the average P content for feed (explained later) of 1.05% was chosen for this.

The export of meal, fish for feed production and fish feed in 2011 was found to be 24 285 tons, 63 716 tons and 14 937 tons, respectively. In addition a total of 1 001 tons of meal not for feed or consumption was also exported. It was decided that the exported goods would have the same P content as the imported goods, except for the exported meal. As it was assumed that the exported meal was produced in Norway, it was decided that the P content of exported meal would be the same as that of meal produced and used in Norway.

Based on collected information it was assumed that the fish to meal yield (kg fish required to produce 1 kg meal) was to be 4.39. (FAO Fishery Industries Division 1986; Skretting 2011a; Skretting 2011b) Based on the mass balance of P in the domestic and imported fish and fish scrap for meal production and the produced meal, it was found that the P content of the domestically produced meal was 1.67%. This appears low compared to the P content of the different fish meal types according to FAO Table 2, and could very well be due to the average P content of the fish for meal production to be artificially low. However, as data for the P content in the fish was hard to come by, it was decided that the P content of the fish was tolerable. This again could very well be a reason to the very large import flow of vegetable feed stuff, as a higher P content in domestic meal would have reduced this flow. Furthermore, due to uncertainties regarding the use, origin and composition of *White fish meal*, it was decided that the meal content would be based on the calculated P content for domestic meal, and the South American type fish meal.

Table 2: The total and bioavailable phosphorus content of the different fish meal types (FAO Fishery Industries Division 1986)

	White fish meal	Herring type fish meal	S. American type fish meal
Phosphorus % (total)	4.80	1.90	2.60
Phosphorus % (available)	4.80	1.90	2.60

For the import of other feed compounds, that are non-fish components (vegetables), this flow was modelled based on the mass balance for the domestic feed production. This was done due to difficulties finding precise enough data on what these vegetables were, and the amount imported. It is important to note that some data exist on this subject as well, but it was deemed to old given the rapid development of the aquaculture feed industry, which can be illustrated by the significant decrease in meal content in fish feed.

Initially it was assumed a meal content in fish feed of 31.8% for salmon feed and 26.6% for cod feed (Skretting 2011a; Skretting 2011b; Bellona 2009), however, from import export data and use data of landed fish in Norway the average amount of meal in feed was redefined to be 23.98%. Comparing this result with data from 2001 where the average meal content in feed was given to be 350g kg^{-1} (Waagbø et al. 2001), these results are in correlation with trends and goals regarding the development of fish feed (Naylor & Hardy 2009; EWOS 2010; Espe et al. 2006). In addition to the different meal content in the feed the amount of feed for the two different species was estimated. This was based on the assumption that feed for Atlantic salmon, Pacific trout and char had the same composition (they are all salmonides), and that feed for cod, halibut and other fish species had the same composition. These assumptions are of course not very solid, however, the amounts of feed for cod, halibut, other and char were so small compared to salmon and trout, and data on feed composition for these species' were not found other than for salmon and cod; making the assumption tolerable. This gave that salmon feed (Atlantic salmon, Pacific trout and char) accounted approximately 98.5% of the total feed, and the remaining 1.5% was for cod, halibut and others. With the calculation of the new meal content of 23.98%, this parameter became somewhat obsolete (as both feed types had 23.98% meal), but it was decided to keep for potential modeling of a more diverse aquaculture industry.

Fish oil was considered redundant as no data on P in fish oil was available, and it therefore showed no greater value for the system as a process. However, if one were to produce a system showing the mass flows in the Norwegian fish industry, this flow would have to be included as importance of the oil and the amounts is essential to both the aquaculture and other industries.

The P content in fish feed in this study was chosen to be 1.05% as this is an average of the P content in the feed fed to the salmon in different life stages (Bergheim & Braaten 2007; SINTEF Fiskeri og Havbruk AS 2011). Given that the farming of Atlantic salmon accounted for more than 93% of the total production in 2011, this value was chosen as a standard value for all feed used. This gave a total input of P to Norwegian aquaculture of 15 240 tons. In another study by Reid et al. (2009) the P content of one Atlantic salmon feed was estimated to be 1.2 %, which would have given a total input of P to Norwegian aquaculture of 17 220 tons. However, as the value of 1.2% only represented one feed type, and the value of 1.05% represented an average, the latter was chosen.

One of the main parameters in the subsystem is the Food Conversion Ratio (FCR), which denominates the ratio between dry feed input to aquaculture, and round wet weight fish produced (OSPAR Commision 2004). Data from FHL (2012a) gave the total amount of feed used in farming of salmon and trout in 2011 to be 1 435 000 tons, and given the data from SSB (2012e) for the total production of salmon and trout of 1 124 339 tons, the FCR was calculated to be 1.28 (1,435,000/1,124,339 = 1.28). This means that for every kg of trout and salmon produced, 1.28 kg of feed is used. As the production of salmon and trout accounted for more than 98% of the total farmed fish in Norway in 2011, and little data on FCR for other species, this FCR was chosen to reflect all farming of fish in Norway. This FCR is somewhat higher than the FCR the main organization for Norwegian fish farmers (FHL) operates with (1.2) (FHL 2012b), but it can be assumed that this value is a guideline, not a factual value.

Compared to the average FCR for aquaculture facilities in Norway which was reported to be 1.23 in 2007, with an average FCR of 0.88 for the 10 best facilities and an FCR of 1.74 for the 12 worst facilities (Bergheim & Braaten 2007), this calculated value indicated a lower feed efficiency. However, it has also been reported that the individual FCR for every facility varied from 0.53 to 2.26. In a more recent study performed by Wang et al. (2012) found that the mean FCR for Norwegian salmon farms in 2009 was 1.16 ± 0.08. The possibility that the higher calculated FCR could be due to the farming of trout being included was checked, but the 2011 FCR for only salmon farming was found to be 1.27, meaning that this was still significantly higher than the previously reported values. The possibility of FCR values lower than 1, is difficult to explain, but could possibly be explained by the fact that the feed and fish is calculated in dry and wet weight, respectively.

Initially the amount of P lost from the farming of fish was determined using an older version of just the aquaculture system (*Aquaculture; fish and slaughter* (Vestrum 2012, unpublished)). After identifying important inconsistencies in this system leading to unbalanced flows, the excretion (DIP) and faeces (POP) flows were adjusted to the total P contained in the farmed fish and the amount of feed fed. This was done by adjusting the excretion coefficient as it is a biological factor, and not as easy to tamper with as the coefficient for the P lost through faeces. This meant that when subtracting the amount of P from feed retained in the fish (given by the P content in fish and produced amount) from the amount of P in feed ingested, the remaining amount of feed eaten was dispersed over the two flows. The amount of P released with excretion would then be 9% of the total non-retained feed, and any remaining P released with faeces. The importance of this change is clear when altering the FCR as this would lead to a smaller amount of feed fed (given a smaller FCR), but the same amount of P retained in the fish. Given the development of fish feed towards a reduced use of fishmeal, the realism of this parameter can be questioned. This is due to the bioavailability of the different feed compounds replacing the fishmeal. As the farmed fish is not able to retain the P in vegetable feed compounds as efficiently as P in fishmeal, feed with less fishmeal is in fact likely to increase the amount of P released through faeces. However, given a lower bioavailability of the P in the feed, this would demand a higher feed uptake of the fish in order to get the necessary amount of P.

In addition to the waste from aquaculture in the form of faeces and excretion, a significant amount of the farmed fish is lost due to escapes, death and “other” causes (“other” is predation, theft and other causes (SSB 2013a)). As can be seen in Appendices j, k and l the total amount of fish lost compared to the total production (number of fish) was estimated to be 26.5%, of which 71.7% was dead, 0.6% escaped and 27.7% was lost due to other reasons. Using these ratios and data from RUBIN (2011) it was found that the total amount of dead fish from aquaculture accounted 60 000 tons, which gave an average weight of dead fish of 1.42 kg. This weight was chosen as the standard weight for all fish lost so as to be able to calculate the total amount of P lost as a result of lost fish. In Appendix h one can also see the estimated round slaughter weight of farmed fish in Norway in 2011 (5.13 kg). This was necessary for estimating the biomass of the lost fish given that the amount of lost fish was based on the number of produced fish, not the biomass. It is also important to note that the dead fish is due to decease, wounds and other injuries (SSB 2013a).

It was found that a total of 1926 tons of shellfish was farmed in Norway in 2011 (Appendix i), of which blue mussels accounted for more than 90% of the total sold shellfish. As mentioned in Chapter 2.3.1 the P content of shellfish is somewhat uncertain. As a result of the uncertainties regarding this data and the uncertainties regarding the state of the shellfish when sold (with or without shell) (data could not be obtained), it was decided to estimate no slaughter waste from shellfish.

In order to model the amount of P in fish caught by anglers, data on salmon, trout and char caught in Norwegian rivers was used. This gave a total amount of 445.3 tons (SSB 2013b) and the standard P content of 0.4% was used. It is important to note that by using this data a potentially significant amount of fish angled, or not registered, could be unaccounted. But it was assumed that angling in rivers is responsible for the majority of the fish caught in fresh water in Norway. This assumption leads to the incitement that angling in marine waters is not taken into account due to difficulties in data collection for this. Given the size of the river angling there is reason to assume that the marine angling would not be of any major significance to the total Aquatic subsystem as well. Furthermore the missing data will be dealt with in Chapter 2.3.1.2.

2.3.1.2 Development of processes and parameters for the Trade and Consumption subsystem

From RUBIN (2011) it was found that the total amount of slaughter waste from the aquaculture industry in 2011 was 215 000 tons, which accounted for 18.8% of the total production of round weight fish in 2011. In salmon the fish scrap account for approximately 41% of the total round weight of the fish (Sandnes et al. 2003) and using this as a standard assumptions for all fish (both marine and farmed) it is clear that a significant amount of the fish was sold with parts not for consumption. From Appendices c and d it is clear that a significant amount of the fish exported (and imported) from Norway was sold with head and spine (back), and as these two parts accounts approx. 20% of the round weight of salmon (Sandnes et al. 2003), one can assume that this is the reason to the significant difference between the registered slaughter waste (18.81%) and the theoretical waste (41%).

The majority of fish landed and produced in Norway in 2011 was exported and from SSB (2013c) it was found that a total of 2 314 619 tons of fish and fish products was exported, and a total of 460 655 tons of fish and fish products was imported. As can be seen in Appendices c and d the different products were separated into different categories according to the production of the goods and the state of the products. This was performed so as to be able to calculate the total amount of phosphorus in the different categories at a detailed enough level and the different P contents used can be found in Appendix e. Details regarding the estimation of the different P contents (except “without head”) can be found in Chapter 2.3.1.1. For the P content of the “without head” products, this was based on the before-mentioned assumption of 87% P in the slaughter waste, and the vast majority of this in the bones and skin. Using this assumption, the distribution of P in the fish scrap was calculated based on a scrap to round weight ratio of 10% head; 10% back/spine and 1% skin (Sandnes et al. 2003). The 1% of skin was based on the weight ratio of skin and the belly part to the round weight of 5 %. It was assumed that the belly accounted most of the weight and therefore it was decided that 1% would be a suitable assumption for the weight of the skin. With these numbers in mind, this meant that the 87% P in fish scrap (bones/skin) was distributed in these three parts, and assuming the same P content in the three parts, this meant a distribution for the 87% of 48% head, 48% spine/back and 2% skin. Using this assumption the P content in fish without head was calculated using Equation 1, and found to be 0.23%. (See Appendix q for parameters).

Equation 1

$$PC - ((PC * PB) * 48\%) = 0.23\%$$

Using the trade data it was found that the total import and export accounted to a total of 7 732 tons and 650 tons of fish and fish products (not counting meal and other feed compounds) was exported and imported, respectively, in 2011.

Based on data from SSB it was found that the Norwegian population in 2011 was 4 985 870 (SSB 2012h). Furthermore, using predictions from the national statistics bureau of Norway (SSB) on population growth in Norway until 2100 the Norwegian population was estimated to be 6 645 153. This estimate was based on an average of the fourteen different scenarios set forth by SSB and not based solely on one of the different scenarios produced by SSB (Appendix m).

In order to estimate the amount of food wasted before reaching the consumers, it was found that approximately 6.2% of all fresh fish and shellfish was thrown at retailers (Hanssen & Schakenda 2011a). There is reason to believe that the waste share for the total flow of products should be smaller. This is because the waste share of frozen products could be assumed to be smaller as these products are not as vulnerable as fresh products, thus causing less waste. This was taken into consideration, but it was chosen to use 6.2% as a transfer coefficient for this process as it was the best estimation currently available for food waste at the retailer level.

The total amount of fish and fish products procured and consumed in Norway in 2011 was estimated to be 16.3 kg per capita. As this was both fish and fish products it was also reported to be equal to a total of 10.5 kg fish filets (The Norwegian Directorate of Health 2012). Furthermore, from the data by SSB (2010) it was estimated that of the total amount fish and fish products purchased, 55.1% was fish; of which 89.2% was whole fish and 10.8% was filets. Of the remaining products, 11.0% was shellfish, and 33.0% miscellaneous products (SSB 2010). Using the P contents dealt with in Chapter 2.3.1.1 and the population in Norway as seen in Chapter 2.3.1 the total P in fish and fish products consumed in Norway was calculated. However, it is important to note that it is very well possible that one could estimate the total amount of P in fish and fish products just by using the fish filet equivalents. This was not performed due to the fact that this data was discovered at a late stage of the thesis and it was decided that the product share would be used as it could allow for modeling of a different consumer diet.

In order to estimate the total amount of wet organic waste from consumers the difference between the total procured products and the fish filet equivalents were used as a basis giving a solid waste share of 35.6% of all food procured. Due to the complexity of wet organic waste (it is registered as a single large entity of solid waste), this was the best estimation that could be made for this flow, and it was thus deemed acceptable.

When checking the flows in and out of the *Market* process, it became obvious that it was not balanced as it showed a surplus of 1 853 tons of P. When trying to solving this imbalance, no good solutions proved themselves. Given that all input data had the highest quality obtainable for this project (national statistics), it was decided that the imbalance would not be artificially balanced, but remain as it was. This led to the development of two different methods in order to find the amount of exported P in other years than 2011. Balancing the domestic input to the *Market* process against the domestic use (consumption) and export the process became more balanced, however, due to the difficulties in quantifying future import of fish and fish products, there will be a certain imbalance in the system due to these flows.

2.3.1.3 Development of processes and parameters for the Waste Management subsystem and the Other use of fish

As described in Chapters 2.2.3 and 2.2.4 the two processes in the *Waste Management* subsystem and the process for *Other use of fish* act as end processes (SWT) or transfer processes with no differentiating regarding the inputs and outputs. As a result of this, no specific parameters were developed for these processes. This might be a source of uncertainty, but as the main focus of the system shifted more towards the aquatic and trade/consumption subsystems, the development of these processes were not prioritized.

2.3.1.4 Calculation of import and export of fish and fish products in Norway

Much of the data used in this thesis is based on international trade data for Norway that is open to the public via the website of Statistics Norway (SSB 2013d). The data used were chosen according to the categories set up by the Norwegian Customs office (The Norwegian Customs Office 2011) in Chapters 3, 5, 23 and 16 dealing with fish, shellfish, products of the two and feed compounds of animal origin.

As the data is given with a high level of detail, the different products had to be aggregated into different product groups in order to make the data sets comprehensible (Appendix c). Using the aggregated data it was found that a total of 460 655 tons of aquatic animals (except mammals) and the products of them was imported to Norway in 2011. Likewise it was found that the total amount of exported animals from Norway in 2011 was 2 314 619 tons. After aggregating the data, the data were disaggregated into different product categories (Appendix d). This was done because some of the product groups (e.g. marine fish) were traded in many different shapes (with/without head, filets, minced meat etc.), and this had to be taken into account when calculating the total P content of the trade flows. The estimation of total P in the trade flows was performed using the same P content (Appendix e) as was used in the rest of the analysis and gave a total P import to Norway of 6 043 tons P, and an export of 8 568 tons of P. When disaggregating the import/export of P it was found that of the imported amount, only 650 tons were food products, and the remaining 5 394 tons were products for feed production (meal, fish for meal production and feed) and a minuscule amount (0.1 tons) of fishmeal not for feed or human consumption. Given the significant trade surplus of goods (2.3 million tons to 0.46 million tons) it could be somewhat unexpected that the difference in P flows is as small as approx. 2500 tons. This is due to the significant amounts of feed components (and especially meal) that have a high P content per mass unit compared to the regular products. Of the exported amount of P it was found that 7 732 tons were food products and that 837 tons were products for feed production.

2.3.1.5 Analytical approach

Given the variables in Figure 5 (see Appendix t for denotation) and the parameters defined (Appendices q and r), an analytical approach was performed in order to calculate the different variables for the system. The analytical solution to the Norwegian fisheries and aquaculture industry can be found in Appendix s.

2.4 Scenarios

Using the collected data for landed fish and production of fish with the respective flows as can be seen in Figure 5, the P cycle for the Norwegian fisheries and aquaculture industry in 2011 was modelled (see Chapter 3 for results). Given the predicted increase in marine fisheries and aquaculture (as mentioned in Chapters 1.2 and 1.3) to 4 million tons landed catch and 5 million tons produced, respectively, the system for 2011 was scaled up according to these predictions. This entailed adjusting all flows to the increased amount of catch and production amount so as to illustrate the potential situation in 2050 given the current production strategies (see Appendix q and Appendix r for parameters for 2011 and 2050, respectively). As these two systems were modelled using the current technology and production practices, it was decided that they would act as Current Technology (*CT*) scenarios.

In addition to the two systems mentioned above, two additional scenarios were modelled for each of the two years, with several parameter changes for each scenario. This was done in order to work as a comment to what the system of 2011 could look like with different production strategies, and also in order to produce different estimates for the system in 2050. Especially for the system of 2050 this was important as predictions could be fragile to any changes in the production that are currently not taken into consideration, and several scenarios would help optimize the results by indicating the potential size of the flows in the system given different strategies for future development of the industry. This means that a total of six scenarios was developed, whereof three were for 2011 and three for 2050.

It should be noted that initially it was decided that a scenario regarding the feed loss rate would be performed, but given the most recent data on feed loss in Norwegian aquaculture, as reported by Wang et al. (2012), it was decided that a scenario involving a further reduction of feed loss was not realistic; the same report stated that due to the low loss rate, little environmental or economic incentives were effectuated in order to reduce the loss rate.

For the two additional scenarios it was decided that they would focus on an increased efficiency regarding the use of resources and increased recycling of generated waste. With this in mind it was decided that the parameters changed would be the FCR (F), meal content in feed (PMC and PMS), fish mortality (DFF), scrap generation (kx813 and SLF) and a reduced dumping of fish scrap at sea (SLF).

The first additional scenario is characterized by an Increased overall Efficiency (*IE*) in the system whilst the second additional scenario does not have an overall increase in efficiency, but still an increase in the Fish Scrap retrieval rate (*FS*). The three different scenarios are therefore the Current Technology scenario (*CT*), the Increased Efficiency scenario (*IE*) and the Fish Scrap retrieval scenario (*FS*). The current variables (for CT) and the target values for these variables (for IE and FS) are found in Table 3. Due to the fact that some of the target values affect several different parameters the development of these variables and parameters are dealt with in Chapter 2.4.1 and the parameters that are altered in the different scenarios for 2011 and 2050 can be found in Table 7 and Table 8, respectively. This means that a total of six scenarios were developed, whereof three were modelled for 2011 and three were modelled for 2050 (CT; IE; FS_{2011} and CT; IE; FS_{2050}).

Table 3: The target values for the different flows and parameters for scenarios CT, IF and FS in 2011 and 2050. The dumping of scrap is aiming at reducing the total amount of fish scrap dumped at sea by the marine fisheries. The scrap generation is the total scrap generation for both marine fish and farmed fish. The fish mortality is the share of lost fish in aquaculture that dies due to different causes. The meal content is the same for the two different types of meal modelled (salmon and cod). The FCR is the feed conversion rate for the total Norwegian fish farming industry.

Scenario	Dumping of scrap, %	Scrap generation, %	Fish mortality, %	Meal content, %	FCR, n
CT	36.3	23.7	71.7	23.9	1.28
IE	15.0	30.0	50.0	15.0	1.15
FS	0.0	41.0	25.0	15.0	0.88

2.4.1 Development of variables and parameters for scenarios

As mentioned in Chapter 2.3.1.1, it was reported in RUBIN (2011) that a total of 541 500 tons of fish scrap was generated by the marine fisheries in Norway in 2011. Of this scrap only 345 000 tons were utilized and the remaining 196 500 tons were dumped at sea. It was assumed that all fish scrap was generated by fish meant for consumption, and this gave a total amount of fish scrap compared to biomass for marine fisheries (2 051 470 tons) (fish for consumption) of 26.4% on a mass basis. However, only 16.8% of the total biomass was retained and used due to dumping of scrap at sea, meaning that of the total amount of scrap generated in the marine fisheries, 36.3% were dumped. As the use of fish scrap as a resource has grown significantly the last decade (global growth was 1 billion NOK in 2001 to almost 5 billion NOK in 2010), and generally increased awareness regarding the potential in fish scrap (Bekkevold & Olafsen 2007; Olafsen et al. 2012), it was decided to model a decrease in the amount of fish scrap dumped at sea. As no good data with predictions for the dumping of scrap could be obtained, it was decided that the $IE_{2011/2050}$ scenario would be modelled with a 15% dumping rate and dumping rate of 0% for the $FS_{2011/2050}$ scenario. This was based on predictions set forth in the report by Olafsen et al. (2012) regarding increased use of fish scrap. With the large quantities of P available within Norway, this change in production practice was also considered to be very interesting as the shear amount of P could be of such a quantity, that an industry based on the reuse and refining of the rest resource could be economically viable.

Being an important means to increase the amount of fish scrap available for recycling and reuse, a reduction in dumping of fish scrap is important for a more efficient industry. However, given the amount of fish scrap generated (26.4% of all marine fish to consumption based on biomass) there will still be a significant amount of fish scrap that remain in the fish. This conclusion follows the assumption that 41% of the round weight of fish is scrap and thus 14.6% of the marine fish biomass is not recycled. In addition it was found that from aquaculture, the amount of fish scrap accounted only 18.8% of the total production of fish. In total this gave a total scrap generation rate for the Norwegian fisheries and aquaculture of 23.7%. Given the expected growth in the scrap generation rate (as mentioned above) it was decided that the $IE_{2011/2050}$ scenario would be modelled with a scrap generation rate of 30% for both the fisheries and the aquaculture; and the $FS_{2011/2050}$ scenario with a scrap generation rate of 41% for both the fisheries and aquaculture (which indicate a 100% fileting of the fish as the fish scrap was estimated to be 41% of the fish).

A scrap generation rate of 30% and 41% would entail a higher amount of fish scrap generated by the marine fisheries than what would be made available through reduced dumping of fish scrap at sea. This meant that the total amount of fish scrap from marine fisheries would have to be adjusted. Taking the dumping rate for the different scenarios into account, it was estimated that the total amount of landed scrap from the fisheries in 2011 would be 345 000 tons for the CT_{2011} scenario, 523 125 tons for the IE_{2011} scenario and 841 103 tons for the FS_{2011} scenario (Table 4). For 2050 it was calculated that the total amount of landed scrap from the fisheries would be 535 161 tons for the CT_{2050} scenario, 811 467 tons for the IE_{2050} scenario and 1 304 711 tons for the FS_{2050} scenario (Table 5)

Table 4: The parameters for the scenarios CT, IF and FS based on the 2011 data. It is important to note that the parameter SLF (scrap from landed fish) is in tons and not percentages. kx8.13 is the generation of slaughter waste from aquaculture. DFF is the share of dead fish of the total amount of fish lost in aquaculture. PMS and PMC is the meal content in salmon feed and cod feed, respectively. F is the Food Conversion Rate (FCR).

2011	SLF, ton	kx8.13, %	DFF, %	PMS, %	PMC, %	F, n
CT_{2011}	345 000	18.8	71.7	23.9	23.9	1.28
IE_{2011}	523 125	30.0	50.0	15.0	15.0	1.15
FS_{2011}	841 103	41.0	25.0	15.0	15.0	0.88

Table 5: The parameters for the scenarios CT, IF and FS for the system of 2050. As the parameter SLF (scrap from landed fish) is based on mass (tons) and not percentage, it is different than what can be seen in the scenarios for 2011. kx8.13 is the generation of slaughter waste from aquaculture. DFF is the share of dead fish of the total amount of fish lost in aquaculture. PMS and PMC is the meal content in salmon feed and cod feed, respectively. F is the Food Conversion Rate (FCR).

2050	SLF, ton	kx8.13, %	DFF, %	PMS, %	PMC, %	F, n
CT_{2050}	535 161	18.8	71.7	23.9	23.9	1.28
IE_{2050}	811 467	30.0	50.0	15.0	15.0	1.15
FS_{2050}	1 304 711	41.0	25.0	15.0	15.0	0.88

In 2011 the amount of fish lost in aquaculture was found to be 26.5% of the total production number of fish. Of these 26.5% a total of 71.7% were dead fish (Appendices j, k and l). This fish mortality was due to decease, cuts and wounds (SSB 2013a), and given the significant amount of fish this share entails, a reduction of this share would be of high importance given the predicted growth in aquaculture (Olafsen et al. 2012). As a result of this it was decided to model a decreasing fish mortality for the three different scenarios. This gave a fish mortality (DFF) of 71.7% for the $CT_{2011/2050}$ scenario, 50.0% for the $IE_{2011/2050}$ scenario and 25% for the $FS_{2011/2050}$ scenario (Table 3). As the fish mortality directly influence the total share of fish lost together with the “other” lost fish and escaped fish, several parameters had to be adjusted in order to model the decreased mortality. This could have been prevented by simply adjusting the total share of lost fish. However, due to the uncertainties regarding the cause of the loss of the “other” lost fish, it was decided to keep this parameter fixed. The decision not to model a reduction in the share of escaped fish was based on the small amount of fish this accounted for compared to the dead and “other” fish. Balancing the parameters against the fish mortality the total share of lost fish (LFA) was balanced to 26.5% for the $CT_{2011/2050}$ scenario, 15.0% for the $IE_{2011/2050}$ scenario and 10.0% for the $FS_{2011/2050}$ scenario. The share of escaped fish was balanced to 0.6% for the $CT_{2011/2050}$ scenario, 1.1 for the $IE_{2011/2050}$ scenario and 1.6 for the $FS_{2011/2050}$ scenario. The share of "other" lost fish was balanced to 27.7% for the CT scenario, 48.9% for the IE scenario and 73.4 for the FS scenario (Table 6).

Table 6: The parameters changed in order to achieve the reduction in fish mortality (DFF) for the three scenarios CT, IF and FS in 2011 and 2050. LFA is the share of fish lost in aquaculture compared to the number of produced fish. DFF is the share of dead fish of the total amount of fish lost in aquaculture. EFF is the share of escaped fish of the total amount of fish lost in aquaculture. OFF is the share of "other" lost fish of the total amount of fish lost in aquaculture.

Scenario	LFA, %	DFF, %	EFF, %	OFF, %
$CT_{2011/2050}$	26.5	71.7	0.6	27.7
$IE_{2011/2050}$	15.0	50.0	1.1	48.9
$FS_{2011/2050}$	10.0	25.0	1.6	73.4

Given the trend of fish feed composition leading towards less use of fish products (fishmeal and oil) in the feed (EWOS 2010), and the effect this would have on the flows of P related to the production of fish feed it was decided that a reduction of the fish meal content in feed would be modelled in the scenarios. Multiple studies have been performed regarding the meal content of fish feed and from Hua & Bureau (2006) a meal content of 15% was found. In addition a meal content of 0% (Espe et al. 2006; Øverland et al. 2009) was considered, but when the model was tested for this it was found that some of the flows in the system did not handle this as expected. Given the potential changes to the system a fish meal content of 0% could entail, the findings could have been important. But given the significant reduction of fishmeal content 15% entails compared to the estimated content of 23.9% (Chapter 2.3.1.1), it was decided to run the model with this meal content. As the meal content was found to be 23.9% for the system it was decided that the same content would be used for both of the salmon feed (PMS) and cod feed (PMC). Thus the meal content was set to 23.9% for the $CT_{2011/2050}$ scenario and 15% for both the $IE_{2011/2050}$ and $FS_{2011/2050}$ scenario (Table 3 and 8).

FCR is one of the main parameters of the system as it directly influences the amount of feed going to the aquaculture. Given the increased efficiency a reduction of FCR would entail (less food consumed per kg output), it was decided to model the scenarios with a reduction of the FCR from the calculated FCR of 1.28 (Chapter 2.3.1.1). The FCR used by Bergheim & Braaten (2007) in their model for estimating effluents from Norwegian aquaculture was reported to be 1.15. In the same report it was found that the best average in Norway in 2005 was an FCR of 0.88. Thus the FCR was set to 1.28 for the $CT_{2011/2050}$ scenario, 1.15 for the $IE_{2011/2050}$ scenario and 0.88 for the $FS_{2011/2050}$ scenario (Table 3). As an FCR value less than 1 would mean a higher output than input, the informative value of the FCR is questionable (Chapter 2.3.1.1). However, as it is the currently preferred factor for estimating feed efficiency in the industry, and does give the correct amount of feed input in dry weight, it was used in this model.

Table 7: The parameters changed for the different scenarios, 2011.

2011	SLF, tons	kx8.13, %	LFA, %	DFF, %	EFF, %	OFF, %	PMS, %	PMC, %	F, n
CT_{2011}	345 000	18.8	26.5	71.7	0.6	27.7	23.9	23.9	1.28
IE_{2011}	523 125	30.0	15.0	50.0	1.1	48.9	15.0	15.0	1.15
FS_{2011}	841 103	41.0	10.0	25.0	1.6	73.4	15.0	15.0	0.88

Table 8: The parameters changed for the different scenarios, 2050.

2050	SLF, tons	kx8.13, %	LFA, %	DFF, %	EFF, %	OFF, %	PMS, %	PMC, %	F, n
CT_{2050}	535 161	18.8	26.5	71.7	0.6	27.7	23.9	23.9	1.28
IE_{2050}	811 467	30.0	15.0	50.0	1.1	48.9	15.0	15.0	1.15
FS_{2050}	1 130 4711	41.0	10.0	25.0	1.6	73.4	15.0	15.0	0.88

3 Results

In the following chapter, the results obtained from the different scenarios are illustrated in the systems accordingly. For practicality, the results can also be found as tables in Chapter 3.7. As can be seen in the following subchapters the amount of P in the Norwegian fisheries and aquaculture industry is significant, and given changes in production strategies significant amounts could be potentially be utilized to a greater extent than what is seen today. In the different systems presented (Figure 6 to Figure 11) the flows are annotated with a flow number (F#) which can be found in Tables Table 9 and Table 10 and is transferable to the system as given in Figure 5. It is important to note that as described in Chapter 2.3.1.2 the *Market* process is not balanced in the results for 2011 as the amount of exported P found using national trade data did not balance against the production and consumption in Norway. For 2050 the export flow from the *Market* process is balanced against the domestic production in order to show the total amount of domestic P is exported. However, it is not balanced against the import of P to the *Market* process due to the previously mentioned difficulties in quantifying future import of food products.

3.1 2011 Current Technology scenario

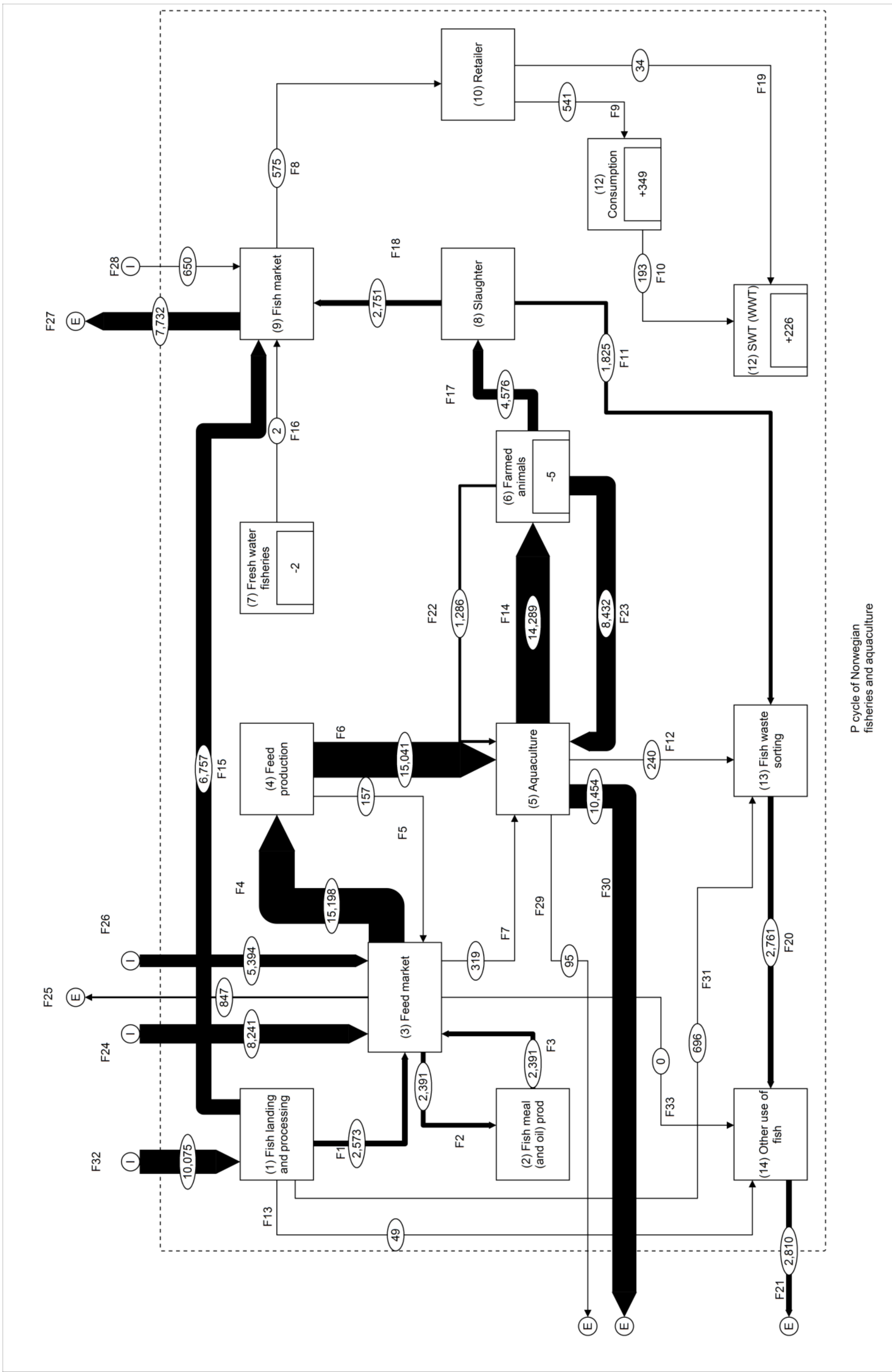

Figure 6: CT scenario 2011. P flows in the Norwegian fisheries and aquaculture industry in 2011 modelled with the CT scenario. F# indicates the flow.

As can be seen in Figure 6 the most significant flows of phosphorus in the Norwegian fisheries and aquaculture industry system are closely connected to the production of fish, both the fishing of natural stocks and the farming of fish in aquaculture. Especially noteworthy is the fact that the flow of waste from aquaculture (F30) is in the same order of magnitude as the total amount of marine fish landed in Norway (F32) in 2011 and that the amount of P in farmed fish for slaughter (F17) is just a third of the total amount of P input to the process (F14). Additionally it is important to note that the majority of the P in fish feed and feed stuff to feed production (F4, F5 and F6) is imported as meal, feed and fish for meal production (F24) and additional feed stuff (vegetables) (F24). Given the substantial amount of fish death in aquaculture the amount of P in flow F12 is almost half of the total amount of P in fish and fish products consumed in Norway in 2011 (F9). In flows F31 and F11 it is clear that significant amounts of fish scrap (slaughter waste) is generated both from the marine fisheries and the aquaculture industry. It is important to note that the export flow of fish and fish products (F27) does not balance against the inputs to the *Market* process, as this was found to be impossible given the data available.

3.2 2011 Increased Efficiency scenario

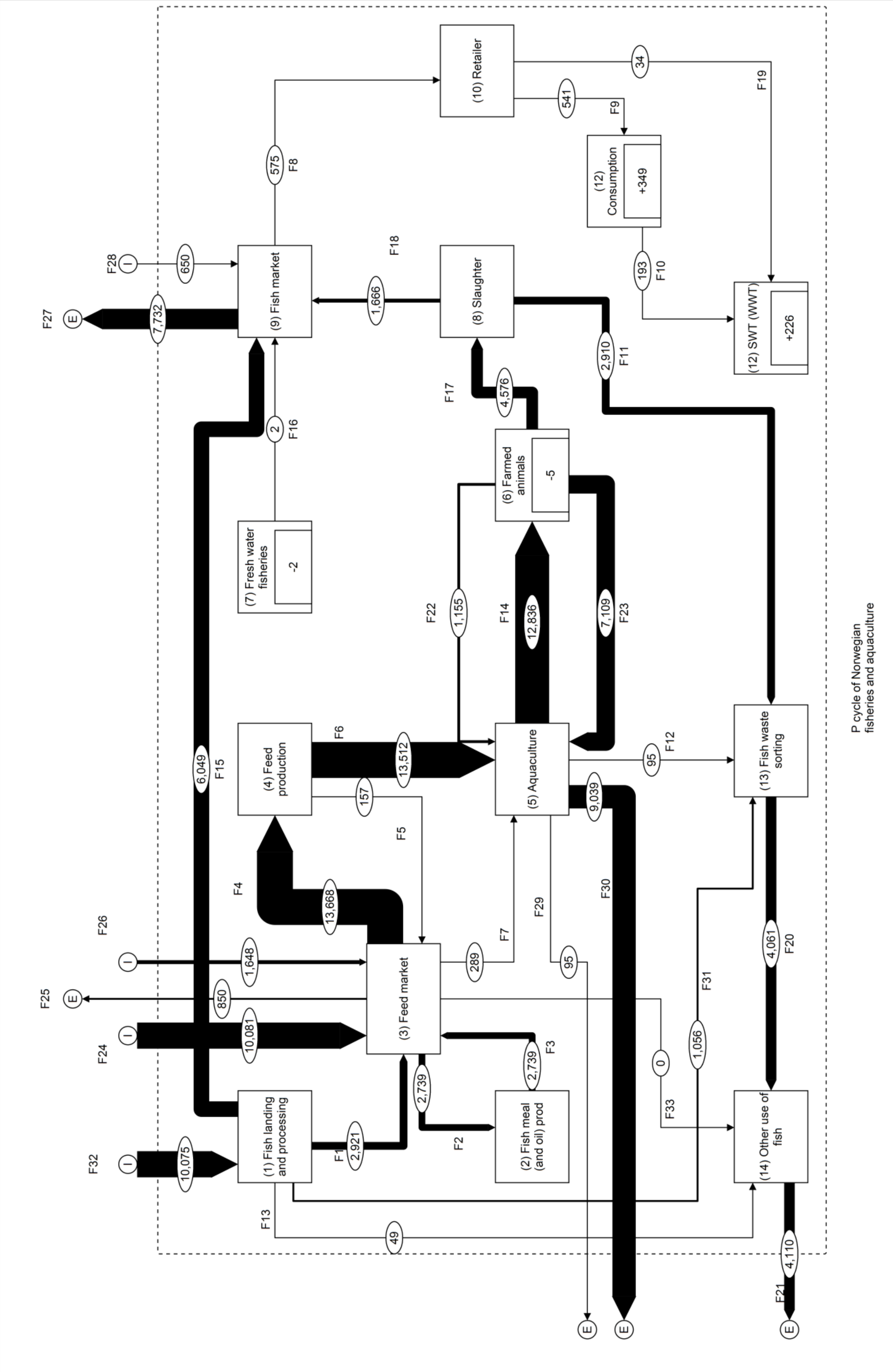

Figure 7: IE scenario 2011. P cycle in Norwegian fisheries and aquaculture industry in 2011 modelled with the IE scenario. F# indicates the flow.

Modelling the Norwegian fisheries and aquaculture industry in 2011 with the medium scenario (Figure 7) it is clear that by managing a reduction of the FCR from 1.28 to 1.15 the total amount of P needed for aquaculture could be reduced significantly. The amount of P lost from aquaculture as POP (F23) and DIP (F22) is still significant as can be seen when comparing the total emissions from aquaculture (F30) to the total input of P to both the aquaculture process (F6 and F7) and the amount of P in fish landed in Norway (F32). Given amount of P in fish lost from the aquaculture (F29 and F12) it is clear that this represent a significant loss of biomass for the aquaculture industry. As can be seen in flows F26 and F24, the amount of imported fish products to feed production is significantly reduced compared to the amount of imported feed stuff (vegetables). Especially noteworthy are flows F11 and F18 showing that the P in slaughter waste from the aquaculture exceeds the amount in farmed fish for consumption, and taking flow F13 into account it is clear that the total amount of P in fish scrap is close to 4000 tons.

3.3 2011 Fish Scrap scenario

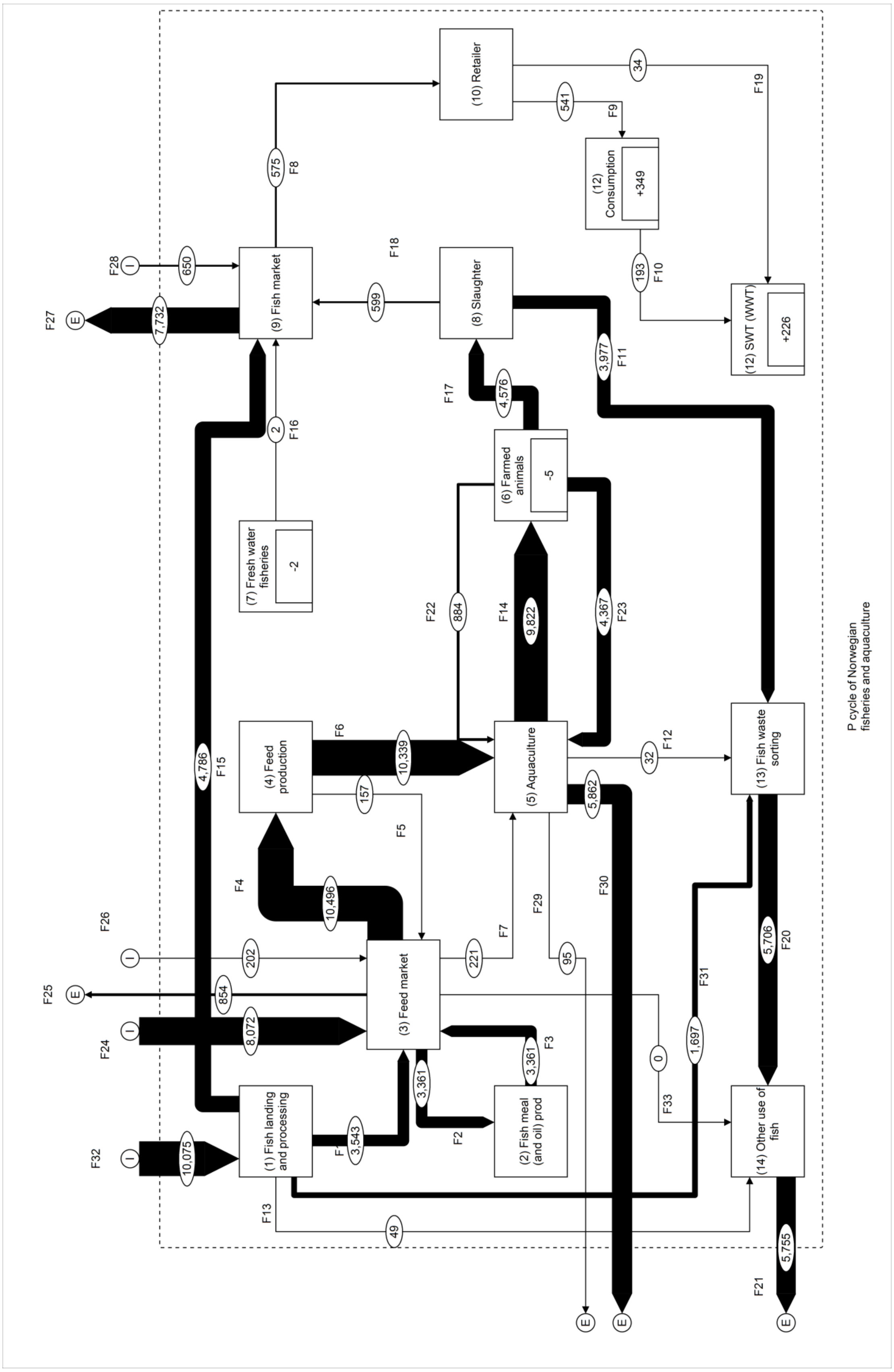

Figure 8: FS scenario 2011. The P cycle for the Norwegian fisheries and aquaculture in 2011 modelled with the FS scenario. F# indicates the flow.

Figure 8 show the phosphorus flows in the Norwegian fisheries and aquaculture industry in 2011 using the best case scenario. It is clear that the marine fisheries (F32) and inputs to the aquaculture industry (F24; F4; F6) still are the major flows of P in the entire system. However, it can be seen that the domestic production of fishmeal (F3) is sufficient to supply the feed production as the import of meal, feed and fish for feed (F26) is significantly reduced. Given the increased retention of fish scrap it is clear that the total amount of P in fish scrap from marine fisheries (F31) and aquaculture (F11) is larger than the total output of P in fish and shellfish from the aquaculture industry (F17). When comparing the amount of P in fish scrap from the marine fisheries (F31) to the amount in fish to consumption (F15) and the correlating flows for the aquaculture industry (F11 and F18) it could seem like the amount of fish scrap from the marine fish to consumption is smaller than what would be assumed given the fileting rate in this scenario. For the emissions from the aquaculture (F30) they are significantly reduced compared to the results seen in the medium and baseline scenario, but the amount of P released is still higher than the total output of P in fish and shellfish farmed (F17).

3.4 2050 Current Technology scenario

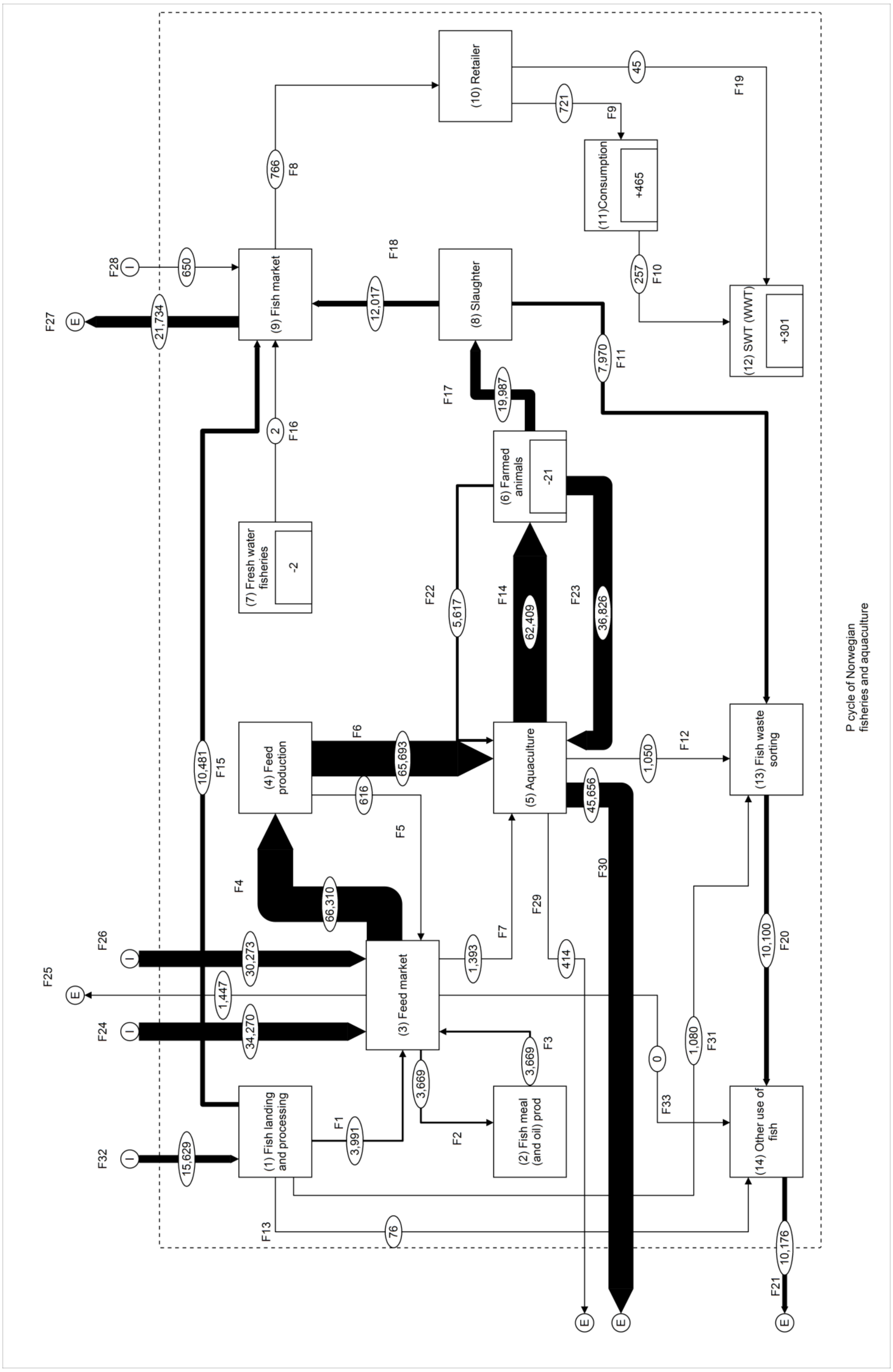

Figure 9: CT scenario 2050. The predicted P cycle of the Norwegian fisheries and aquaculture in 2050 based on a scale-up of the 2011 CT scenario. F# indicates the flow.

In Figure 9 it is clear that similar to the 2011 baseline scenario the inputs and outputs of the aquaculture are some of the most significant flows of P in the 2050 baseline scenario. As can be seen in flow F32 the increase in marine fisheries does not lead to the same increase in P flows as the increase in aquaculture. This can be illustrated with the increased amount of P in feed in flow F6, and also the significant amounts of P in the imported feed stuff (F24 and F26). One important flow is flow F12 indicating the amount of dead fish from aquaculture. This flow is almost as big as the amount of feed imported to Norway (F7) and together with the fish scrap from aquaculture (F11) and marine fish to consumption (F31), it can be seen in flow F20 that the total amount of lost P from these flows is in the same order of magnitude as the total amount of marine fish going to consumption (F15). The amount of P in sold food products (F8) is one of the smaller flows in the system, and it is worth noting that the dead fish from aquaculture (F12) is more than 30% larger, meaning that the dead fish in theory could fed more than the Norwegian population if it could have been used for this. In addition it is important to note that the amount of P in farmed fish and shellfish to consumption (F18) is almost as big as the total amount of P in marine fish landed in Norway.

3.5 2050 Increased Efficiency scenario

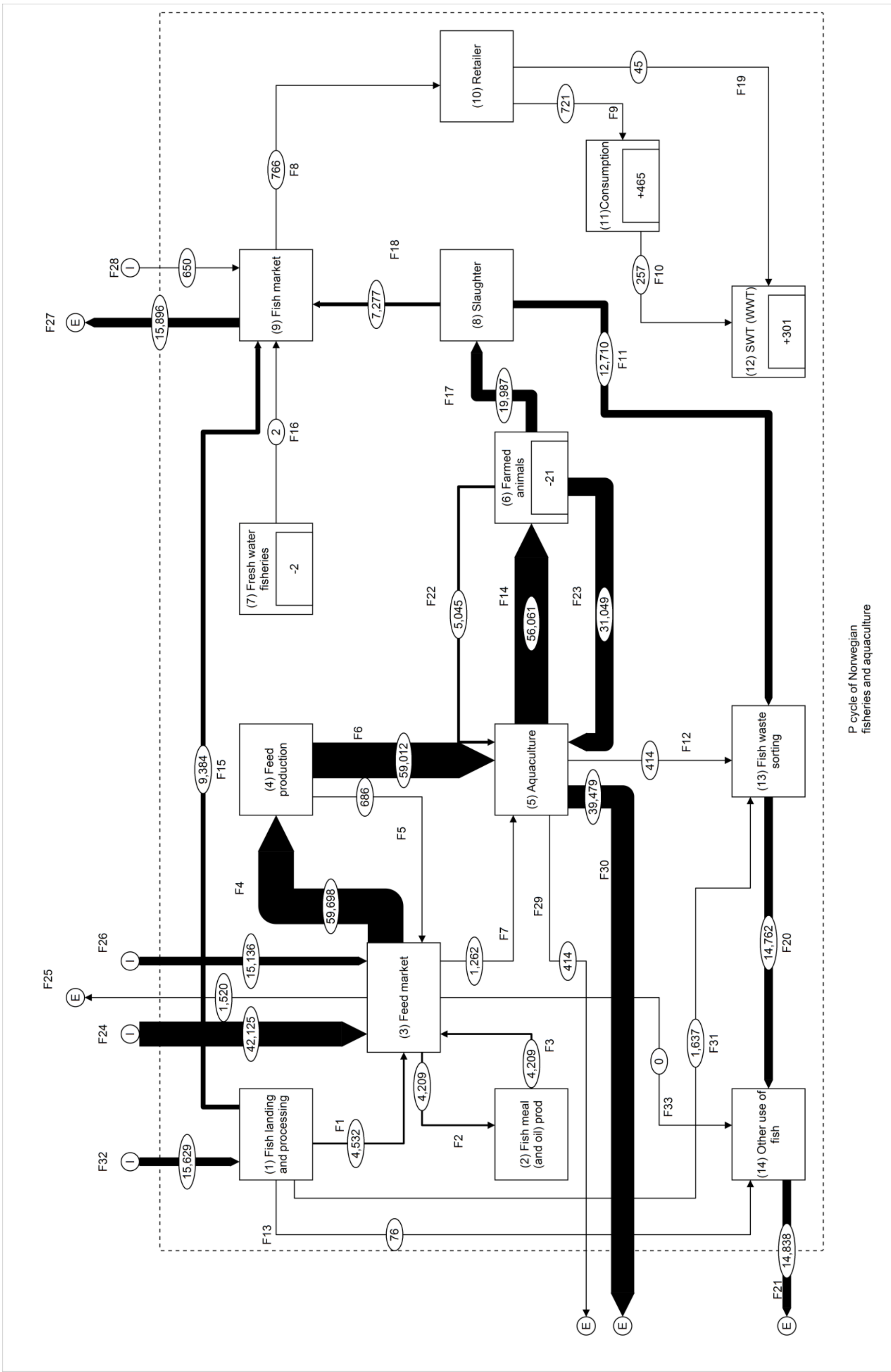

Figure 10: IE scenario 2050. The predicted P cycle of the Norwegian fisheries and aquaculture in 2050 modelled using the IE scenario. F# indicates the flow.

The Medium scenario for 2050, as seen in Figure 10, show a reduction in the most significant flows of P compared to the Baseline scenario, but compared to the situation in 2011 the numbers are still high. It is important to note that the amount of P in dead fish (F12) is significantly reduced compared to the baseline, but the total amount of P in fish waste (F20) has increased, and is almost as big as the total amount of P in the landed catch (F32). This is due to the increased amount of fish scrap from the slaughter process (F11) and the marine fisheries (F31), thus allowing a significant amount of P from fish to leave the system for other use of the fish (F21). An important observation is that the total amount of P in fish and fish products from the *Market* process (F27) is as big as the total amount of P in fish landed in Norway (F32) even with the increased scrap generation.

3.6 2050 Fish Scrap scenario

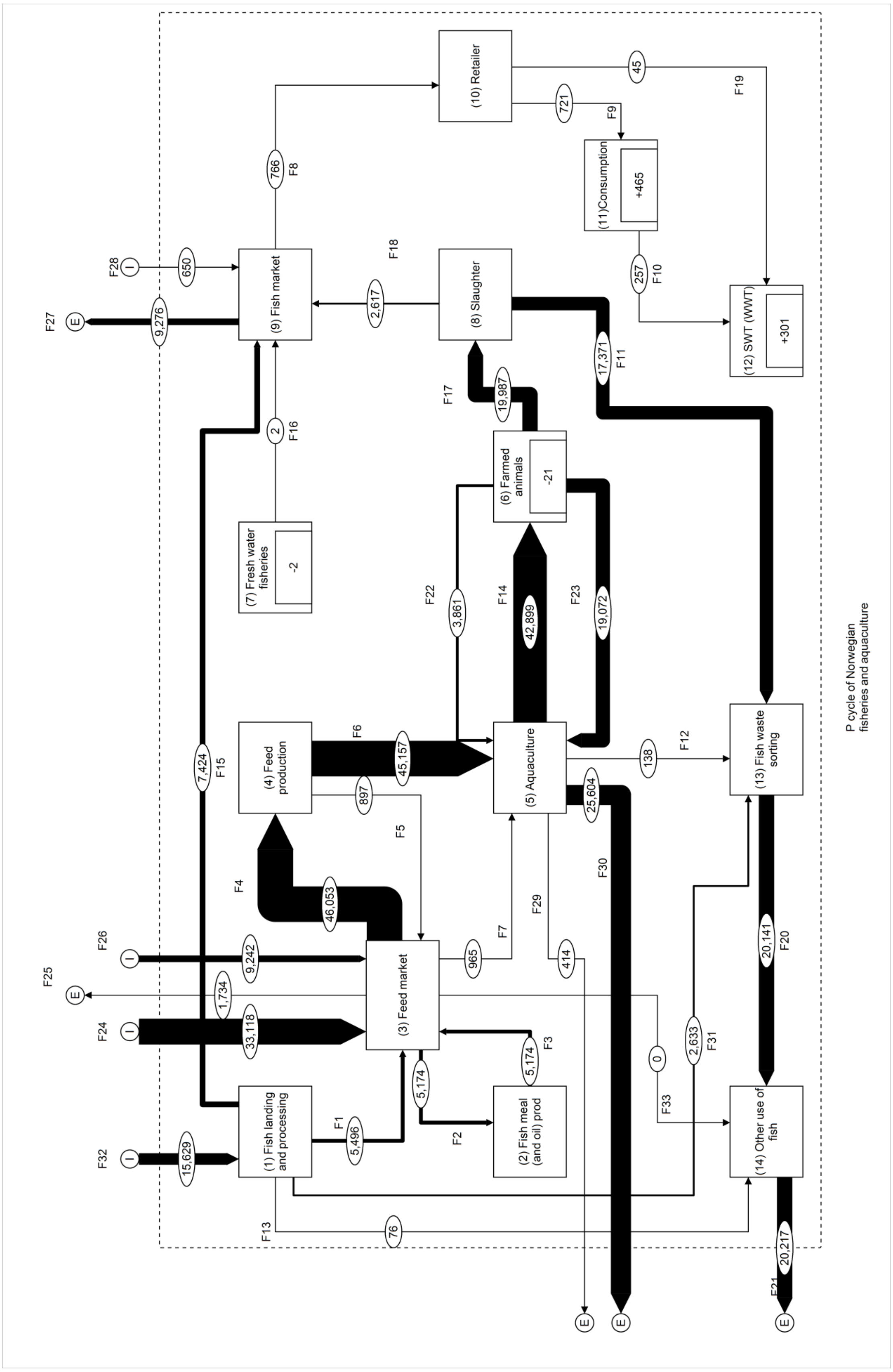

Figure 11: FS scenario 2050. The predicted P cycle of the Norwegian fisheries and aquaculture in 2050 modelled using the FS scenario. F# indicates the flow.

The most significant input to the system in Figure 11 is the P in the vegetable feed compounds (F24), which is more than three times larger than the amount of P in the imported meal, feed and fish for feed production (F26). Compared to the medium scenario, the importance of domestically produced fishmeal (F3) has increased as this flow is responsible for more than 50% of the P input of animal origin to the feed production (F26 and F3 to F4). It is noteworthy that the total amount of P in farmed fish and shellfish to consumption (F18) is smaller than the total amount of P lost through excretion (F22), equal to the amount of P in fish scrap from marine fisheries (F31), and significantly smaller than the total amount of P in fish scrap from aquaculture (F11). As a result of the large amount of scrap generated the amount of P in fish and fish products exported (F27) is also significantly smaller than what could be observed in the CT and IE scenarios for 2050, and not much larger than the corresponding flow for 2011.

3.7 Results tables

For simplicity and increased transparency, the results presented in Chapters 3.1 to 3.6 for 2011 and 2050 can be found in Table 9 and Table 10, respectively.

Table 9: 2011 Results table. The amount of P in the different flows according to the different scenarios for 2011. F# indicates the flow

Flow name	From process #	To process #	F#	CT 2011, t P	IE 2011, t P	FS 2011, t P
Marine animals landed in Norway	0	1	F32	10075	10075	10075
Marine fish to consumption	1	9	F15	6757	6049	4786
Fish for feed production	1	3	F1	2573	2921	3543
Fish scrap	1	13	F31	696	1056	1697
Fish for "other" use	1	14	F13	49	49	49
Meal to feed	2	3	F2	2391	2739	3361
Imp. Meal, fish for feed and feed	0	3	F26	5394	1648	-202
Imp. feed stuff, not fish	0	3	F24	8241	10081	8072
Exp. Meal, fish for feed and feed	3	0	F25	847	850	854
Fish to meal production	3	2	F3	2391	2739	3361
Feed stuff for feed production	3	4	F4	15198	13668	10496
Imp Fish feed to aquaculture	3	5	F7	319	289	221
Meal not for feed or food	3	14	F33	0	0	0
Excess fish feed	4	3	F5	157	157	157
Fish feed	4	5	F6	15041	13512	10339
Waste from aquaculture	5	0	F30	10454	9039	5862
Escaped and other loss of fish from aquacult.	5	0	F29	95	95	95
Feed eaten	5	6	F14	14289	12836	9822
Dead fish	5	13	F12	240	95	32
Excretion	6	5	F22	1286	1155	884
Faeces	6	5	F23	8432	7109	4367
Animals for slaughter	6	8	F17	4576	4576	4576
Fresh water fish to consumption	7	9	F16	2	2	2
Aqua. Animals from aquaculture	8	9	F18	2751	1666	599
Slaughter waste	8	13	F11	1825	2910	3977
Imp. Aquatic animals, excluding mammals	0	9	F28	650	650	650
Exp. Aquatic animals, excluding mammals	9	0	F27	7732	7732	7732
Aquatic animals, excluding mammals to retailer	9	10	F8	575	575	575
Sold fish food (food products)	10	11	F9	541	541	541
Waste from retailer	10	12	F19	34	34	34
Solid waste from consumer	11	12	F10	193	193	193
Fish scrap to other use of fish	13	14	F20	2761	4061	5706
Other products with fish	14	0	F21	2810	4110	5755
Net stock accumulation #6	-	-	-	-5	-5	-5
Net stock accumulation #7	-	-	-	-2	-2	-2
Net stock accumulation #11	-	-	-	349	349	349
Net stock accumulation #12	-	-	-	226	226	226

Table 10: 2050 Results table. The amount of P in the different flows according to the different scenarios for 2050. F# indicates the flow.

Flow name	From process #	To process #	F#	CT 2050 , t P	IE 2050, t P	FS 2050, t P
Marine animals landed in Norway	0	1	**F32**	15629	15629	15629
Marine fish to consumption	1	9	**F15**	10481	9384	7424
Fish for feed production	1	3	**F1**	3991	4532	5496
Fish scrap	1	13	**F31**	1080	1637	2633
Fish for "other" use	1	14	**F13**	76	76	76
Meal to feed	2	3	**F2**	3669	4209	5174
Imp. Meal, fish for feed and feed	0	3	**F26**	30273	15136	9242
Imp. feed stuff, not fish	0	3	**F24**	34270	42125	33118
Exp. Meal, fish for feed and feed	3	0	**F25**	1447	1520	1734
Fish to meal production	3	2	**F3**	3669	4209	5174
Feed stuff for feed production	3	4	**F4**	66310	59698	46053
Imp Fish feed to aquaculture	3	5	**F7**	1393	1262	965
Meal not for feed or food	3	14	**F33**	0	0	0
Excess fish feed	4	3	**F5**	616	686	897
Fish feed	4	5	**F6**	65693	59012	45157
Waste from aquaculture	5	0	**F30**	45656	39479	25604
Escaped and other loss of fish from aquacult.	5	0	**F29**	414	414	414
Feed eaten	5	6	**F14**	62409	56061	42899
Dead fish	5	13	**F12**	1050	414	138
Excretion	6	5	**F22**	5617	5045	3861
Faeces	6	5	**F23**	36826	31049	19072
Animals for slaughter	6	8	**F17**	19987	19987	19987
Fresh water fish to consumption	7	9	**F16**	2	2	2
Aqua. Animals from aquaculture	8	9	**F18**	12017	7277	2617
Slaughter waste	8	13	**F11**	7970	12710	17371
Imp. Aquatic animals, excluding mammals	0	9	**F28**	650	650	650
Exp. Aquatic animals, excluding mammals	9	0	**F27**	21734	15896	9276
Aquatic animals, excluding mammals to retailer	9	10	**F8**	766	766	766
Sold fish food (food products)	10	11	**F9**	721	721	721
Waste from retailer	10	12	**F19**	45	45	45
Solid waste from consumer	11	12	**F10**	257	257	257
Fish scrap to other use of fish	13	14	**F20**	10100	14762	20141
Other products with fish	14	0	**F21**	10176	14838	20217
Net stock accumulation #6	-	-	-	-21	-21	-21
Net stock accumulation #7	-	-	-	-2	-2	-2
Net stock accumulation #11	-	-	-	465	465	465
Net stock accumulation #12	-	-	-	301	301	301

4 Discussion

Using a material flow analysis in order to characterize the phosphorus flows in the Norwegian fisheries and aquaculture industry for three different scenarios for both 2011 and 2050, it was found that significant amounts of phosphorus is at stake and that the efficiency of the system could be improved significantly by a change in production strategies and techniques.

The Current Technology scenario for 2011 (CT_{2011}) (Figure 6) act as a baseline for the scenarios set to 2011 as it was based on the best available data for the Norwegian fisheries and aquaculture industry. It was found that a total of 10 075 tons of P was landed in Norway as a result of marine fisheries. Of this the majority (6 757 tons) was consumed, and contributed to the export of 7 732 tons of P as food products of fish and shellfish. In addition to the marine fisheries, it was found that the production of fish and shellfish (aquaculture) was responsible for the most significant flows of P in the system. It was found that a total of 13 515 tons of P was imported as feed, feed components and raw material for feed, of which 5 394 tons was fish feed, fish meal or fish for feed, and 8 121 tons vegetable feed components. In total this import to the system accounted more than 88% of the total amount of the P input (15 240 tons) to the aquaculture industry. This means that the Norwegian aquaculture is to a very high degree dependent of imported goods.

Due to loss of P as a result of excretion and faeces only 4 576 tons of the P input to the aquaculture system was retained in the fish. Of the remaining P a total of 10 334 tons were lost as Dissolved inorganic P (DIP) (1 276 tons) and Particulate organic P (POP) (8 328 tons), 95 tons due to escaped and other lost fish, and 240 due to dead fish. Of the P retained in the farmed fish it was found that after the slaughter only 2 751 tons were sold as food as 1 825 tons were to be found in the slaughter waste. In addition to the slaughter waste a total of 696 tons of P as fish scrap from the marine fisheries, 240 tons in dead fish and 49 tons in marine fish this gave a total of 2 810 tons of P output from the system as raw material for other industries. Of the total P input to the system it was found that only 575 tons reached the consumer market (retailer), of which a total of 226 tons were discarded as solid waste.

In the Increased Efficiency scenario for 2011 (IE_{2011}) (Figure 7) the total amount of imported feed components was reduced to 11 729 tons, of which 10 081 tons were vegetable feed components. This occurred due to a reduction of the meal content in the feed (15%) in combination with an increased domestic production of fishmeal (2 739 tons) due to increased fish scrap generation from the marine fisheries. In addition the total amount of feed needed in the aquaculture was reduced due to an FCR of 1.15, which gave a total input of P to the aquaculture of 13 801 tons. Given a lower mortality rate for the farmed fish, 95 tons of P was lost from the aquaculture as dead fish. This gave a total loss of P from the aquaculture as DIP and POP of 1 155 tons and 7 109 tons, respectively. As a result of the higher scrap generation rate only 1 666 tons of P were sold as food products from aquaculture. This gave a total amount of P from fish going to other industries of 4 110 tons (slaughter waste from aquaculture and fisheries, dead fish and marine fish).

The Fish Scrap generation scenario for 2011 (FS_{2011}) (Figure 8) show a further reduction of the total amount of P input to the aquaculture (10 560 tons) as a result of the reduced FCR. The decreased feed demand also affect the import of vegetable feed components (8 072 tons), which, even though the meal content is reduced, is smaller than what was observed in the CT scenario. As a result of the decrease in feed demand, the amount of P lost as DIP and POP is reduced to 884 tons and 4 367 tons, respectively, which totally is almost half of what was observed in the CT_{2011} scenario.

As the scrap generation is 100%, meaning that the total amount of fish scrap is 41% of the total fish biomass, the amount of slaughter waste (3 977 tons) from aquaculture is significantly higher than the amount of fish sold as food (599 tons). However, when comparing the relationship between the slaughter waste from aquaculture and fileted fish to the relationship between the marine fish to consumption and the amount of slaughter waste generated there is reason to believe that the amount of P in the marine fish to consumption is too high. This can be stated based on the assumption that 87% of the P in fish is found in 41% of the biomass. As the total landed amount of P in Norway was 10 075 tons and a significant share of this goes to the consumption the total amount of P in fish to consumption, given the fileting rate of 100%, one should expect a total amount of P to consumption of approx. 1000 tons. The reason for this discrepancy is most likely a miscalibration of the flow and the higher P concentration of the fish scrap is thus not taken into account when the new amounts were calculated. Furthermore, as it was assumed that 49% of the fish scrap was used for meal production this should have given an increase in the flow of P in fishmeal of approx. 1500 tons. Given the low meal content of the feed, this would contribute significantly to the amount of feed components exported from Norway.

The CT_{2050} scenario (Figure 9) work as a baseline scenario for the other scenarios for 2050. As this scenario is based on the same relationship between the flows as the CT_{2011} scenario, but given the predicted increase in production and landed catch the flows are similar to that observed for CT_{2011}. However, as the aquaculture is expected to increase more than the fisheries, the flow of P in landed catch (15 629 tons) is approx. 50% larger than what was observed in CT_{2011} (10 075 tons). In comparison the P in produced fish from aquaculture (19 987 tons) is approx. four times larger than what was observed in CT_{2011} (4 576 tons). Due to this growth in aquaculture, the input of feed components to the system has also grown and is totally 64 024 tons. Mainly due to the significant amount of fish produced in aquaculture the total amount of fish used in other industries (10 176 tons) is as large as the total amount of P in marine fish to consumption (10 481 tons). Together with the farmed fish to consumption (12 017 tons) this gave an exported amount of P in food products of 21 734 tons. In CT_{2050} the importance of reducing the fish mortality in aquaculture is also clear as the total amount of P in dead fish (1 050 tons) is larger than the total consumption of P in fish in Norway (766 tons).

From the IE_{2050} scenario (Figure 10) it is clear that the reduction of meal content in feed is an effective means in order to reduce the dependency upon fish as a feed component for fish feed. This is clearly illustrated in the import flow of feed, meal and fish for feed (15 136 tons) which is effectively halved compared to what was observed in CT_{2050}. However, it is also clear that the total amount of P in feed to the aquaculture is reduced (60 274 tons) due to a reduced FCR. Of this total input to the aquaculture it can be seen that a total of 39 479 tons of P is lost to the system due to DIP and POP, and only 19 987 tons is extracted as fish. Of this only 7 277 tons is in the sold food products, which together with the marine fish to consumption give a total export of 22 615 tons of P in food products from Norway.

In the FS_{2050} scenario (Figure 11) the importance of increased efficiency in the aquaculture becomes clear as the total amount of P in feed to the aquaculture is reduced from 60 274 tons in the IE_{2050} scenario to a total of 46 122 tons. This contributes further in the system as the total amount of DIP and POP from aquaculture is reduced from 45 132 tons in the CT_{2050} scenario to a total of 25 604 tons in this scenario. Taking into account the fact that the total use of P in Norwegian agriculture in 2010/11 was 20 901 tons (SSB 2012i) it is clear that this is still a significant amount of P lost. Given the high fileting rate (scrap generation), only 2 617 tons of P, of the total 19 987 tons, is sold as food products. Together with the P in marine fish to consumption (7 424 tons) this give an export of P in food products of 9 276 tons, but as previously mentioned there is reason to believe that the amount in marine fish to consumption should be smaller.

The results of the analysis indicate the importance of improving the efficiency of the aquaculture industry, as it can be expected to be the main driver of the P cycle in this system in the future. However, it is also important to take into account that an increase in Norwegian production in aquaculture could lead to a problem shifting, as more of the feed will have to be replaced with vegetables. Given the current situation there is reason to assume that most of this will be imported as the Norwegian climate and agriculture does not allow for the production of important species as soybeans. Given the shear amount of vegetables, such a growth in production would require, it is also questionable whether the Norwegian agriculture would be able to produce the amounts needed as well. This increased import of goods for feed production would put pressure on the agriculture in the producing countries, meaning that they would most likely have to increase the amount of mineral fertilizers in order to increase the production. This would again lead to increased stress on the limited P reserves of the world.

As a consequence of this it could be beneficial to develop other feed types, which could utilize currently unused resources. As stated by Thorarinsdottir et al. (2011) the development of feed components based on local raw materials will be crucial in increasing the sustainability of the aquaculture industry. As seen in FS_{2050} the amounts of fish scrap that could be made available with a higher rate of fileting are significant. If all of this fish scrap had been used to produce fish feed, instead of being used in other industries, this could allow for feed types with a higher fishmeal content. This could then reduce the pressure on the natural fish stocks, the agricultural areas where the vegetable feed components are grown and thus the global reservoirs of rock phosphate.

Furthermore, as seen in the results, it can be expected that the significant growth in aquaculture will lead to massive emissions of DIP and POP. And as illustrated with $CT_{2050,}$ the amount of P emitted given the use of current technology would be more than double of the total amount of P used in Norwegian agriculture. As the amounts of DIP and POP emitted in 2050 given a higher efficiency of the industry (FS_{2050}) also are larger than the total P usage in Norwegian agriculture, this could open up for important questions and problems, and possibly for an increased focus on this P as a resource.

As explained in Chapter 1.4.1 the emission of P from aquaculture is currently not a problem when it comes to eutrophication. However, as the amount of P emitted fluctuates throughout the year with a peak in the summer (Wang et al. 2012), the predicted amounts could possibly cause local environmental problems, such as eutrophication. In order to counter the effects of excessive P, marine biofarming of micro algae or other species with a potential for use as feed in aquaculture could possibly help reduce the negative effects of the effluents and produce sustainable fish feed (Thorarinsdottir et al. 2011).

With an increased awareness to the potential problem, one could expect to see new preventive or solutions (such as increased feed efficiency), or technology reducing the amount reaching the environment. As explained in Chapter 1.5.2 many studies have been performed with the aim at treating the effluents from aquaculture and various degrees of treatment has been observed. However, as it would be more efficient and easily controllable to treat effluents from aquaculture if the fish is reared in closed systems, this would require a shift in the production of fish in Norway as this mainly is done in open net cages.

4.1 Qualitative robustness of the model

As it has previously been estimated the total amount of phosphorus released to Norwegian coastal waters due from aquaculture in 2009 was 10 470 tons (Selvik et al. 2010). The result indicating a total of 10 338 tons released from Norwegian aquaculture in 2011 (excluding the P in escaped and other lost fish) would therefore seem to be slightly low given the increase in aquaculture production from 2009 to 2011 from 960 111 tons to 1 142 892 tons (including shellfish) , respectively. However, the apparently low emission value could also be due to different parameters used in the development of the two models. It was found that the TEOTIL2 model (used to estimate the amount of P emissions from aquaculture by Selvik et al. (2007)) used a higher P content in the feed (1.2%) and in the fish (0.45%). With this in mind, it is possible that the amount in this study could have presented the same results if the same parameters had been used. However, as stated in Chapter 2.3.1.1 the P content used was based on an average P content of the fish feed. Given the different P content of the fish, the parameter used in this study was based on back calculation of other studies (Bergheim & Braaten 2007), and it is also known that more recent studies have used this P content (Wang et al. 2012).

Given the difficulties regarding quantification of international trade (import/export) in Norway in the future, the trade flows are to a high degree based on assumptions. Especially difficult flows to make a prediction for are the import of fish as food and the consumption of fish in Norway. In addition, the prediction of future waste management is difficult to predict as a number of different technologies may be invented and implemented in the period between the current date and 2050. However, given the expected increase in both Norwegian fisheries and aquaculture this system still give a good illustration of what the situation can be given the certain shifts in production culture and an increased focus on rest resources such as fish scrap and the inherent potential in these.

One of the major issues of the system was the *Market* process and the imbalance of this. This could be due to the use of an average P content for the many different fish species landed in Norway as this could potentially give a too small or too large P content. However, as there is a consistency in the P content used, this is likely not the case. Another reason for this discrepancy could be the process of which the amount of fish landed in Norway is estimated. When the fish is landed in Norway the bought note determines the further use of the fish, and the purchaser of the fish fills this out. On the bought note the amounts are given in product weight, and this is later recalculated to round weight by the Department of Fisheries (Berit Storbråten; Personal correspondence). When the fish is then traded the amount of fish products traded is put on record by the Norwegian Customs office, which use the product weight. Keeping in mind that the Department of Fisheries recently changed the conversion factors used in order to estimate the round weight of the fish the reliability of this data can be questioned. As a result of this there is reason to believe that either the information about traded goods or the information on landed catch is erroneous and the reason to the discrepancy between the production and trade.

Because the consumption of fish in Norway was modeled independently of the output of fish from aquaculture and marine fisheries, it is not shown to change according to the scenarios as it should have given the change in the fish for consumption. Given that the total consumption of fish and fish products was calculated to be equal to 541 tons of P for CT_{2011}, this should be significantly reduced IF_{2011} and FS_{2011}. Taking into account that the amount of fish consumed, of the total fish and fish products consumed, in 2009 was 55%, and that 89.2% of this fish was whole (SSB 2010) it is clear that the amount of P consumed given the FS_{2011} scenario should be significantly smaller than what is seen in the results. However, the estimation for P consumed for CT_{2011} and CT_{2050} would seem reasonable given the data available.

4.2 Limitations of the model

As the trend for fish feed is a reduction of the fish components in the feed is in favor of vegetable feed components, it is important to take the bioavailability of the P in the different feed components into account. As previously described the P content in vegetable components is not as high as that of fishmeal (Lall 1991). Taking into account the P requirements of the fish (see Chapter 1.4) an increase of vegetable feed components would require an increased P content in the feed in order to meet the P requirements of the fish. In this model this is not done due to the increased complexity of the system this would cause, and also because good data on the use of vegetable feed components could not be obtained.

As previously stated the model does not take the potential of a total fileting of marine fish to consumption into account as expected. This was due to a misconfiguration of the flow and most likely the amount of marine fish to consumption in FS_{2050} should be approx. 3000 tons smaller. Later studies would be wise to take this into account to avoid this deviation.

With the main focus of the study on the fisheries and aquaculture industry, the waste management systems were not given enough attention. As a result of this all waste from consumers and retailers are modeled as being landfilled. Given the variety of waste management methods currently used in Norway (Miljøstatus i Norge 2013), it would have been beneficial to model other systems, such as composting and reuse of wet organic waste.

4.3 Conclusion and assessment of the goals

The role of the Norwegian fisheries and aquaculture industry in the future will undoubtedly be of great importance in the future, both as a food source and a source to other resources currently not utilized.

With this study the flows of phosphorus in the Norwegian fisheries and aquaculture industry have been identified and characterized. Given the first goal of the study, which was to characterize the system in terms of feed inputs and phosphorus emissions it is clear that this goal has been fulfilled. It has been shown that the Norwegian aquaculture is responsible for the majority of both inputs and outputs of the system in the form of imported feed components, exported fish and especially the emissions of phosphorus in the form of dissolved inorganic P and particulate organic P. From this it can be stated that by using a mass flow analysis this system has been successfully characterized.

Furthermore it has been shown that the Norwegian fisheries and aquaculture industry hold a significant potential for recycling of P from fish scrap in order to produce fish meal and oil, and this could prove a significant and valuable raw material for the fishmeal and oil production. In addition such recycling could reduce costs related to transport of imported feed components and reduce stress on natural fish stocks. However, given current rules and regulations this recycling could only use fish from the marine fisheries and not from the aquaculture industry. This is a significant barrier to this question as the amounts of fish scrap from the aquaculture industry can only be expected to increase in the coming years. Therefore, more research should be performed with the aim of developing new technologies making the scrap from the aquaculture industry available for recycling. Given the content of phosphorus in this fish scrap, one could possibly replace the entire import of P in fish meal with a high rate of recycling. Due to the significant amounts of feed currently used and expected to be used in the future other alternative domestic feed sources would possibly be too small and not necessarily cost-efficient.

As for the implications of alternative feed sources for the P cycle of the Norwegian fisheries and aquaculture industry this relies on the type of alternative feed source. As stated above an increased use of fish scrap for the production of fishmeal and oil would significantly reduce the dependence upon imported feed components. An important aspect of the aquaculture industry is the significant amounts of nutrients released due to low feed efficiency. With the large amount of phosphorus this entails alternative feeds based on e.g. algae or mussels could feed of these emissions and thus allow us to move closer to a closing of the loops for the aquaculture system. As this was not modeled in this study it is highly recommended for future studies to include this in their analysis.

As a concluding remark future work should include the expansion of the model to in order to characterize other essential nutrients in the system, such as nitrogen. It would also be beneficial to include a second economic layer to the system so as to illustrate the potential economic worth of the different flows and resources.

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Appendix

Appendix a: Total sold amount of farmed fish in Norway, round weight in tons, 1997-2011 (SSB 2012a)

	I alt	Laks	Regnbueørret	Røye/sjørøye	Torsk	Kveite	Andre fiskearter
1997	367 115	332 581	33 295	350	304	[1] 113	472
1998	410 449	360 806	48 431	190	199	[1] 290	534
1999	476 291	425 154	48 692	498	157	451	1 340
2000	490 278	440 061	48 778	282	170	562	425
2001	508 497	435 119	71 764	317	535	377	385
2002	548 718	462 495	83 559	319	1 258	424	663
2003	582 587	509 544	68 931	272	2 185	426	1 229
2004	633 110	563 914	63 401	324	3 165	648	1 658
2005	656 894	586 512	58 875	352	7 409	1 197	2 549
2006	708 558	629 888	62 703	897	11 087	1 185	2 798
2007	838 856	744 220	77 465	395	11 104	2 307	3 365
2008	846 353	737 694	85 266	468	18 052	1 587	3 286
2009	960 110	862 908	74 072	421	20 924	1 568	218
2010	1 017 711	939 575	54 538	492	21 240	1 610	256
2011	1 142 892	1 065 975	58 364	276	15 273	2 767	237

Appendix b: Bioavailability of phosphorus from common feedstuffs and mineral supplements for Atlantic salmon, feedstuffs with no values are not considered for salmon or results are missing (Lall 1991)

Source	Bioavailability for Atlantic salmon, %
Animal by-products	
Blood meal	81

Brewer’s yeast	79
Casein	92
Egg Albumin	-
Feather meal, hydrolyzed	77
Poultry by-product meal	81
Fishery by-products	
Anchovy meal	-
Brown meal, Jap.	-
Capelin meal	53
Herring meal	52
Menhaden meal	87
Whitefish meal	79
Whitefish meal, Jap	-
Plant products	
Rice bran	-
Wheat germ	-
Wheat middlings	32
Corn, ground	-
Soybean meal, with hulls	-
Soybean meal, dehulled	36
Phytate	0
Inorganic phosphorus	
Sodium phosphate, NaH_2PO_4	95
Potassium phosphate, KH_2PO_4	94
Calcium phosphates	
$CaH_4(PO_4).H_2O$	90
$CaHPO_4$	72
$Ca_{10}(OH)_2(PO_4)_6$	56

Appendix c: Import and export of fish and fish products to Norway, Part 1, derived from (SSB 2013d)**. With total amount and share of different product categories.**

	Total 2011 fresh water	Total 2011 aquaculture	Total 2011 marine	Total 2011 feed fish	Total 2011 non-fish	Total 2011 aquarium	Total 2011 meal, feed	Total 2011 meal, not feed	Total 2011, fish feed	Total 2011, fish conserved	Total 2011, fish products	Total 2011, non-fish products
Import, ton/yr	3,06	1 361,61	156 731,50	18 197,24	15 933,06	81,36	230 046,68	5,54	30 382,96	13 634,05	6 575,75	5 899,86
Export, ton/yr	230,36	886 089,62	1 350 306,76	63 716,20	8 752,58	-	24 284,50	1 000,49	14 936,98	15 343,19	3 617,36	10 056,86
SUM, ton/yr	233,42	887 451,23	1 507 038,26	81 913,44	24 685,64	81,36	254 331,18	1 006,03	45 319,94	28 977,24	10 193,11	15 956,72
Trade balance, ton/yr	227,30	884 728,01	1 193 575,27	45 518,95	-7 180,49	-81,36	-205 762,18	994,95	-15 445,98	1 709,15	-2 958,40	4 157,01
% of total import	0,00	0,00	0,34	0,04	0,03	0,00	0,50	0,00	0,07	0,03	0,01	0,01
% of total export	0,00	0,38	0,58	0,03	0,00	-	0,01	0,00	0,01	0,01	0,00	0,00
% whole fish, import	1,00	0,12	0,92	-	-	1,00	-	-	-	-	-	-
% whole fish, export	1,00	0,86	0,75	-	-	-	-	-	-	-	-	-
% without head, import	-	0,08	0,00	-	-	-	-	-	-	-	-	-
% without head, export	-	0,03	0,08	-	-	-	-	-	-	-	-	-
% filets/meat, import	-	0,80	0,08	-	-	-	-	-	-	1,00	1,00	-
% filets/meat, export	-	0,12	0,15	-	-	-	-	-	-	1,00	1,00	-
% misc. Import	-	-	0,00	1,00	-	-	-	-	-	-	-	-
% misc. Export	-	-	0,03	1,00	-	-	-	-	-	-	-	-
% non-fish, import	-	-	-	-	1,00	-	-	-	-	-	-	1,00
% non-fish, export	-	-	-	-	1,00	-	-	-	-	-	-	1,00
% fish feed, import	-	-	-	-	-	-	-	-	1,00	-	-	-
% fish feed, export	-	-	-	-	-	-	-	-	1,00	-	-	-
% meal, feed, import	-	-	-	-	-	-	1,00	-	-	-	-	-
% meal, feed, export	-	-	-	-	-	-	1,00	-	-	-	-	-
% meal, not feed, import	-	-	-	-	-	-	-	1,00	-	-	-	-
% meal, not feed, export	-	-	-	-	-	-	-	1,00	-	-	-	-

Appendix d: : Import and export of fish and fish products to Norway, Part 2 derived from SSB(2013b) **and Appendix e. P content for the different product categories can be found in Appendix e.**

	Total 2011 fresh water	Total 2011 aquaculture	Total 2011 marine	Total 2011 feed fish	Total 2011 non-fish	Total 2011 aquarium	Total 2011 meal, feed	Total 2011 meal, not feed	Total 2011, fish feed	Total 2011, fish conserved	Total 2011, fish products	Total 2011, non-fish products
Ton whole fish, import	3,06	164,11	143 882,50	-	-	1,00	-	-	-	-	-	-
Ton whole fish, export	230,36	759 576,73	1 010 570,48	-	-	-	-	-	-	-	-	-
ton without head, import	-	112,62	224,31	-	-	-	-	-	-	-	-	-
ton without head, export	-	24 149,28	104 070,68	-	-	-	-	-	-	-	-	-
ton filets/meat, import	-	1 084,89	12 351,09	-	-	-	-	-	-	13 634,05	6 575,75	-
ton filets/meat, export	-	102 363,61	201 415,06	-	-	-	-	-	-	15 343,19	3 617,36	-
ton misc., import	-	-	273,59	18 197,24	-	-	-	-	-	-	-	-
ton misc.,export	-	-	34 250,54	63 716,20	-	-	-	-	-	-	-	-
Ton fish feed, import	-	-	-	-	-	-	-	-	30 382,96	-	-	-
ton fish feed, export	-	-	-	-	-	-	-	-	14 936,98	-	-	-
ton non-fish, import	-	-	-	-	15 933,06	-	-	-	-	-	-	5 899,86
ton non-fish, export	-	-	-	-	8 752,58	-	-	-	-	-	-	10 056,86
Ton meal, feed, import	-	-	-	-	-	-	230 046,68	-	-	-	-	-
Ton meal, feed, export	-	-	-	-	-	-	24 284,50	-	-	-	-	-
Ton meal, n-feed, import	-	-	-	-	-	-	-	5,54	-	-	-	-
Ton meal, n-feed, export	-	-	-	-	-	-	-	1 000,49	-	-	-	-
Total P, imported, t/yr	0,01	1,48	583,57	72,79	39,52	0,33	5 001,77	0,09	319,02	7,09	3,42	14,63
Total P, exported, t/yr	0,92	3 147,79	4 526,46	254,86	21,71	-	402,33	16,58	156,84	7,98	1,88	24,94
% P of total, imported	0,00	0,00	0,10	0,01	0,01	0,00	0,83	0,00	0,05	0,00	0,00	0,00
% P of total, exported	0,00	0,37	0,53	0,03	0,00	-	0,05	0,00	0,02	0,00	0,00	0,00

Appendix e: P content used to calculate total amount of P imported and exported to Norway in 2011

Product condition	% P
Ton whole fish, import	0,40 %
Ton whole fish, export	0,40 %
ton without head, import	0,23 %
ton without head, export	0,23 %
ton filets/meat, import	0,05 %
ton filets/meat, export	0,05 %
ton misc., import	0,40 %
ton misc., export	0,40 %
Ton fish feed, import	1,05 %
ton fish feed, export	1,05 %
ton non-fish, import	0,25 %
ton non-fish, export	0,25 %
Ton meal, feed, import	2,17 %
Ton meal, feed, export	1,66 %
Ton meal, n-feed, import	1,66 %
Ton meal, n-feed, export	1,66 %

Appendix f: : Amount of salmon, trout and charr fished and killed in Norwegian rivers, kg/yr (SSB 2013b)

	2010	2011	2012
Fish killed, kg	437917	445300	495458

Appendix g: Total amount of sold slaughtered farmed fish, tons/yr (SSB 2012e)

Fish species	2009	2010	2011
Laks	862908	939575	1065975
Regnbueørret	74072	54538	58364
Røye	421	492	276
Torsk	20924	21240	15273
Kveite	1568	1610	2767
Skalldyr	1728	2001	1926

Andre fiskearter	218	256	237
SUM fisk	960111	1017711	1142892

Appendix h: Average round weight of farmed fish for slaughter in Norway, 2009-2011, derived from (SSB 2012b) **and Appendix g. The value used as a basis for the calculations is 5.13 kg which was derived from the total number of farmed fish and total weight of farmed fish**

Fish species	2009	2010	2011
Total nr fish (1000)	204402	213347	222989
Weight per fish (kg)	4,70	4,77	5,13
Total nr salmon (1000)	175071	189355	200541
weight per salmon (kg)	4,93	4,96	5,32
Total nr trout (1000)	19176	15088	15543
weight per trout (kg)	3,86	3,61	3,76
Total nr charr (1000)	650	253	473
weight per charr (kg)	0,65	1,94	0,58
Total nr cod (1000)	8944	8066	5623
weight per cod (kg)	2,34	2,63	2,72
Total nr halibut (1000)	441	442	639
weight per halibut (kg)	3,56	3,64	4,33
Total nr other fish (1000)	120	143	170
weight per other (kg)	1,82	1,79	1,39

Appendix i: Total amount of farmed shellfish in Norway, tons/yr (SSB 2012d)

	2009	2010	2011
Blåskjell	1649	1930	1743
Kamskjell	8	10	13
Østers	2	2	2
Andre arter	68	59	169
SUM	**1727**	**2001**	**1927**

Appendix j: Stock, input, output and loss of fish in Norwegian aquaculture (PART 1). The percentage lost of output (Tap/svinn av uttak) was calculated by the author in order to estimate the total amount of fish lost compared to the amount of fish slaughtered. (SSB 2012b)

#	2009	2010	2011
Total fish			
Beholdning 1.1 (1 000 stk)	349999	357899	375095
Tilgang (utsatt) (1 000 stk)	267226	285561	310439
Uttak (1 000 stk)	204402	213347	222989
Tap/svinn (1 000 stk)	56787	54196	59115
Beholdning 31.12 (1 000 stk)	878414	375259	403429
Tap/svinn (prosent)	9,2	14,8	15,5
Tap/svinn av uttak (prosent)	27,8	25,4	26,5
Salmon			
Beholdning 1.1 (1 000 stk)	295649	316042	336422
Tilgang (utsatt) (1 000 stk)	238644	257320	281218
Uttak (1 000 stk)	175071	189355	200541
Tap/svinn (1 000 stk)	45817	46850	50970
Beholdning 31.12 (1 000 stk)	313405	337157	366130
Tap/svinn (prosent)	15	14,3	14,5
Tap/svinn av uttak (prosent)	26,2	24,7	25,4
Rainbow trout			
Beholdning 1.1 (1 000 stk)	26246	21159	22924
Tilgang (utsatt) (1 000 stk)	16742	20259	21298
Uttak (1 000 stk)	19176	15088	15543
Tap/svinn (1 000 stk)	2662	3251	2564
Beholdning 31.12 (1 000 stk)	21149	23079	26115
Tap/svinn (prosent)	11,2	14,7	10,5
Tap/svinn av uttak (prosent)	13,9	21,5	16,5

Appendix k: Stock, input, output and loss of fish in Norwegian aquaculture (PART 2). The percentage lost of output (Tap/svinn av uttak) was calculated by the author in order to estimate the total amount of fish lost compared to the amount of fish slaughtered. (SSB 2012b)

#	2009	2010	2011
Charr			

Beholdning 1.1 (1 000 stk)	1886	1620	1197
Tilgang (utsatt) (1 000 stk)	662	639	846
Uttak (1 000 stk)	650	253	473
Tap/svinn (1 000 stk)	517	220	837
Beholdning 31.12 (1 000 stk)	1382	1128	732
Tap/svinn (prosent)	31,6	16	86,8
Tap/svinn av uttak (prosent)	79,5	87,0	177,0
Cod			
Beholdning 1.1 (1 000 stk)	23763	16853	10693
Tilgang (utsatt) (1 000 stk)	10369	6215	3555
Uttak (1 000 stk)	8944	8066	5623
Tap/svinn (1 000 stk)	7289	3539	2821
Beholdning 31.12 (1 000 stk)	17898	11462	5803
Tap/svinn (prosent)	35	25	34,2
Tap/svinn av uttak (prosent)	81,5	43,9	50,2
Halibut			
Beholdning 1.1 (1 000 stk)	2113	1914	3068
Tilgang (utsatt) (1 000 stk)	689	884	1040
Uttak (1 000 stk)	441	442	639
Tap/svinn (1 000 stk)	460	309	466
Beholdning 31.12 (1 000 stk)	1900	2047	3003
Tap/svinn (prosent)	22,9	15,6	15,4
Tap/svinn av uttak (prosent)	104,3	69,9	72,9
Other species			
Beholdning 1.1 (1 000 stk)	342	311	791
Tilgang (utsatt) (1 000 stk)	120	244	2482
Uttak (1 000 stk)	120	143	170
Tap/svinn (1 000 stk)	42	27	1457
Beholdning 31.12 (1 000 stk)	302	385	1646
Tap/svinn (prosent)	13	7,8	119,6
Tap/svinn av uttak (prosent)	35,0	18,9	857,1

Appendix I: Loss of fish in Norwegian aquaculture in three categories; death, escapes and other causes; with share of loss according to the different causes. (SSB 2012f)

Cause of loss and species	2009	% of total lost, 2009	2010	% of total lost, 2010	2011	% of total lost, 2011
Total	#	%	#	%	#	%
Totalt tap/svinn	56 350	100,00	54 034	100,00	59 029	100,00
Død	41 826	74,23	40 100	74,21	42 341	71,73
Rømming	570	1,01	387	0,72	357	0,60
Andre årsaker	13 955	24,76	13 550	25,08	16 356	27,71
Salmon	#	%	#	%	#	%
Totalt tap/svinn	45 817	100,00	46 851	100,00	50 971	100,00
Død	36 894	80,52	36 629	78,18	37 314	73,21
Rømming	199	0,43	215	0,46	346	0,68
Andre årsaker	8 724	19,04	10 008	21,36	13 310	26,11
Rainbow trout	#	%	#	%	#	%
Totalt tap/svinn	2 662	100,00	3 241	100,00	2 563	100,00
Død	2 073	77,87	1 808	55,79	1 808	70,54
Rømming	133	5,00	6	0,19	4	0,16
Andre årsaker	457	17,17	1 428	44,06	779	30,39
Cod	#	%	#	%	#	%
Totalt tap/svinn	7 294	100,00	3 538	100,00	2 823	100,00
Død	2 415	33,11	1 377	38,92	885	31,35
Rømming	222	3,04	166	4,69	7	0,25
Andre årsaker	4 657	63,85	1 995	56,39	1 930	68,37
Other species	#	%	#	%	#	%
Totalt tap/svinn	577	100,00	404	100,00	2 672	100,00
Død	444	76,95	286	70,79	2 334	87,35
Rømming	16	2,77	0	0,00	0	0,00
Andre årsaker	117	20,28	119	29,46	337	12,61

Appendix m: Population predictions for Norway in 2050 with 14 scenarios and the average used in this thesis. Derived from SSB (2012h)**.**

Growth Scenario	2050
Middels nasjonal vekst (Alternativ MMMM)	6 680 814
Lav nasjonal vekst (Alternativ LLML)	5 645 543
Høy nasjonal vekst (Alternativ HHMH)	8 392 569
Lav fruktbarhet (Alternativ LMMM)	6 408 826
Høy fruktbarhet (Alternativ HMMM)	6 956 309
Lav levealder (Alternativ MLMM)	6 500 007
Høy levealder (Alternativ MHMM)	6 828 723
Lav innvandring (Alternativ MMML)	6 070 134
Høy innvandring (Alternativ MMMH)	7 926 540
Sterk aldring (Alternativ LHML)	5 963 116
Svak aldring (Alternativ HLMH)	8 048 289
Ingen netto innvandring (Alternativ MMM0)	5 325 102
Ingen flytting (Alternativ MM00)	5 270 951
Ingen vekst i levealder (Alternativ MKMM)	6 417 326
Konstant innvandring (Alternativ MMMK)	7 243 054
AVERAGE	**6 645 154**

Appendix n: Fish landed in Norway by Norwegian vessels, divided into different use categories with use share. Derived from SSB (2013b)

Type fish	Use category	2010	2010 use share, %	2011	2011 use share, %	2012	2012 use share, %
Pelagisk fisk	Konsum	1 367 307	76,1	988 622	72,2	1 000 414	81,0
	Mjøl og olje	427 469	23,8	379 271	27,7	231 568	18,8
	Dyrefor/fiskefor, agn og anna	2 008	0,1	1 775	0,1	2 838	0,2
Torsk og torskeartet fisk	Konsum	675 300	99,9	724 383	99,9	713 724	98,0
	Mjøl og olje	489	0,1	157	0,0	284	0,0
	Dyrefor/fiskefor, agn og anna	330	0,0	539	0,1	14 554	2,0
Flatfisk og bunnfisk	Konsum	51 311	97,4	48 506	98,7	51 320	97,1
	Mjøl og olje	1 328	2,5	584	1,2	441	0,8
	Dyrefor/fiskefor, agn og anna	63	0,1	56	0,1	1 083	2,0
Diverse dypvannsarter	Konsum	1 329	69,1	784	65,9	789	53,2
	Mjøl og olje	566	29,4	366	30,8	548	37,0
	Dyrefor/fiskefor, agn og anna	27	1,4	40	3,4	146	9,8
Annen uspesifisert fisk	Konsum	1 164	76,2	1 293	81,6	1 279	80,3
	Mjøl og olje	9	0,6	-	0,0	1	0,1
	Dyrefor/fiskefor, agn og anna	354	23,2	292	18,4	312	19,6
Skalldyr og bløtdyr	Konsum	25 032	17,3	44 368	30,2	21 199	19,1
	Mjøl og olje	104 424	72,4	88 143	60,0	88 807	79,9
	Dyrefor/fiskefor, agn og anna	14 870	10,3	14 399	9,8	1 198	1,1

Appendix o: Fish landed in Norway by foreign vessels, round weight in tons. (Fiskeridirektoratet 2012a)

	Landed fish in tons			
Type fish	**2008**	**2009**	**2010**	**2011**
Pelagisk fisk	159 681	184 071	169 284	135 353
Torsk og torskeartet fisk	113 000	106 223	116 825	132 445
Flatfisk og bunnfisk	4 186	5 149	4 222	6 657
Diverse dypvannsarter	-	-	1	4
Annen uspesifisert fisk	26	81	12	6
Skalldyr og bløtdyr	5 547	4 328	3 805	5 298
TOTAL	282 440	299 852	294 149	279 763

Appendix p: Total landed fish in Norway by Norwegian and foreign vessels, divided into different use categories with use share. Derived from Appendix n and Appendix o

Use category	Tons	Use share, %
Konsum	2051470	79,6
Mjøl og olje	509289	19,8
Dyrefor/fiskefor etc	17904	0,7

Appendix q: Baseline parameters for 2011 for the Norwegian fisheries and aquaculture industry

Parameter name	2011 baseline	Unit	Parameter
P concentration in feed	1,05	%	Pf
Feed loss	5,00	%	kx56
FCR	1,28	n	F
Lost through excretion of total	9,00	%	kx65a
Total P in fish bones/meat	87,00	%	PB
% of fish is bones and scales	41,00	%	PBS
Marine animals landed in Norway	2 578 663,00	t	ML
Avg % P in marine animals landed in Norway	0,39	%	PML
Avg. P content in fish	0,40	%	PC
Marine fish to meal and oil	509 288,93	t	MMO
Exp fish to meal and oil	63 716,20	t	EFMO
Avg % P in fish to meal and oil	0,37	%	PMO
Marine fish to other feed	17 903,96	t	MFOF
Avg % P in fish to other feed	0,27	%	PFF
Marine fish to consumption	2 051 470,11	t	MC
Avg % P in fish to consumption	0,40	%	PFC
% meal in cod feed	23,98	%	PMC
% meal in salmon feed	23,98	%	PMS
% cod feed	1,51	%	PCF
% salmon feed	98,49	%	PSF
Total sold farmed fish	1 142 892,00	t	S
Total sold farmed molluscs and shellfish	1 926,00	t	M
Exported marine species, t/P/yr	7 731,69	t	EMP
Imported marine species, t/P/yr	650,05	t	IMP
Excess fish feed, t/yr	14 936,98	t	EF
Norwegian population	4 985 870,00	p	NP
Fish products consumed/cap/yr	16,30	kg	FC
fish to meal yield	4,39	p	kx23
Fresh water fish to consumption	445,30	t	FF
P content in herring type fish meal	1,90	%	PHM
P content in S. American type fish meals	2,60	%	PSM
Food waste at retailer	6,20	%	kx1012
Food waste at consumer	35,58	%	kx1112
Loss of fish in aquaculture by sold fish	26,51	%	LFA
% dead fish of lost farmed fish	71,73	%	DFF
% escaped fish of lost farmed fish	0,60	%	EFF
% other lost farmed fish	27,71	%	OFF
Avg P content in whole farmed shellfish	0,25	%	PM
Slaughter waste	18,81	%	kx813
Avg weight of fish for slaughter	5,13	kg	WFS
Avg weight of fish lost	1,42	kg	WFL
Imp fish feed of total feed fed	2,09	%	IFF
Exp. Meal	25 284,98	t	EM
Imp meal	230 046,68	t	IM
Imp fish for meal and oil	18 197,24	t	IFM
% P in fish for meal and oil (waste products)	0,40	%	PFMO
% of imported meal from pacific countries	39,18	%	PSM
% of fish consumed, whole	89,19	%	PCW
% of fish consumed, filets	10,81	%	PCF
% of consumption fish	55,11	%	CF
% of consumption shellfish	11,06	%	CS
% of consumption misc.	33,00	%	CM
Avg P content in misc.	0,40	%	PCM
Imp meal - not for food, t/P/yr	0,09	t	IMNF
Exp meal - not for food, t/P/yr	16,82	t	EMNF
Scrap from landed fish in 2011	345 000,00	t	SLF
Avg P content for scrap resource	0,40	%	PSR
Fish scrap used for meal prod.	49,22	%	FSMP

Appendix r: Baseline parameters for 2050 for the Norwegian fisheries and aquaculture industry

Parameter name	2050 baseline	Unit	Parameter
P concentration in feed	1,05	%	Pf
Feed loss	5,00	%	kx56
FCR	1,28	n	F
Lost through excretion of total	9,00	%	kx65a
Total P in fish bones/meat	87,00	%	PB
% of fish is bones and scales	41,00	%	PBS
Marine animals landed in Norway	4 000 000,00	t	ML
Avg % P in marine animals landed in Norway	0,39	%	PML
Avg. P content in fish	0,40	%	PC
Marine fish to meal and oil	790 004,64	t	MMO
Exp fish to meal and oil	98 836,02	t	EFMO
Avg % P in fish to meal and oil	0,37	%	PMO
Marine fish to other feed	27 772,47	t	MFOF
Avg % P in fish to other feed	0,27	%	PFF
Marine fish to consumption	3 182 222,89	t	MC
Avg % P in fish to consumption	0,40	%	PFC
% meal in cod feed	15,00	%	PMC
% meal in salmon feed	15,00	%	PMS
% cod feed	1,51	%	PCF
% salmon feed	98,49	%	PSF
Total sold farmed fish	4 991 574,01	t	S
Total sold farmed molluscs and shellfish	8 425,99	t	M
Exported marine species, t/P/yr	-	t	EMP
Imported marine species, t/P/yr	650,05	t	IMP
Excess fish feed, t/yr	59 172,76	t	EF
Norwegian population	6 645 153,53	p	NP
Fish products consumed/cap/yr	20,00	kg	FC
fish to meal yield	4,39	p	kx23
Fresh water fish to consumption	445,30	t	FF
P content in herring type fish meal	1,90	%	PHM
P content in S. American type fish meals	2,60	%	PSM
Food waste at retailer	6,20	%	kx1012
Food waste at consumer	35,58	%	kx1112
Loss of fish in aquaculture by sold fish	26,51	%	LFA
% dead fish of lost farmed fish	71,73	%	DFF
% escaped fish of lost farmed fish	0,60	%	EFF
% other lost farmed fish	27,71	%	OFF
Avg P content in whole farmed shellfish	0,25	%	PM
Slaughter waste	18,81	%	kx813
Avg weight of fish for slaughter	5,13	kg	WFS
Avg weight of fish lost	1,42	kg	WFL
Imp fish feed of total feed fed	2,09	%	IFF
Exp. Meal	-	t	EM
Imp meal	-	t	IM
Imp fish for meal and oil	-	t	IFM
% P in fish for meal and oil (waste products)	0,40	%	PFMO
% of imported meal from pacific countries	39,18	%	PSM
% of fish consumed, whole	89,19	%	PCW
% of fish consumed, filets	10,81	%	PCF
% of consumption fish	55,11	%	CF
% of consumption shellfish	11,06	%	CS
% of consumption misc.	33,00	%	CM
Avg P content in misc.	0,40	%	PCM
Imp meal - not for food, t/P/yr	0,09	t	IMNF
Exp meal - not for food, t/P/yr	16,82	t	EMNF
Scrap from landed fish in 2011	535 161,05	t	SLF
Avg P content for scrap resource	0,40	%	PSR
Fish scrap used for meal prod.	49,22	%	FSMP

Appendix s: The analytical solution for the Norwegian fisheries and aquaculture industry. For flow 27 (X9.0) the solution for 2011 is marked in red, and the rest of the solution is for 2050 as it balances better against the inputs to the process.

Analytical Solution		
1	X0.1	ML*PML
2	X1.3	(MMO*PMO)+((SLF*FSMP)*PSR)
3	X1.9	(MC*PFC)-(SLF*PSR)
4	X1.13	(SLF*(1-FSMP))*(PSR)
5	X1.14	MFOF*PFF
6	X2.3	(IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC)
7	X0.3a	(IMNF)+(IFM*PC)+((((((S*F)*PSF)*PMS)+(((S*F)*PCO)*PMC))-(((IFM+(MMO+(SLF*FSMP))-EFMO)*kx23^-1)-(EM+(EMNF*((((IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC))*((IFM+(MMO+(SLF*FSMP))-EFMO)*kx23^-1)^-1*100)/100)^-1)))))*(((PSAM*PSM)+(PHM*(1-PSM)))*100)/100)+(((S*F)*IFF)*Pf)
8	X0.3b	((EF*Pf)+((S*F-((S*F)*IFF))*Pf))-((((IMNF)+(IFM*PC)+((((((((S*F)*PSF)*PMS)+(((S*F)*PCO)*PMC))-((((IFM+(MMO+(SLF*FSMP))-EFMO)*kx23^-1))-(EM+(EMNF*((((IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC))*((IFM+(MMO+(SLF*FSMP))-EFMO)*kx23^-1)^-1*100)/100)^-1)))))*(((PSAM*PSM)+(PHM*(1-PSM)))*100)/100))+(((S*F)*IFF)*Pf))-(((S*F)*IFF)*Pf)-IMNF-(IFM*PC))+((((IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC))-EMNF-(EM*((((IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC))*((IFM+(MMO+(SLF*FSMP))-EFMO)*kx23^-1)^-1*100)/100)))))
9	X3.0	EMNF+(EM*(((IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC))*((IFM+(MMO+(SLF*FSMP))-EFMO)*kx23^-1)^-1*100)/100)+(EFMO*PC)+(EF*Pf)
10	X3.2	(IFM*PFMO)+((MMO*PMO)+((SLF*FSMP)*PSR))-(EFMO*PC)
11	X3.4	(EF*Pf)+((S*F-((S*F)*IFF))*Pf)
12	X3.5	((S*F)*IFF)*Pf
13	X3.14	IMNF
14	X4.3	EF*Pf
15	X4.5	(S*F-((S*F)*IFF))*Pf
16	X5.0a	((((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56))*(1-(((S*PC)*(((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56))^-1)+kx65)))+((((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56))*kx65)+((((S*F-((S*F)*IFF))*Pf)+(((S*F)*IFF)*Pf))-(((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56)))-(((((S*WFS^-1)*LFA)*DFF)*WFL)*PC)-(((((S*WFS^-1)*LFA)*(EFF+OFF)*WFL))*PC)
17	X5.0b	((((S*WFS^-1)*LFA)*(EFF+OFF)*WFL))*PC
18	X5.6	((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56)
19	X5.13	((((S*WFS^-1)*LFA)*DFF)*WFL)*PC
20	X6.5a	(((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56))*kx65
21	X6.5b	(((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56))*(1-(((S*PC)*(((S*F-((S*F)*IFF))*Pf)-(((S*F-((S*F)*IFF))*Pf)*kx56))^-1)+kx65))
22	X6.8	(S*PC)+(M*PM)
23	X7.9	FF*PC
24	X8.9	((S*PC)+(M*PM))-((S*PC)*PB)*(S*PBS)^-1*(S*kx813)
25	X8.13	((S*PC)*PB)*(S*PBS)^-1*(S*kx813)
26	X0.9	IMP
27	X9.0	EMP;(((MC*PFC)-(SLF*PSR))+(((S*PC)+(M*PM))-((S*kx813)*PC))-

		((((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3))*(1+kx1012))))
28	X9.10	((((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3))*(1+kx1012))
29	X10.11	((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3)
30	X10.12	((((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3))*(1+kx1012)-(((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3))
31	X11.12	((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3)*kx1112
32	X13.14	((((S*(kx813)+((((S/WFS)*LFA)*DFF)*WFL)+(SLF*(1-FSMP)))-(SLF*(1-FSMP)))*PC)+((SLF*(1-FSMP))*PSR)
33	X14.0	(MFOF*PFF)+(((((S*kx813)+((((S*WFS^-1)*LFA)*DFF)*WFL)+(SLF*(1-FSMP)))-(SLF*(1-FSMP)))*PC)+((SLF*(1-FSMP))*PSR))+IMNF
34	ΔS6	0-(M*PM)
35	ΔS7	0-(FF*PC)
36	ΔS11	(((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3))-(((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3)*kx1112)
37	ΔS12	(((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3)*kx1112)+(((((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3))*(1+kx1012)-(((((((NP*FC)*CF)*PCW)*PC)+((((NP*FC)*CF)*PCF)*((1-PB)*PC))+(((NP*FC)*CS)*PM)+(((NP*FC)*CM)*PCM))*10^-3)))

Appendix t: The variables for the Norwegian fisheries and aquaculture industry

Flows		Changes in stock	
1	X0>1	34	ΔS6
2	X1>3	35	ΔS7
3	X1>9	36	ΔS11
4	X1>13	37	ΔS12
5	X1>14		
6	X2>3		
7	X0>3a		
8	X0>3b		
9	X3>0		
10	X3>2		
11	X3>4		
12	X3>5		
13	X3>14		
14	X4>3		
15	X4>5		
16	X5>0a		
17	X5>0b		
18	X5>6		
19	X5>13		
20	X6>5a		

21	X6>5b
22	X6>8
23	X7>9
24	X8>9
25	X8>13
26	X0>9
27	X9>0
28	X9>10
29	X10>11
30	X10>12
31	X11>12
32	X13>14
33	X14>0

Appendix u: The Mass balance equations for the Norwegian fisheries and aquaculture industry

Mass Balance Equations	
1	ΔS6=X5>6-X6>5a-X6>5b-X6>8
2	ΔS7=X10>11-X11>12
3	ΔS11=X11>12+X10>12
4	ΔS12=-X7>9
5	0=X0>1-X1>3-X1>9-X1>13-X1>14
6	0=X3>2-X2>3
7	0=X0>3a+X0>3b+X1>3+X2>3+X4>3-X3>0-X3>2-X3>4-X3>5-X3>14
8	0=X3>4-X4>3-X4>5
9	0=X3>5+X4>5+X6>5a+X6>5b-X5>6-X5>0a-X5>0b-X5>13
10	0=X6>8-X8>9-X8>13
11	0=X8>9+X7>9+X1>9+X0>9-X9>0-X9>10-X0>9-Xu
12	0=X9>10-X10>11-X10>12
13	0=X1>13+X5>13+X8>13-X13>14
14	0=X1>14+X3>14+X13>14-X14>0