Master's degree thesis

LOG950 Logistics

Minimizing the cost of fish sludge recycling for land based hatcheries in Møre og Romsdal

Iselin B. Sæther

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Preface and acknowledgements

This Master thesis presents the main results of my academic work as a master student at Molde University College – Specialized University in Logistics. The research work was carried out from December 2013 to May 2014 and has been conducted to obtain an MSc degree in Logistics.

First of all, I would like to thank Associate Professor Johan Oppen for his constructive criticism, humor and guidance throughout the process of working on this paper. Furthermore, I would also like to thank Møreforskning Molde, and especially Gabriele H. Jünge, for introducing me to the topic and for all the help and support I have received during the last six months. In addition I would like to thank Svein Martinsen, managing director of Nekton AS, and other participants in the Slam-Bep project, for providing information and data needed in the research.

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Åndalsnes, Norway
May 2014

Abstract

This master thesis considers a real world problem of determining the appropriate fish sludge recycling strategy for the land based hatchery Smøla Klekkeri og Settefiskanlegg AS, and a problem of locating centralized biogas plants to serve all hatcheries in Møre og Romsdal. The topic was introduced to me by Møreforskning Molde, a research institution currently involved in a project called Slam-Bep. The project, which is managed by Smøla Klekkeri og Settefiskanlegg AS and the research and development company Nekton AS, will develop knowledge and technologies for gathering and using fish sludge for biogas and as fertilizer. The need for research on this topic is mainly triggered by mandatory requirements for land based fish sludge treatment, implemented by the Norwegian Climate and Pollution Agency. While land based fish farms were previously able to dispose of the sludge by dumping it into the ocean, most of them now have to prepare to handle it in a more environmental friendly way.

Several relevant internal sludge handling techniques and technologies are compared in a financial analysis to evaluate different strategies for Smøla Klekkeri og Settefiskanlegg AS. In addition a facility location analysis is carried out to suggest locations and sizes of biogas plants in Møre og Romsdal.

The findings from both analyses have been compared and the results suggest that fish farmers can reduce the cost of fish sludge disposal by cooperating and building centralized biogas plants in the region.

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1. Introduction

Norwegian fishing and aquaculture industry is one of the world's largest exporters of seafood with an annual income of around 50 billion NOK (Ntnu.no). Hatcheries and fish farms provide the foundation for the land based aquaculture production as they hatch eggs and raise salmon from fry to smolt (juvenile salmon) before sending them off to floating sea cages along the coast (Hallenstvedt, 2009).

The Climate and Pollution Agency in Norway has implemented mandatory requirements for land based fish sludge treatment which result in significant costs for new and excising fish farms wanting to increase their production (Ytrestøyl et al., 2013). While the land based fish farms previously were able to dispose of the sludge by dumping it into the ocean, most of them now have to prepare to handle it in a more environmental friendly way. Since the costs will be substantial for the affected hatcheries, a five year dispensation has been arranged. This will give the industry time to adapt and evaluate different disposal alternatives.

The sludge from fish farms consist of mainly two components, fish feces and spilled fish feed. Primary sludge has a very small amount of dry substance and quickly deteriorates and cause odor problems (Blytt et al., 2011). Delivering the sludge without increasing the dryness will give very high transportation costs and is also problematic due to the fast deterioration of the sludge.

Fish sludge can, however, also be viewed as a resource both for the society as a whole and the fish farmers as it contains energy, nitrogen, phosphorus and other minerals which can be used to produce biogas and/or fertilizer either locally or centrally (Ytrestøyl et al., 2013). In order to use it for such purposes the sludge has to go through several stages of transformation.

Smøla Klekkeri og Settefiskanlegg AS is a land based fish farm located at Smøla in the county of Møre og Romsdal. The fish farm is currently producing 2,5 million salmon smolts a year, but plans to increase the production to 5 million, and will therefore have to start recycling their sludge. By using a recirculation aquaculture system (RAS) in their production the farm is able to remove the fish feces as well as the left-over fish feed and discharge it as sludge. At the current production level a staggering 400 tons of primary sludge is created, of which approximately 10% is dry substance (Smolaks, 2013). The amount of sludge created will of course increase as the production goes up.

Today the cost of submitting fish sludge to an appropriate waste management facility is around 1,20-1,50 NOK per kg (excluding transportation costs) (Ytrestøyl et al., 2013). This is a huge expense for the company, especially since the closest disposal facility is located almost 300 km away, and they are therefore looking for other ways of handling the sludge. They are currently, together with the research and development company Nekton AS, managing an industrial research project called Slam-bep, where the possibilities of transforming fish sludge into biogas and plant fertilizer are examined. Nekton AS was developed as a resource center for the two smolt production plants Smøla Klekkeri og Settefiskanlegg AS and Sagafisk. These three companies, together with Nekton Havbruk AS form the holding company Smølen Handelskompani AS (Len.no)

The project was launched in 2013 and is scheduled to last for three years. Together with the managing companies other participants in the project are Møreforsking Molde, Global Enviro, Storvik Aqua, Salsnes Filter, Biotek, NOFIMA, Lerøy Midt, Sævareid Fiskeanlegg, Lingalaks, Måsøval Fiskeoppdrett, Marine Harvest and Bioforsk (Rødal, 2013). They all wish to develop methods and knowledge to increase the dry substance of the sludge to 80-90% which will make it more stable and easier to recycle. As part of the project small biogas plants will also be tested to see if they can generate extra power to local fish farmers (Smolaks, 2013), and the use of processed (dried) fish sludge in biogas production will be investigated.

The company needs to find a good, low cost and sustainable way of recycling the sludge, and therefore needs to examine several possibilities before making any large investments. A large cost driver is expected to be logistics, and Møreforsking Molde is therefore going to do a logistical analysis.

A total of 31 hatcheries produce salmon smolt in Møre og Romsdal, and many, if not all of these, will be affected by the implemented policies. With so many smolt farms in the region it could be possible to generate a common fish sludge recycling option to benefit both the industry as well as the county. Currently no suitable organic waste management facilities or biogas plants are situated in Møre og Romsdal. Instead of treating food waste and sewage sludge within the county, the organic waste is, in the worst case scenario, transported to Sweden or Denmark (Energuide AS, 2011). It is therefore evident that locating one or more biogas plants in the region could benefit not only fish farmers, but also other industries in the region.

2. Problem description

This chapter presents the problem which is divided into two main parts, an internal sludge handling problem and a biogas plant location problem. Each problem is described in detail and relevant information is added to elaborate further on each topic. At the end research questions and objectives are presented.

2.1. Internal sludge handling problem

In response to the mandatory requirements imposed by the Climate and Pollution Agency in Norway, Smøla Klekkeri og Settefiskanlegg AS can choose to implement internal sludge treatment methods to reduce the cost of disposal. Three main groups of methods exist; methods for increasing dry substance, methods for stabilizing and methods for sanitation (Blytt et al., 2011). These methods serve different purposes and their usefulness is determined by the choice of end disposal.

Because of strict environmental regulations in Norway the company has only two main end disposal alternatives; either the fish sludge is sent to an appropriate waste management facility or it is used on appropriate land areas. If the sludge is to be transported to a waste management facility the only way of reducing cost is to increase the dry substance, which in turn will reduce the transportation costs and the disposal fee. However, the cost of investing in appropriate technologies might be too high to offset the price/cost reductions. According to Blytt et al. (2011) there are three different ways to dispose of fish sludge on land areas. It can be used on agricultural land (used for food production), green areas or as an ingredient in soil mixtures. Each of these options requires different treatment methods, and, if appropriate land areas are not in the immediate proximity of the fish farm, transportation costs will also arise.

Within all three groups of treatment methods different technologies and techniques can be used, all with different results and costs. The most appropriate techniques for increasing the dry substance are filters followed by a technology called Global Enviro. The filters can increase the dry substance to around 20% while Global Enviro can further increase the dry substance up to 90%. Combining these methods will in theory give a stable and dry substance, but so far they have failed to work effectively on fish sludge. An alternative method for stabilizing the sludge is by adding burnt chalk. This method will also sanitize the sludge but requires a substance containing at least 20% dry matter beforehand. Both stabilization and sanitation can also be achieved by utilizing a biogas plant. This method will enable the fish farm to produce biogas which in turn can be used to reduce energy costs at the facility. It is, however, a costly investment and, according to Blytt et al. (2011), such a solution could only be reasonable for a large fish farm receiving additional sludge from other farms.

No matter what treatment method is chosen, certain amounts of sludge or digestate (left over material after biogas production) needs to be disposed of.

2.2. Biogas plant location problem

Using fish sludge for biogas production might, as mentioned above, not be economically reasonable unless a large amount of fish sludge is obtainable. It is therefore necessary to investigate if cooperation among fish farms on a large, centralized biogas plant could benefit the industry. Nielsen et al. (2002) has analyzed the possibility of economies of scale in centralized Danish biogas plants, and found a clear connection between size and costs; the larger the plant, the smaller the cost per m^3 biomass treated. Their findings indicate that both investment and production costs can be reduced by establishing larger biogas plants, even though transportation costs will increase as distances increase (see Table 1).

Per day treatment capacity, in m^3	**300**	**550**	**800**
Investment costs, DKK per m^3 biomass treated per year	**405**	**325**	**272**
Production costs, in DKK			
- **Transportation costs**	**16**	**16**	**18**
- **Biogas plant**	**53**	**41**	**35**
DKK per m^3 biomass treated per year	**69**	**57**	**53**

Table 1: Investment and production costs for different biogas plant sizes (Adapted from Nielsen et al. 2002).

According to the Norwegian directorate of fisheries (Fiskeridir.no) there are a total of 31 licensed salmon smolt farms in Møre og Romsdal as shown in Figure 1. In coming years all of these might have to start recycling their sludge and in turn they create a great potential for biogas production in the region. However, in order to create a sustainable fish sludge supply chain, the location, and size, of the biogas plant or plants needs to be optimized.

Møre og Romsdal is a county with many fjords and mountains, and travelling between communities is time-consuming do to fjords and ferry crossings. It is therefore important to utilize exact distances and not use, for instance, Euclidian distances which only consider the direct line between two points, in the location analysis.

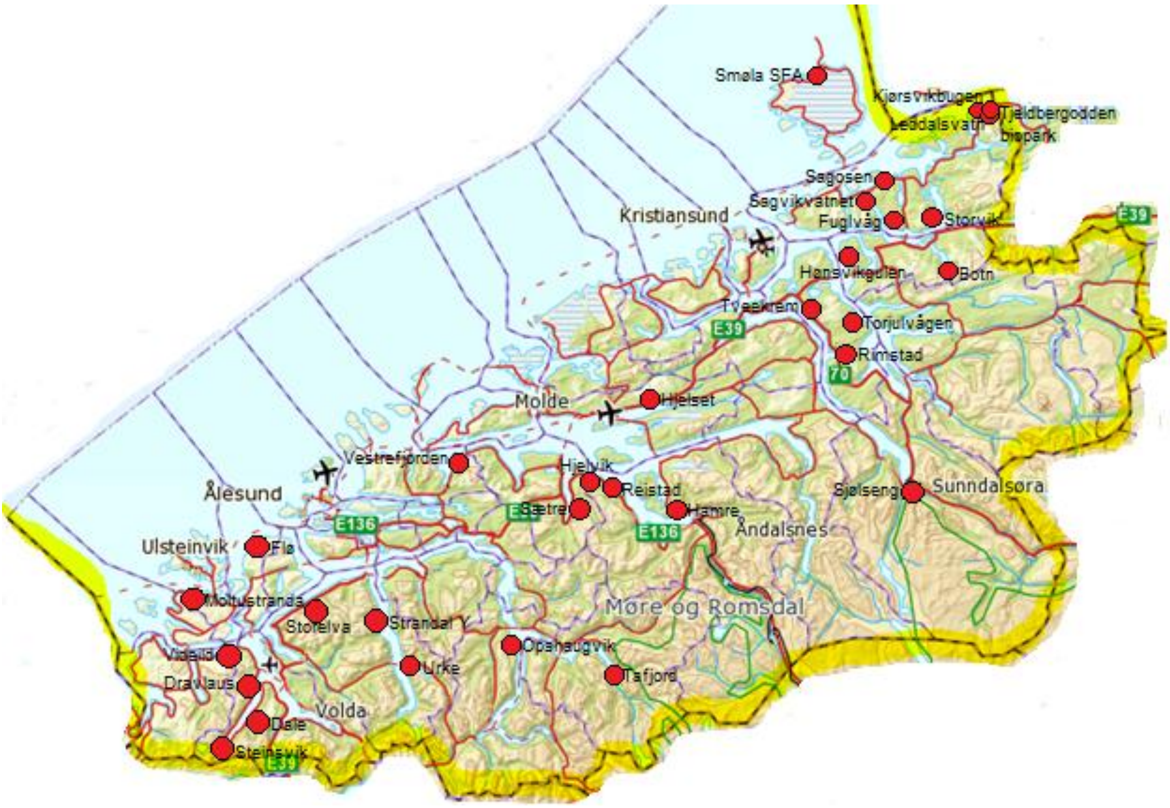

Figure 1: Location of land based salmon smolt farms in Møre og Romsdal. (Adapted from Fiskeridir.no and Norgeskart.no)

The use of fish sludge for biogas production is still in the developing stages, but small scale tests have shown that it can provide a high methane yield per ton volatile solid (VS) (Ytestøyl et al. 2013). Since the volatile solids, also called organic dry matter, represent the fraction of dry substance (DS) that can be transformed into biogas (Wilkie, 2013) these findings suggest that fish sludge has a high potential for gas production. An even higher methane yield (per ton VS) was found when combining livestock manure and fish sludge in a ratio of 12,5:87,5, which imply that a co-digestion could result in increased biogas output. Mixing different substrates is also recommended by Schnürer and Jarvis (2009) as it can provide a more stable and robust production process. It is therefore also necessary to investigate biogas plant locations based on distance to both fish and livestock farms.

Biogas mainly consists of a mixture of methane and carbon dioxide and is created as organic matter decomposes in the absence of oxygen (anaerobic) (SGC, 2012). The produced biogas can be used to generate heat and energy in a Combined Heat and Power Plant (CHP) or alternatively, it can be upgraded and used to produce biomethane (REA, 2011). In European countries the CHP engines is the dominant choice, mostly due to financial benefits and grants provided by the government. The Norwegian Parliament has also realized the need to support renewable energy sources and has established a company called Enova. This company will in certain cases offer investment support for establishing biogas plants, but no grants per kWh produced will be provided (Enova.no). According to Nielsen et al. (2002), Danish biogas production would not be economically feasible without tax exemption on heat sales as well as electricity production grants per kWh created. Since such support is not available in Norway the profitability of biogas plants will, to a great extent, rely on receiving gate-fees from industries using this disposal alternative. No income will be generated from livestock manure fees as farmers are not yet compelled to recycle this material. A group of hatcheries cooperating would not receive such gate-fees, so in order for this production to be economically beneficial, the capital and variable cost associated with building and running a biogas plant, as well as the transportation cost to and from this, would have to be smaller than the cost of delivering to an already established waste facility.

As explained above CHP plants is the norm in Europe, and this type of plant will also be assumed to be the most suitable choice in Møre og Romsdal. These plants produce both thermal and electric energy. While the latter can be sold to a national grid, the thermal energy is normally used onsite in the production process as illustrated in Figure 2.

Some of the energy in the produced biogas will be lost in the converting process; therefore only 70-80% of the potential can be transformed into usable energy. Around 35% of this is electric energy while the rest is thermal (Biogas-info.co.uk).

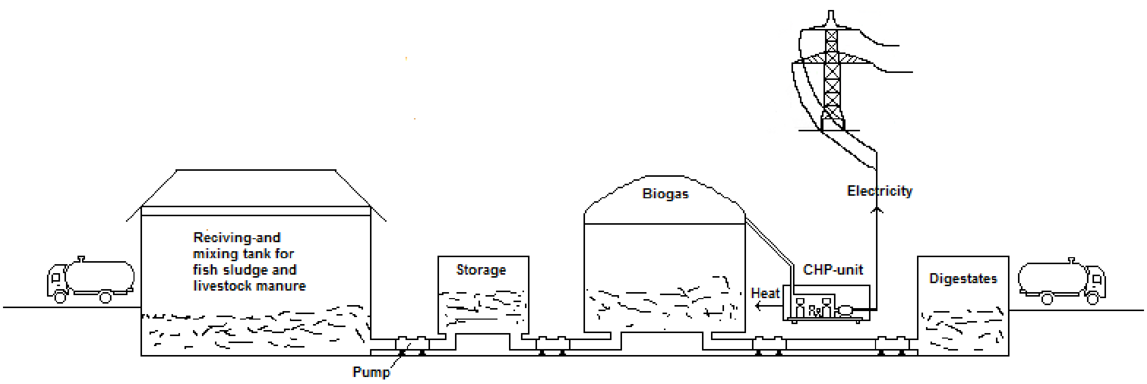

Figure 2: Illustration of a biogas plant for fish sludge and manure.

The total investment costs for biogas plants depend not only on their size and layout, but also on external factors such as price of land and need for ground work (Hagen et al. 2011). Such costs are not considered in the location problem, and all biogas plants of a given size are assumed to cost the same, regardless of where they are located. It is also assumed that both the capital cost and the production costs go down as the amount of biomass treated goes up. This corresponds to the findings of Nielsen et al. (2002). The selling price for electricity is, in contrast, assumed to be fixed per kWh. Therefore income goes up, as production goes up, since higher production rates correspond to higher incomes from energy sales. Given that this is the case, the profits per kWh sold will only rise as capital and production costs goes down. Hence, based on this alone, a large scaled plant would be more profitable then several small ones. One centralized biogas plant will however increase transportation costs, which could result in diseconomies of scale. According to Waldman and Jensen (2013, pp. 41) shipment of bulky, low-value products, often lead to this phenomenon as transportation costs quickly rises with an increase in travelling distance. Both biomass and digestate (unless pelletized) fit into this category, and the transportation costs might therefore offset the economical benefits of a larger plant size.

In the future digestate might become a valuable product as it can potentially replace mineral fertilizers, however, so far there is little, or no, willingness to pay for it (Stoknes, 2014). Most biogas plant owners therefore still have to cover the cost of digestate disposal, which normally involves the transportation cost to agricultural land areas. It is still unknown if untreated digestate generated from fish sludge, or fish sludge and manure, can utilize the same disposal alternative. Despite this uncertainty, it is throughout the paper assumed that this digestate can be used on agricultural land areas. The cooperating fish farms will therefore have to cover the cost of digestate disposal on land areas. In addition, they will also have to pay for transportation of manure, if this biomass is needed to optimize biogas production.

According to Blytt et al. (2011) only 200-400 kg DS from manure is allowed to be used on one dekar (1000 m^2) land each year. Assuming that this is also the case for digestate, it is necessary to include capacity restrictions on land areas in the location analysis.

A cost minimizing fish farmer would most likely only be willing to cooperate with other farmers if the biogas plant is located closer to the hatchery than an alternative waste facility. Today, only one appropriate waste facility is situated in close proximity to Møre og Romsdal, namely Ecopro, a large scale biogas plant located in Verdalen in Nord-Trøndelag.

Transportation costs are not only affected by the distance, but also the amount of sludge transported, it is therefore necessary to gather information on how much sludge is produced at each fish farm. The amount of sludge created depends on a variety of factors such as feed input, water temperatures, growth rate and production method, and it is therefore difficult to predict with certainty (Blytt et al., 2011). The most common production method in Norway to date is the so called flow-through (FT) systems, mainly because of the earlier abundance of fresh water resources in the country. As the water only passes through the system once, before being discharged, no sludge is collected in the process. This method has been effectively used for decades, but with increasing smolt demand, limited fresh water resources are seen as a hinder towards increased smolt production. A different production method has therefore received growing attention, namely the recirculation aquaculture system (RAS) (Del Campo et al. 2010). This system has several advantages over the flow through system, not only does it reduce the use of water in production and improve control and environmental conditions for the fish, but it also removes sludge in the process which helps fulfillment of discharge limits (Solheim, 2010). A combination between the two methods is also possible. This allows farmers with FT systems to reuse some of the incoming water and increase their production. A mixed production method will, as the RAS, improve environmental conditions as some of the sludge is removed in the process. Only five of the hatcheries in Møre og Romsdal are using or preparing to use RAS today, as shown in Table 2.

Although very few of the fish farms are currently collecting their sludge, this is expected to change in the years to come as a result of the implemented regulations and due to limited water supplies. Location, as well as sludge production, for all fish farms in the region should therefore be taken into account when placing a biogas plant or plants.

Municipality	Local name	Yearly production (number of smolts)	Production method
Aure	Sagosen	2 000 000	Flow Through
Aure	Leddalsvatn	1 500 000	Flow Through
Aure	Kjørsvikbugen	1 500 000	Flow Through
Aure	Fuglvåg	200 000	Flow Through
Aure	Storvik	200 000	Flow Through
Halsa	Botn	2 500 000	Flow Through
Halsa	Hønsvikgulen	1 000 000	Flow Through
Molde	Hjelset	500 000	Flow Through
Norddal	Tafjord	1 000 000	Flow Through
Ørsta	Storelva	800 000	Flow Through
Ørsta	Standal Y	2 500 000	Flow Through
Ørsta	Urke	5 000 000	Flow Through
Rauma	Reistad	500 000	Flow Through
Rauma	Hamre	300 000	Flow Through
Rauma	Hjelvik	1 000 000	Flow Through
Smøla	Aunvågen	5 000 000	RAS
Stranda	Opshaugvik Land	750 000	Flow Through
Tingvoll	Rimstad	500 000	Flow Through
Tingvoll	Tveekrem	600 000	Flow Through
Tingvoll	Torjulvågen	2 000 000	Flow Through
Ulstein	Flø	850 000	Flow Through
Vanylven	Videild	2 000 000	Flow Through
Vestnes	Sætre	2 000 000	Flow Through
Volda	Dale	5 000 000	Flow Through
Aure	Tjeldbergodden biopark	5 000 000	RAS
Aure	Sagvikvatnet	7 500 000	Mix
Haram	Vestrefjorden	1 000 000	Flow Through
Herøy	Moltustranda	5 000 000	RAS
Volda	Dravlaus	2 500 000	RAS
Volda	Steinsvik	7 500 000	RAS
Sunndal	Sjølseng	480 000	Flow Through

Table 2: Production rate and method of fish farms in Møre og Romsdal. Smøla Klekkeri og Settefiskanlegg AS is located in Aunvågen, Smøla. (Adapted from norskeutslipp.no and fiskeridir.no)

A common method to calculate expected fish sludge production is to use a feed factor (kg fed per kg growth) (Blytt et al., 2011), as illustrated in Figure 3. This means that in order to estimate the amount of sludge produced at each fish farm the average fish size must be predicted.

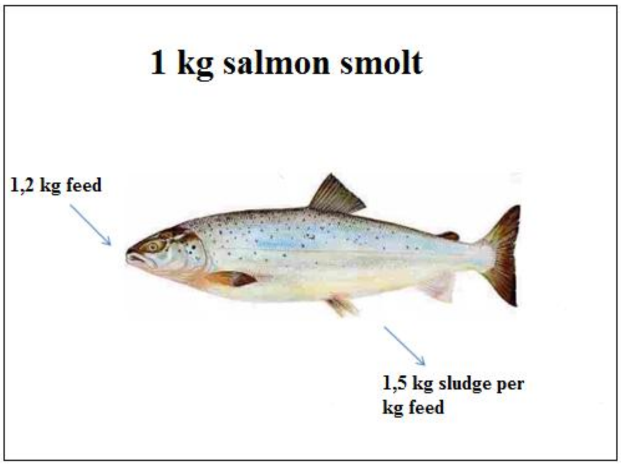

Figure 3: Feed factor and sludge production. (Adapted from Martinsen, 2013)

Several different smolt production strategies can be applied, all of which have incentive to spread the release of smolt into the ocean throughout the year. In RAS production water temperatures are regulated to speed up the growth of the fish and increase the throughput. This is more difficult and costly in traditional flow through systems which instead, for the most part, release a group of fall-smolt and a group of spring-smolt. Since the smolt growth rates differ from hatchery to hatchery, depending on their production method and strategy, average smolt sizes are difficult to determine. A generalization has therefore been made, and all fish farms are assumed to produce 40% fall-smolt and 60% spring-smolt, with an average end weight of 70 and 110 gram respectively.

To reduce transportation cost it is, as previously described, possible to increase the DS of the fish sludge. Very dry fish sludge (DS>20%) has not yet been tested as a substrate in biogas production, and although it might work just as well as primary sludge it is assumed that the maximum DS content of fish sludge used for biogas production is 20%. Each fish farm can invest in technologies separately or larger pre-treatment facilities can be established to serve several hatcheries. The second alternative can be favorable, not only because of reduced investment costs, but also because it can be used as a storage and help secure a stable supply of fish sludge to one or more biogas plants. This is important as the amount of fish sludge created varies throughout the year, and most hatcheries have the largest production at the same time. The location analysis should therefore also look into location of large pre-treatment facilities to reduce the transportation costs for fish farmers.

2.3. Research questions

Below the main research questions and sub-questions are presented.

2.3.1. Main research questions

1: What internal strategy should Smøla Klekkeri og Settefiskanlegg AS use to minimize the total costs associated with fish sludge recycling?

2: Where should one or more biogas plants be located?

2.3.2. Sub-questions

1.1: Should the fish sludge be transported to the already established waste facility, Ecopro?

1.2: Should the primary sludge be dried, stabilized and sanitized before transportation?

1.3: What type of technologies and techniques should be used for the sludge treatment?

1.4: Can a small scale biogas plant located at the hatchery be economically sensible?

2.1: Can cooperation between fish farmers to build and operate one, or several, biogas plants reduce the cost associated with fish sludge recycling?

2.2: What biogas plant sizes should be used?

2.3: Which fish farms should cooperate?

2.4: Should the sludge go through pre-treatment before potential biogas production? And, if so, where should it take place?

2.5: How do the costs of establishing biogas plants in Møre og Romsdal compare to the costs of delivering fish sludge to Ecopro?

3. Literature Review

A large amount of literature can be found on recycling of wastewater (sewage) and livestock manure, while so far little literature can be found on the supply chain challenges, and costs, associated with recycling fish sludge. Since there are several similarities between these three wastes the following theory review outlines logistical challenges, costs and methodologies for different types of organic waste as well as other biomass. In addition, relevant literature for the location problem is presented.

3.1. Logistics and supply chain

Smøla Klekkeri og Settefiskanlegg AS is examining the possibility of placing a local biogas plant in close proximity to the hatchery in order to use the energy produced as a subsidy for diesel fuel. In such a case the logistics involved becomes simpler as they do not need to transport the primary sludge, and they can possibly use the remaining digestate as fertilizer for their own green areas. Several authors do however lean towards central location and larger facilities.

There are two major approaches to manure-based biogas production-: farm-based biogas production and larger cooperative biogas plants (Tybrik and Jensen, 2013). Blytt et al. (2011) suggests that a large amount of dried fish sludge (more than 500 ton per year) is needed before biogas plants are financially sustainable, and that transportation to shared facilities therefore should be evaluated. This also supported by Iakovou et al. (2010, pp. 1861):

> *"The structure of the global market for biomass and the associated supply chains is evolving quite dynamically. Traditionally, biomass has been used for energy (mainly thermal) production in areas close to its production sites. However, an emerging practice for energy producers is to procure waste biomass from several suppliers in order to develop the critical mass necessary for the justification of an energy production facility."*

The complexity of the supply chain of fish sludge varies depending on the level of cooperation between farmers and the disposal methods used.

Tybrik and Jensen (2013) have analyzed the sustainable supply chain of manure for fertilizer and energy. They, for instance, looked into two simplified supply chains for manure recycling, namely manure to energy and manure to improved fertilizer products, and evaluated the social, environmental and economical aspects of these.

De mol et al. (1997) developed two models, a simulation model and an optimization model, which give insight to the costs and energy consumptions of the logistics of biomass fuel collection.

Recycling the fish sludge involves several challenges and costs. The option of using it for energy production is of large interest both for farmers and scientists, but as Iakovou et al. (2010, pp. 1860) states: “Two significant bottlenecks that hinder the increased biomass utilization for energy production are the cost and complexity of its logistics operations”.

3.2. Location problems

Facility location problems have a long history in the operation research and management society (Current, Daskin and Schilling, 2004) and a large amount of applications and methods exists. Drezner and Hamacher (2004) provides insight into the most main stream topics in this field and the book is a great source of information as it covers both theory and applications.

Klose and Drexl (2005) have also reviewed and gathered work contributing to the topic. Their paper focuses on the fundamental assumptions, mathematical models and solution approaches used to solve location problems and it provides a large amount of relevant references.

Location models are case specific, meaning that the structural form of a model is determined by the specific problem at hand. Much of the literature on location problems is however aimed at formulating new models as well as modifying existing models and are less concerned with specific case studies (Current, Daskin and Schilling, 2004).

To avoid locating biogas plants and pre-treatment facilities at inappropriate sites, potential locations should be pre-determined. These locations should preferably be selected based on important criteria such as good infrastructure, distance to residential areas and access to existing heat supplies. Since a set of potential locations, as well as existing locations of fish and livestock farms and agricultural land areas will be specified, the problem at hand can be formulated as a discrete facility location model. In such models the distance between fixed locations (location of fish and livestock farms as well as agricultural land areas) and potential locations (location of pre-treatment facilities and biogas plants) can be found using whatever method the decision maker finds most appropriate (Eiselt and Sandblom, 2004, pp. 160). Since this is the case, discrete models allow for the use of exact distances, which is, as previously explained, an important part of this particular biogas plant location problem.

Realizing that biogas plants, pre-treatment facilities and agricultural land areas have capacity restrictions, the problem can be further classified as a capacitated facility location problem (CFLP). According to Klose and Drexl (2005) the CFLP can be applied with multiple- or single-sourcing strategies. It is unrealistic to assume that a fish farm would deliver sludge to several biogas plants or pre-treatment facilities, and therefore the problem becomes a capacitated facility location problem with single sourcing (CFLPSS). Klose and Drexl (2005) describes the problem as being NP-hard (non-deterministic polynomial time-hard), which means it is very difficult to find exact solutions for instances of realistic size. In order to solve larger instances heuristics must be used and several authors suggest using Lagrangean relaxation (dual decomposition) techniques. Among others Klincewicz and Luss (1986) describe a heuristic algorithm based on the Lagrangian relaxation technique which incorporates the capacity constraint into the objective function to generate an uncapacitated facility location problem.

3.2.1. Biogas facility location problems

This thesis is not the first to address the problem of locating biogas plants. Delzeit and Kellner (2013) investigate what impacts the location and size of biogas facilities have on the total profitability, when considering different processing alternatives for digestate. They argue that it is important to take into account the transportation costs of by-products (digestate) when considering the profitability of facilities and state that: “The choice of location is a crucial factor for addressing cost reduction” (Delzeit and Kellner 2013, pp. 51).

Another approach for determining the location of biogas plants is presented by Delzeit, Britz and Holm-Müller (2012). They propose a simple and flexible approach for simulating locations and size of biogas plants, which is able to find solutions to problems with up to several thousand possible location combinations.

4. Solution Methodology

This section of the paper describes how I address the problems and answer the research questions.

4.1. Financial analysis

A financial analysis is used to suggest which internal strategy Smøla Klekkeri og Settefiskanlegg AS should use to minimize the total cost of fish sludge recycling. Four relevant options are evaluated and corresponding value chains help visualize the impact of each treatment method.

4.2. Facility location analysis

The facility location analysis utilize linear optimization techniques to suggest location and size of biogas plants, as well as location of pre-treatment facilities. In addition it also suggests which fish farms should cooperate on these establishments. Four different supply chains are looked into to thoroughly investigate different future possibilities. These are displayed in Figure 4.

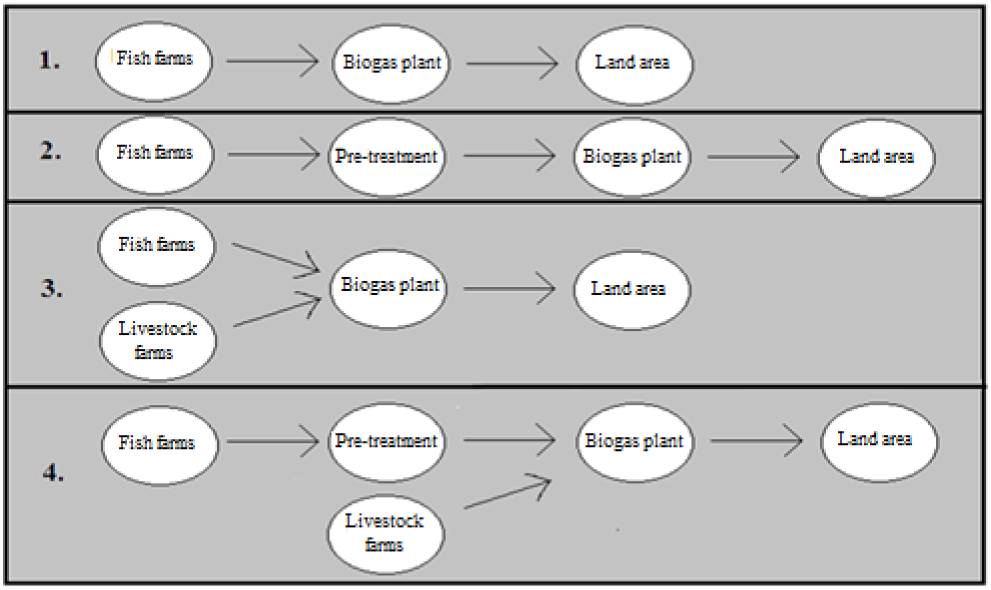

Figure 4: The four supply chains.

A modified capacitated facility location model (CFLM) has been developed to consider the first supply chain. Three variants of this model were then formulated and used to look into the other three possibilities. All models minimize capital and production costs associated with building and operating biogas plants as well as transportation costs for fish sludge and digestate. Models 2 and 4 in addition minimize costs associated with building pre-treatment facilities. If manure is needed in the production process transportation cost for this biomass also needs to be minimized, this is therefore also added to the objective function of Models 3 and 4.

The models are tested under different scenarios to investigate how the input data affect the location and size of plants, as well as the assignment of fish farms (see Table 3). Both current and increased fish sludge production is evaluated, together with changes in transportation cost. In addition a scenario where all fish farms dewater their sludge themselves is looked into. In the end all models are restricted to locating only one biogas plant each. This scenario investigates if one common location is the best alternative for all supply chains.

Scenario 1 is used as the baseline for the analysis, and all the other scenarios are compared to this. In the end the results from all five scenarios are compared to the cost of delivering all fish sludge to Ecopro as well as to the results from the financial analysis.

Scenarios	
1. Initial	Represents the current situation. The four locations models are tested with initial input data. (Model 1-4)
2. Reduced transportation cost	The initial transportation costs are lowered to see how this affects the results. (Model 1-4)
3. Increased salmon smolt production	The initial fish sludge production is increased to see if size- and location of biogas plants change. (Model 1-4)
4. Pre-treatment at fish farms	All fish farms dewater their sludge at their location before transporting it to a biogas plant. (Model 1 and 3)
5. Only one biogas plant	Use the initial data, but restrict the models to only locate one biogas plant. (Model 1-4)

Table 3: Investigated scenarios.

5. Financial analysis

This chapter presents the financial analysis used to investigate different strategies for Smøla Klekkeri og Settefiskanlegg AS. The evaluated value chains are presented and explained before data collection and results are displayed.

5.1. Investigated value chains

Four different value chains are evaluated and compared in the financial analysis, as depicted in Figure 5. In the first chain the primary sludge is collected and stored at Smøla Klekkeri og Settefiskanlegg AS, before being transported to Ecopro. Costs are mainly related to transportation and gate-fees due to the large volume of the sludge. The second value chain illustrates how the company can reduce transportation costs by investing in Salsnes Filters, and dewater the sludge before delivery. Another disposal alternative is presented in Value Chain 3, where the primary sludge is both dewatered and dried before transportation to end disposal. In the end the possibility of locating a small biogas plant at the fish farm is evaluated.

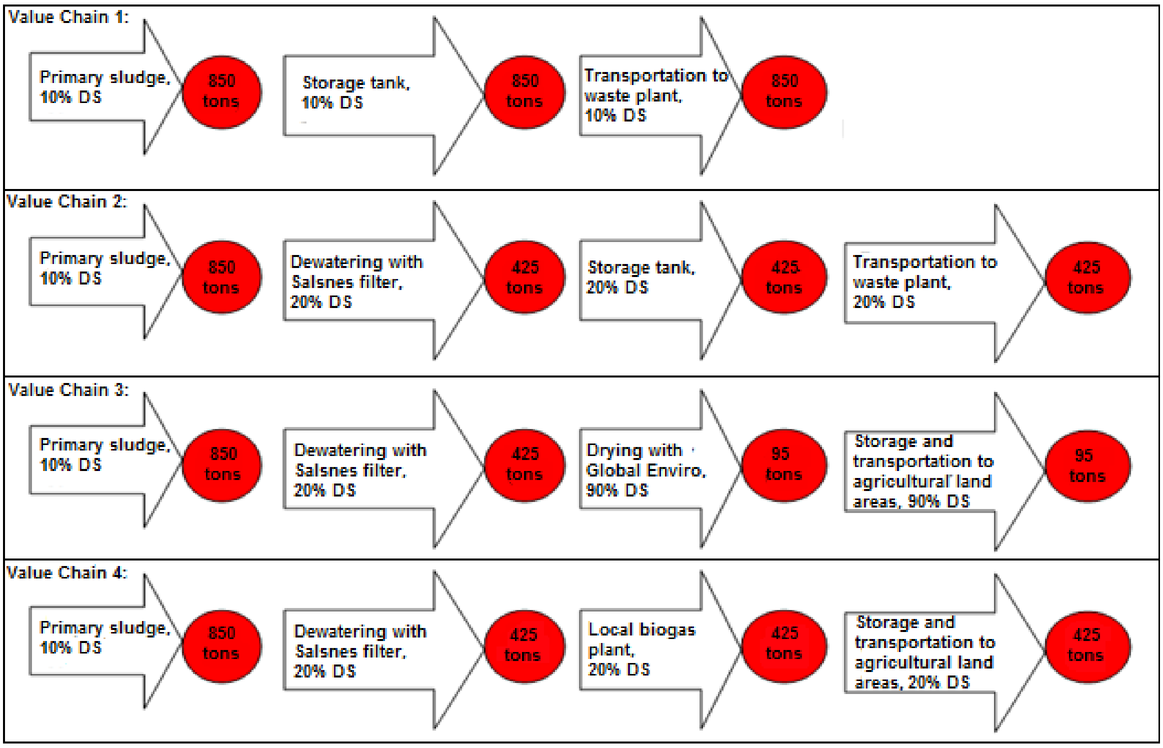

Figure 5: The four value chains investigated in the financial analysis.

5.2. Data collection for the financial analysis

Most of the input data related to fixed assets were, with help from Møreforsking Molde, collected from scientists and researchers participating in the Slam-Bep project. However, since very few fish farms in Norway are currently storing their sludge, it was not possible to obtain data on investment costs for different sized storage tanks or suitable ventilation systems. The costs for these are therefore based on assumptions and could consequently differ substantially from actual figures. While ventilation systems are assumed to cost the same for all four value chains, the cost for storage tanks varies depending on the amount of fish sludge to be stored. Operations and maintenance cost for Salsnes Filter systems were also not provided and these have therefore been assumed to be the same as for Global Enviro. All input data used in the analysis is presented in Appendix A.

The annual costs were found using the annuity method, with an interest rate of 6% and a 15 year down-payment period. Operation and maintenance costs associated with fixed assets were mainly related to personnel costs and electricity consumption. To calculate these costs a personnel rate of 400 NOK/hour and a electricity cost of 0,31 NOK/kWh were used.

Transportation costs for fish sludge and digestate have been assumed to be linear and a cost of 2,50 NOK/ton/km is used in the analysis. Google Maps was used to determine the distance from the hatchery to Ecopro, which was found to be 294 km. Further, the gate-fees charged by Ecopro have been assumed to be 1200 NOK/ton, which is consistent with the disposal cost suggested by Ytrestøyl et al. (2013).

Due to the fact that there are large agricultural land areas at the island of Smøla, it should not be necessary to transport stabilized and sanitized fish sludge or digestates to the mainland. Therefore the distance from the hatchery to land areas has been set to 15 km.

Calculations were used to predict fish sludge creation at Smøla Klekkeri og Settefisk-anlegg AS for a production of 5 million salmon smolts a year, as shown in Table 4.

Fish farm	Yearly production	Spring smolts (110 grams	Fall smolts (70 grams each)	Weight of smolts	Feed factor	Sludge factor
		60 %	40 %		1,2 kg feed/kg smolt	1,5 kg sludge/kg feed
	Number of smolts	Total (in grams)	Total (in grams)	Total (in tons)	Total feed used (in tons)	Total sludge (in tons)
Smøla Klekkeri og Settefiskanlegg AS	5000000	330000000	140000000	470	564	**846**

Table 4: Yearly fish sludge production at Smøla Klekkeri og Settefiskanlegg AS.

To calculate electricity savings attained by utilizing biogas from a local biogas plant (Value Chain 4), a methane yield of 560 m^3/ton volatile solids and a electricity cost of 0,31 NOK/kWh was used. In addition, an electrical conversion efficiency of 35% has been utilized. Further, it is assumed that 20% of the electricity is used to maintain the biogas process while the remaining energy can be used to reduce electricity costs at the hatchery.

5.3. Results from the financial analysis

Since some of the data used in the financial analysis was based purely on assumptions or generated randomly the results shown below are unreliable. To obtain more reliable results it is necessary to carry out a more thorough analysis as more accurate data becomes available.

The total cost was found to be smallest in Value Chain 4, where a small scale biogas plant is built at the hatchery (see Table 5). This shows that a small scale biogas plant can potentially be economically sensible, at least in situations where alternative value chains have larger fixed or variable costs.

Value chain 1:						
Fixed costs	Investment cost (NOK)	Capital cost (NOK/year)	Cost per ton DS (NOK/year)	Variable costs	Cost (NOK/year)	Cost per ton DS (NOK/year)
Closed storage tank	100000	10296	122	Transportation	621810	7350
Ventilation system	50000	5148	61	Gate-fees	1015200	12000
Sum	150000	15444	183	Total variable cost	1637010	19350
Total fixed and varible costs					1652454	19533
Value chain 2:						
Fixed costs	Investment cost (NOK)	Capital cost (NOK/year)	Cost per ton DS (NOK/year)	Variable costs	Cost (NOK/year)	Cost per ton DS (NOK/year)
Salsnes Filter system	1000000	102923	1217	O&M	71155	841
Closed storage tank	75000	7722	91	Transportation	310905	3675
Ventilation system	50000	5148	61	Gate-fees	507600	6000
Sum	1125000	115793	1369	Total variable cost	889660	10516
Total fixed and varible costs					1005453	11885
Value chain 3:						
Fixed costs	Investment cost (NOK)	Capital cost (NOK/year)	Cost per ton DS (NOK/year)	Variable costs	Cost (NOK/year)	Cost per ton DS (NOK/year)
Salsnes Filter system	1000000	102923	1217	O&M	71155	841
Global enviro	1300000	133852	1582	O&M	71155	841
Closed storage tank	50000	5148	61	Transportation	3525	42
Ventilation system	50000	5148	61			
Sum	2400000	247071	2920	Total variable cost	145835	1724
Total fixed and varible costs					392906	4644
Value chain 4:						
Fixed costs	Investment cost (NOK)	Capital cost (NOK/year)	Cost per ton DS (NOK/year)	Variable costs	Cost (NOK/year)	Cost per ton DS (NOK/year)
Salsnes Filter system	1000000	102963	1217	O & M	71155	841
Biogas plant	1000000	102963	1217	O & M	73000	863
Closed storage tank	75000	7722	91	Transportation	15863	188
Ventilation system	50000	5148	61			
Sum	2125000	218796	2586	Total variable cost	160018	1891
Total fixed and varible cost (per year)					378814	4478
Electricity Savings					37010	437
				Total cost	341804	4040

Table 5: Result from the financial analysis

While Value Chain 1 has the smallest capital cost it is still the most expensive alternative. This is due to the high variable costs seen as a consequence of not dewatering, sanitizing or stabilizing the fish sludge. Compared to Value Chain 1, Value Chain 2 has much smaller variable costs. This is because the latter chain dewaters the sludge, which in turn reduces both transportation and gate-fee costs.

In Value Chain 3 the dry substance content of the fish sludge is, by investing in both a Salsnes Filter system and the Global Enviro technology, increased to 90%. These investments pay-off as the total cost is found to be much smaller than for Value Chains 1 and 2. However, the capital cost seen in Value Chain 3 is higher than the capital cost seen in Value Chain 4, and therefore, despite higher variable costs, the latter chain has the smallest total cost. In contrast to the other value chains, Value Chain 4 is also able to benefit from cost reductions by utilizing some of the produced biogas.

6. Facility location analysis

This chapter of the paper presents the facility location analysis. The first section presents the assumptions made before developing the four models, followed by their description and formulation. In the end data collection and results are presented.

6.1. Assumptions

As already established in the problem description, several assumptions have been made to both specify and simplify the problem at hand. All assumptions used to develop the mathematical models are presented below. Additional assumptions also had to be made when gathering data for the scenario analysis; these are presented and explained in Chapter 6.3.

1. Each fish farm has to deliver fish sludge to exactly one biogas plant or pre-treatment facility.
2. A fish farm can only be assigned directly to a biogas plant if this plant is located closer than Ecopro.
3. If pre-treated the dry substance content of the fish sludge increase from 10- to 20%. This corresponds to a 50% weight reduction.
4. The fixed cost of building a biogas plant only depends on the size of the plant.
5. Transportation costs can be presented in NOK per/ton/km, and are the same for primary sludge, pre-treated sludge, livestock manure and digestate. (Extra costs for ferry crossings are not taken into account.)
6. The amount of digestate created at a biogas plant is the same as the amount of biomass delivered to the plant. This means that the digestate is used as is, and is not dewatered before transportation to agricultural land areas.
7. Untreated digestate generated from fish sludge, or fish sludge and manure, can be used on agricultural land areas.
8. Both capital and production cost goes down as the amount of biomass treated goes up.
9. All digestate should be transported to agricultural land areas.
10. Transportation and storage of primary and pre-treated fish sludge is possible.
11. All fish farms in Møre og Romsdal collect fish sludge, and they use the same production method and strategy.
12. All collected fish sludge has the same dry substance and volatile solids content.

13. All livestock manure has the same dry substance and volatile solids content.
14. The dry substance content of the produced digestate only depends on the dry substance content of the biomass used for biogas production.
15. If both manure and fish sludge is used, the volatile solids content of the biomass should consist of 87,5 % VS from fish sludge and a 12,5% VS from manure.

6.2. Models

Below the four models developed to describe the four supply chains are presented and explained.

6.2.1. Model 1

Model 1 is a modified capacitated facility location model (CFLM) developed to look into the first supply chain (see Figure 6). Here all fish farms will deliver primary sludge directly to one or more biogas plant locations. The model proposes locations and size of biogas plants, and in addition it suggests which fish farms should cooperate in order to minimize the cost of fish sludge recycling in the region.

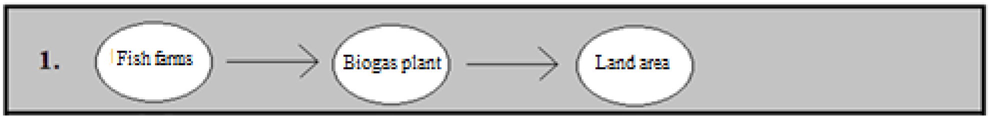

Figure 6: Supply Chain 1.

Sets:

$\mathcal{I}$ – set of fish farms

$\mathcal{J}$ – set of potential biogas plant locations

$\mathcal{K}$ – set of biogas plant sizes

$\mathcal{L}$ – set of agricultural land areas

Parameters:

C_{ij} Shortest distance between fish farm i and potential biogas plant location j (in km)

H_{jl} Shortest distance between potential biogas plant location j and agricultural land area l (in km)

Q_k Capacity of a biogas plant of size k (in tons per year)

G_l Maximum amount of digestate allowed to be spread on agricultural land area l (in ton dry substance per year)

F_k Yearly capital cost in NOK associated with building a biogas plant of size k

W_k Production cost in NOK per ton associated with a biogas plant of size k

S_i Yearly production of fish sludge at fish farm i (in tons)

B Transportation costs (NOK per ton/km)

Δ_i Distance from fish farm i to Ecopro (in km)

T Dry substance portion of the produced digestate

Decision variables:

u_{jk} Indicates if a biogas plant of size k is built at potential biogas plant location j

x_{ijk} Indicate if a fish farm i is assigned to a biogas plant of size k at potential biogas plant location j

n_{jl} Amount of digestate transported from potential biogas plant location j to agricultural land area l (in tons)

Objective function:

$$\min \sum_{j \epsilon J} \sum_{k \epsilon K} F_k u_{jk} + \sum_{i \epsilon I} \sum_{j \epsilon J} \sum_{k \epsilon K} W_k S_i x_{ijk} + \sum_{i \epsilon I} \sum_{j \epsilon J} \sum_{k \epsilon K} C_{ij} S_i x_{ijk} B + \sum_{j \epsilon J} \sum_{l \epsilon L} H_{jl} n_{jl} B \quad (1.1)$$

Subject to:

$$\sum_{j \epsilon J} \sum_{k \epsilon K} x_{ijk} = 1 \qquad \forall\ i \epsilon I \qquad (1.2)$$

$$\sum_{k \epsilon K} u_{jk} \leq 1 \qquad \forall\ j \epsilon J \qquad (1.3)$$

$$\sum_{i \epsilon I} x_{ijk} S_i \leq u_{jk} Q_k \qquad \forall\ j \epsilon J, k \epsilon K \qquad (1.4)$$

$$\sum_{j \epsilon J} n_{jl} T \leq G_l \qquad \forall\ l \epsilon L \qquad (1.5)$$

$$\sum_{i \epsilon I} \sum_{k \epsilon K} x_{ijk} S_i = \sum_{l \epsilon L} n_{jl} \qquad \forall\ j \epsilon J \qquad (1.6)$$

$$\sum_{j\epsilon J}\sum_{k\epsilon K} x_{ijk} C_{ij} \leq \Delta_i \qquad \forall\ i\epsilon I \qquad (1.7)$$

$$u_{jk} \epsilon\ \{0,1\} \qquad \forall\ j\epsilon J, k\epsilon K \qquad (1.8)$$

$$x_{ijk} \epsilon\ \{0,1\} \qquad \forall\ i\epsilon I, j\epsilon J, k\epsilon K \qquad (1.9)$$

$$n_{jl} \epsilon\ \geq 0 \qquad \forall\ j\epsilon J, l\epsilon L \qquad (1.10)$$

6.2.1.1. Model description

The objective function minimizes capital and production costs associated with building and operating biogas plants as well as transportation costs for fish sludge and digestate. Restriction 1.2 ensures that each fish farm is assigned to exactly one biogas plant location, while restriction 1.3 makes sure that at most one biogas plant size is built at each location. Capacities of biogas plants and agricultural land areas are respected due to restriction 1.4 and 1.5, 1.4 also makes sure that fish sludge is only sent to opened biogas plants. Restriction 1.6 makes sure that the amount of fish sludge transported to a biogas plant is equal to the amount of digestate transported away from the plant. The distance between a biogas plant and all fish farms assigned to it has to be smaller than the distance from these to Ecopro, this is achieved due to restriction 1.7. Restrictions 1.8 to 1.10 determine the range of values for variables.

6.2.2. Model 2

Model 2, which is a variant of model 1, locate both pre-treatment facilities and biogas plants, and is used to investigate Supply Chain 2 (see Figure 7). Instead of being directly assigned to biogas plant locations all fish farms are now directly assigned to pre-treatment locations. Here the fish sludge is dewatered before being transported to opened biogas plants. In addition to proposing location and size of biogas plants this model also suggests location of pre-treatment facilities. These facilities, in contrast to biogas plants, all have the same size, capacity and costs. The model also suggests which fish farms should cooperate on which pre-treatment facility and which biogas plants should receive the dewatered fish sludge.

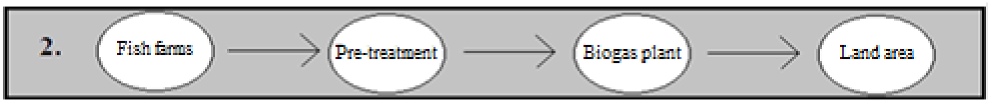

Figure 7: Supply Chain 2.

Sets:

$\mathcal{I}$ – set of fish farms

$\mathcal{P}$ – set of potential pre-treatment locations

$\mathcal{J}$ – set of potential biogas plant locations

$\mathcal{K}$ – set of biogas plant sizes

$\mathcal{L}$ – set of agricultural land areas

Parameters:

C_{ip} Shortest distance between fish farm i and potential pre-treatment location p (in km)

O_{pj} Shortest distance between potential pre-treatment location p and potential biogas plant location j (in km)

H_{jl} Shortest distance between potential biogas plant location j and agricultural land area l (in km)

Λ_p Capacity of a pre-treatment facility built at potential pre-treatment location p (in tons per year)

Q_k Capacity of a biogas plant of size k (in tons per year)

G_l Maximum amount of digestate allowed to be spread on agricultural land area l (in ton dry substance per year)

Z_p Yearly capital cost in NOK associated with building a pre-treatment facility at location p

F_k Yearly capital cost in NOK associated with building a biogas plant of size k

W_k Production cost in NOK per ton associated with a biogas plant of size k

E_p Production cost in NOK per ton associated with a pre-treatment facility at location p

S_i Yearly production of fish sludge at fish farm i (in tons per year)

B Transportation costs (NOK per ton/km)

R Weight reduction of fish sludge after pre-treatment (in portion)

T Dry substance portion of the produced digestate

Decision variables:

v_p Indicates if a pre-treatment facility is built at potential pre-treatment location p

x_{ip} Indicate if a fish farm i is assigned to a potential pre-treatment location p

u_{jk} Indicates if a biogas plant of size k is built at potential biogas plant location j

y_{pjk} Amount of fish sludge transported from potential pre-treatment location p to potential biogas plant location j, dependent on biogas plant size k (in tons)

n_{jl} Amount of digestate transported from potential biogas plant location j to agricultural land area l (in tons)

Objective function:

$$\min \sum_{p\epsilon P} Z_p v_p + \sum_{j\epsilon J}\sum_{k\epsilon K} F_k u_{jk} + \sum_{i\epsilon I}\sum_{p\epsilon P} E_p S_i x_{ip} + \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{k\epsilon K} W_k y_{pjk} + \sum_{i\epsilon I}\sum_{p\epsilon P} C_{ip} S_i x_{ip} B$$
$$+ \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{k\epsilon K} O_{pj}\, y_{pjk} B + \sum_{j\epsilon J}\sum_{l\epsilon L} H_{jl} n_{jl} B \qquad (2.1)$$

Subject to:

$$\sum_{p\epsilon P} x_{ip} = 1 \qquad \forall\ i\epsilon I \qquad (2.2)$$

$$\sum_{k\epsilon K} u_{jk} \leq 1 \qquad \forall\ j\epsilon J \qquad (2.3)$$

$$\sum_{i\epsilon I} x_{ip} \mathrm{S_i} \leq \Lambda_p v_p \qquad \forall\ p\epsilon P \qquad (2.4)$$

$$\sum_{p\epsilon P} y_{pjk} \leq \mathrm{u_{jk} Q_k} \qquad \forall\ j\epsilon J, k\epsilon K \qquad (2.5)$$

$$\sum_{j\epsilon J} n_{jl} \mathrm{T} \leq G_l \qquad \forall\ l\epsilon L \qquad (2.6)$$

$$\sum_{i\epsilon I} x_{ip} \mathrm{S_i R} = \sum_{j\epsilon J}\sum_{k\epsilon K} y_{pjk} \qquad \forall\ p\epsilon P \qquad (2.7)$$

$$\sum_{p\epsilon P}\sum_{k\epsilon K} y_{pjk} = \sum_{l\epsilon L} n_{jl} \qquad \forall\ j\epsilon J \qquad (2.8)$$

$$u_{jk}\epsilon\ \{0,1\} \qquad \forall\ j\epsilon J, k\epsilon K \qquad (2.9)$$

$$v_{p}\epsilon\ \{0,1\} \qquad \forall\ p\epsilon P \qquad (2.10)$$

$$x_{ip}\epsilon\ \{0,1\} \qquad \forall\ i\epsilon I, p\epsilon P \qquad (2.11)$$

$$y_{pjk}\epsilon\ \geq 0 \qquad \forall\ p\epsilon P, j\epsilon J, k\epsilon K \qquad (2.12)$$

$$n_{jl}\epsilon\ \geq 0 \qquad \forall\ j\epsilon J, l\epsilon L \qquad (2.13)$$

6.2.2.1. Model description

The objective function minimizes costs associated with building and operating pre-treatment facilities and biogas plants, as well as all transportation costs to and from these. Restriction 2.2 ensures that each fish farm is assigned to exactly one potential pre-treatment location, while restriction 2.3 makes sure that at most one biogas plant size is built at each potential biogas plant location. Capacities of pre-treatment facilities, biogas plants and agricultural land areas are respected due to of restriction 2.4 to 2.6, 2.4 and 2.5 also makes sure that fish sludge is only sent to opened pre-treatment facilities and biogas plants. Restriction 2.7 makes sure that the amount of fish sludge sent from a pre-treatment facility to a biogas plant is the same as the amount left after pre-treatment, while 2.8 makes sure that the amount of fish sludge going into a biogas plant is the same as the amount of digestate leaving the plant. Restrictions 2.9 to 2.13 determine the range of values for variables.

6.2.3. Model 3

Model 3 is also a variant of model 1. It has been developed to look into Supply Chain 3, where both fish sludge and livestock manure is needed to optimize biogas production (see Figure 8). The total amount of VS used in biogas production should now consist of exactly 87,5% VS from fish sludge and 12,5% VS from manure.

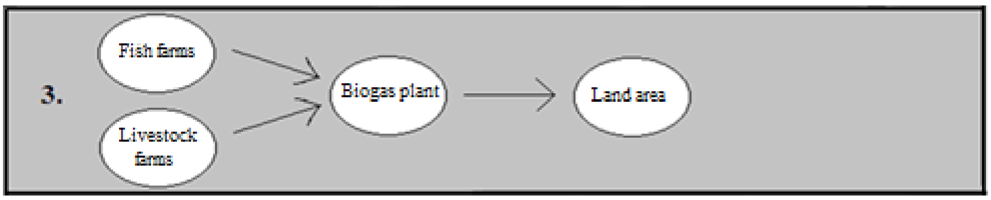

Figure 8: Supply Chain 3.

Sets:

$\mathcal{I}$ – set of fish farms

$\mathcal{A}$ – set of livestock farms

$\mathcal{J}$ – set of potential biogas plant locations

$\mathcal{K}$ – set of biogas plant sizes

$\mathcal{L}$ – set of agricultural land areas

Parameters:

C_{ij} Shortest distance between fish farm i and potential biogas plant location j (in km)

N_{aj} Shortest distance between livestock farmer a and potential biogas plant locations j (in km)

H_{jl} Shortest distance between potential biogas plant location j and agricultural land area l (in km)

Q_k Capacity of a biogas plant of size k (in tons per year)

G_l Maximum amount of digestate allowed to be spread on agricultural land area l (in ton dry substance per year)

F_k Yearly capital cost in NOK associated with building a biogas plant of size k

W_k Production cost in NOK per ton associated with a biogas plant of size k

S_i Yearly production of sludge at fish farm i (in tons)

D_a Yearly production of manure at livestock farm a (in tons)

B Transportation costs (NOK per ton/km)

Δ_i Distance from fish farm i to Ecopro (in km)

T Dry substance portion of the produced digestate

Γ Factor for determining the amount of manure to transport (in portion): (% of total VS required to be from manure/ % VS in the used manure) / (% of total VS required to be from fish sludge/ % VS in the used fish sludge)

Decision variables:

u_{jk} Indicates if a biogas plant of size k is built at potential biogas plant location j

x_{ijk} Indicate if a fish farm i is assigned to a biogas plant of size k at potential biogas plant location j

e_{ajk} Amount of manure transported from livestock farmer a to potential biogas plant location j, depending on biogas plant size k (in tons)

n_{jl} Amount of digestate transported from potential biogas plant location j to agricultural land area l (in tons)

Objective function:

$$\min \sum_{j\epsilon J}\sum_{k\epsilon K} F_k u_{jk} + \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K} W_k S_i x_{ijk} + \sum_{a\epsilon A}\sum_{j\epsilon J}\sum_{k\epsilon K} W_k e_{ajk} + \sum_{i\epsilon I}\sum_{j\epsilon J}\sum_{k\epsilon K} C_{ij} S_i x_{ijk} B$$

$$+ \sum_{a\epsilon A}\sum_{j\epsilon J}\sum_{k\epsilon K} N_{aj} e_{ajk} B + \sum_{j\epsilon J}\sum_{l\epsilon L} H_{jl} n_{jl} B \qquad (3.1)$$

Subject to:

$$\sum_{j\epsilon J}\sum_{k\epsilon K} x_{ijk} = 1 \qquad \forall\ i\epsilon I \qquad (3.2)$$

$$\sum_{k\epsilon K} u_{jk} \leq 1 \qquad \forall\ j\epsilon J \qquad (3.3)$$

$$\sum_{i\epsilon I} x_{ijk} S_i + \sum_{a\epsilon A} e_{ajk} \leq u_{jk} Q_k \qquad \forall\ j\epsilon J, k\epsilon K \qquad (3.4)$$

$$\sum_{j\epsilon J} n_{jl} T \leq G_l \qquad \forall\ l\epsilon L \qquad (3.5)$$

$$\sum_{j\epsilon J}\sum_{k\epsilon K} e_{ajk} \leq D_a \qquad \forall\ a\epsilon A \qquad (3.6)$$

$$\sum_{i\epsilon I}\sum_{k\epsilon K} x_{ijk} S_i + \sum_{a\epsilon A}\sum_{k\epsilon K} e_{ajk} = \sum_{l\epsilon L} n_{jl} \qquad \forall\ j\epsilon J \qquad (3.7)$$

$$\sum_{j\epsilon J}\sum_{k\epsilon K} C_{ij}\, x_{ijk} \leq \Delta_i \qquad \forall\ i\epsilon I \qquad (3.8)$$

$$\sum_{a\epsilon A} e_{ajk} = \sum_{i\epsilon I} x_{ijk} S_i \Gamma \qquad \forall\ j\epsilon J, k\epsilon K \qquad (3.9)$$

$$u_{jk} \epsilon \{0,1\} \qquad \forall\ j\epsilon J, k\epsilon K \qquad (3.10)$$

$$x_{ijk} \epsilon \{0,1\} \qquad \forall\ i\epsilon I, j\epsilon J, k\epsilon K \qquad (3.11)$$

$n_{jl} \epsilon \ \geq 0 \qquad \forall\ j\epsilon J, l\epsilon L \qquad (3.12)$

$e_{ajk} \epsilon \geq 0 \qquad \forall\ a\epsilon A, j\epsilon J, k\epsilon K \qquad (3.13)$

6.2.3.1. Model description

The objective function minimizes costs associated with building and operating biogas plants, as well as all transportation costs to and from these. Restriction 3.2 ensures that each fish farm is assigned to exactly one biogas plant location, while restriction 4.3 makes sure that at most one biogas plant size is built at each location. Capacities of biogas plants and agricultural land areas are respected due to restriction 3.4 and 3.5, 3.4 also make sure that fish sludge and manure is only sent to opened biogas plants. Restriction 3.6 ensures that the amount of manure sent from a livestock farm is smaller than the production of manure at that farm. Restriction 3.7 sees to it that the amount of fish sludge and manure going in to a biogas plant is the same as the amount of digestate leaving the plant. Biogas plants are located closer to their assigned fish farms than Ecopro due to restriction 3.8. The total amount of VS used in biogas production should consist of 12,5% VS from manure and 87,5% VS from fish sludge, restriction 3.9 takes care of this. Restrictions 3.10 to 3.13 determine the range of values for variables.

6.2.4. Model 4

Model 4 looks into Supply Chain 4 where both pre-treatment facilities and biogas plants need to be located and manure is required to optimize biogas production (see Figure 9). Fish farms are directly assigned to pre-treatment locations where facilities of a given size are established. After pre-treatment the dewatered fish sludge is transported to opened biogas plants where it is mixed with livestock manure. In addition to locating pre-treatment facilities and biogas plants the model also suggest which biogas plant sizes should be used to minimize costs. It also suggests which fish farms should cooperate on which pre-treatment facility, and which biogas plants should receive the dewatered sludge.

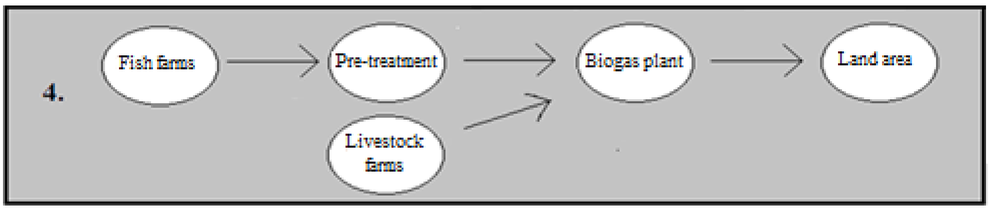

Figure 9: Supply Chain 4.

Sets:

$\mathcal{I}$ – set of fish farms

$\mathcal{P}$ – set of potential pre-treatment locations

$\mathcal{A}$ – set of livestock farms

$\mathcal{J}$ – set of potential biogas plant locations

$\mathcal{K}$ – set of biogas plant sizes

$\mathcal{L}$ – set of agricultural land areas

Parameters:

C_{ip} Shortest distance from fish farm i to potential pre-treatment location p (in km)

O_{pj} Shortest distance from potential pre-treatment location p to potential biogas plant location j (in km)

N_{aj} Shortest distance from livestock farm a to potential biogas plant locations j (in km)

H_{jl} Shortest distance from potential biogas plant location j to agricultural land area l (in km)

Λ_p Capacity of a pre-treatment facility built at potential pre-treatment location p (in tons per year)

Q_k Capacity of a biogas plant of size k (in tons per year)

G_l Maximum amount of digestate allowed to be spread on agricultural land area l (in ton dry substance per year)

F_k Yearly capital cost in NOK associated with building a biogas plant of size k

Z_p Yearly capital cost in NOK associated with building a pre-treatment facility at potential pre-treatment location p

W_k Production cost in NOK per ton associated with a biogas plant of size k

E_p Production cost in NOK per ton associated with a pre-treatment facility at location p

S_i Yearly production of fish sludge at fish farm i (in tons)

D_a Yearly production of manure at livestock farm a (in tons)

B Transportation costs (in NOK per ton/km)

R Weight reduction of fish sludge after pre-treatment (in portion)

T Dry substance portion of the produced digestate

Γ Factor for determining the amount of manure to transport (in portion): (% of total VS required to be from manure/ % VS in the used manure) / (% of total VS required to be from fish sludge/ % VS in the used fish sludge)

Decision variables:

v_p Indicates if a pre-treatment facility is built at potential pre-treatment location p

u_{jk} Indicates if a biogas plant of type k is built at potential biogas plant location j

x_{ip} Indicate if a fish farm i is assigned to a potential pre-treatment location p

y_{pjk} Amount of fish sludge transported from potential pre-treatment location p to potential biogas plant location j, dependent on biogas plant type k (in tons)

e_{ajk} Amount of manure transported from livestock farm a to potential biogas plant location j, dependent on biogas plant type k (in tons)

n_{jl} Amount of digestate transported from biogas plant location j to agricultural land area l (in tons)

Objective function:

$$\min \sum_{p\epsilon P} Z_p v_p + \sum_{j\epsilon J}\sum_{k\epsilon K} F_k u_{jk} + \sum_{i\epsilon I}\sum_{p\epsilon P} E_p S_i x_{ip} + \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{k\epsilon K} W_k y_{pjk} + \sum_{a\epsilon A}\sum_{j\epsilon J}\sum_{k\epsilon K} W_k e_{ajk}$$

$$+ \sum_{i\epsilon I}\sum_{p\epsilon P} C_{ip} S_i x_{ip} B + \sum_{p\epsilon P}\sum_{j\epsilon J}\sum_{k\epsilon K} O_{pj} y_{pjk} B + \sum_{a\epsilon A}\sum_{j\epsilon J}\sum_{k\epsilon K} N_{aj} e_{ajk} B + \sum_{j\epsilon J}\sum_{l\epsilon L} H_{jl} n_{jl} B \quad (4.1)$$

Subject to:

$$\sum_{p\epsilon P} x_{ip} = 1 \qquad \forall\ i\epsilon I \qquad (4.2)$$

$$\sum_{k\epsilon K} u_{jk} \leq 1 \qquad \forall\ j\epsilon J \qquad (4.3)$$

$$\sum_{i\epsilon I} x_{ip} S_i \leq \Lambda_i v_p \qquad \forall\ p\epsilon P \qquad (4.4)$$

$$\sum_{p\epsilon P} y_{pjk} + \sum_{a\epsilon A} e_{ajk} \le u_{jk}Q_k \qquad \forall\ j\epsilon J, k\epsilon K \qquad (4.5)$$

$$\sum_{j\epsilon J} n_{jl}\, T \le G_l \qquad \forall\ l\epsilon L \qquad (4.6)$$

$$\sum_{j\epsilon J}\sum_{k\epsilon K} e_{ajk} \le D_a \qquad \forall\ a\epsilon A \qquad (4.7)$$

$$\sum_{i\epsilon I} x_{ip}S_iR = \sum_{j\epsilon J}\sum_{k\epsilon K} y_{pjk} \qquad \forall\ p\epsilon P \qquad (4.8)$$

$$\sum_{p\epsilon P}\sum_{k\epsilon K} y_{pjk} + \sum_{a\epsilon A}\sum_{k\epsilon K} e_{ajk} = \sum_{l\epsilon L} n_{jl} \qquad \forall\ j\epsilon J \qquad (4.9)$$

$$\sum_{a\epsilon A}\sum_{k\epsilon K} e_{ajk} = \sum_{p\epsilon P}\sum_{k\epsilon K} y_{pjk}\Gamma \qquad \forall\ j\epsilon J \qquad (4.10)$$

$$v_p \epsilon \{0,1\} \qquad \forall\ p\epsilon P \qquad (4.11)$$

$$u_{jk} \epsilon \{0,1\} \qquad \forall\ j\epsilon J, k\epsilon K \qquad (4.12)$$

$$x_{ip} \epsilon \{0,1\} \qquad \forall\ i\epsilon I, p\epsilon P \qquad (4.13)$$

$$y_{pjk}\epsilon\ \ge 0 \qquad \forall\ a\epsilon A, j\epsilon J, k\epsilon K \qquad (4.14)$$

$$e_{ajk}\epsilon\ \ge 0 \qquad \forall\ p\epsilon P, j\epsilon J, k\epsilon K \qquad (4.15)$$

$$n_{jl}\epsilon\ \ge 0 \qquad \forall\ j\epsilon J, l\epsilon L \qquad (4.16)$$

6.2.4.1. Model description

The objective function minimizes costs associated with building and operating pre-treatment facilities and biogas plants, as well as all transportation costs to and from these. Restriction 4.2 ensures that each fish farm is assigned to exactly one potential pre-treatment location, while restriction 4.3 makes sure that at most one biogas plant size is built at each potential biogas plant location. Capacities of pre-treatment facilities, biogas plants and agricultural land areas are held due to restriction 4.4 to 4.6, 4.4 and 4.5 also makes sure that fish sludge is only sent to opened pre-treatment facilities, and that fish sludge and manure is only sent to opened biogas plants. Restriction 4.7 makes sure that the amount of manure sent from a livestock farm is smaller than the production of manure at that farm. The amount of fish sludge transported to a biogas plant should be equal to the amount left after pre-treatment; this is achieved by restriction 4.8. Restriction 4.9 sees to it that the amount of fish sludge and manure going in to a biogas plant is the same as the amount of digestate leaving the plant. The total amount of VS used in biogas production should consist of 12,5% VS from manure and 87,5% VS from fish sludge, restriction 4.10 make sure that this is done. Restrictions 4.11 to 4.16 determine the range of values for variables.

6.3. Data collection for the scenario analysis

This section of the paper presents the data used for the scenario analysis and describes how it was generated. First the initial input data used for Scenario 1 is presented, followed by the modifications made for the other scenarios.

An effort was made to compile as good data as possible; however, despite the effort, it was not possible to obtain all the necessary data. Assumptions therefore had to be made and some of the used input data is, as a consequence, quite uncertain or, at times, even random.

6.3.1. Initial input data

6.3.1.1. Fish farms

Data on location and smolt production of fish farms in Møre og Romsdal has been gathered from the Norwegian directorate of fisheries (Fiskeridir.no), as well as the Norwegian emission authority (Norskeutslipp.no). In total 31 hatcheries were found to be located in the region and together these have a total production capacity of 68,66 million salmon smolts.

The collected data was transferred into excel and calculations were made to generate the amount of fish sludge produced at each hatchery as shown in Table 6.

Municipality	Local name	Yearly production	Spring smolts (110 grams each)	Fall smolts (70 grams each)	Weight of smolts	Feed factor	Sludge factor
			60 %	40 %		1,2 kg feed/kg smolt	1,5 kg sludge/kg feed
		Number of smolts	Total (in grams)	Total in grams)	Total (in tons)	Total feed used (in tons)	Total sludge (in tons)
Aure	Sagosen	2000000	132000000	56000000	188	226	338
Aure	Leddalsvatn	1500000	99000000	42000000	141	169	254
Aure	Kjørsvikbugen	1500000	99000000	42000000	141	169	254
Aure	Fuglvåg	200000	13200000	5600000	19	23	34
Aure	Storvik	200000	13200000	5600000	19	23	34
Halsa	Botn	2500000	165000000	70000000	235	282	423
Halsa	Hønsvikgulen	1000000	66000000	28000000	94	113	169
Molde	Hjelset	500000	33000000	14000000	47	56	85
Norddal	Tafjord	1000000	66000000	28000000	94	113	169
Ørsta	Storelva	800000	52800000	22400000	75	90	135
Ørsta	Standal Y	2500000	165000000	70000000	235	282	423
Ørsta	Urke	5000000	330000000	140000000	470	564	846
Rauma	Reistad	500000	33000000	14000000	47	56	85
Rauma	Hamre	300000	19800000	8400000	28	34	51
Rauma	Hjelvik	1000000	66000000	28000000	94	113	169
Smøla	Aunvågen	5000000	330000000	140000000	470	564	846
Stranda	Opshaugvik Land	750000	49500000	21000000	71	85	127
Tingvoll	Rimstad	500000	33000000	14000000	47	56	85
Tingvoll	Tveekrem	600000	39600000	16800000	56	68	102
Tingvoll	Torjulvågen	2000000	132000000	56000000	188	226	338
Ulstein	Flø	850000	56100000	23800000	80	96	144
Vanylven	Videild	2000000	132000000	56000000	188	226	338
Vestnes	Sætre	2000000	132000000	56000000	188	226	338
Volda	Dale	5000000	330000000	140000000	470	564	846
Aure	Tjeldbergodden biopark	5000000	330000000	140000000	470	564	846
Aure	Sagvikvatnet	7500000	495000000	210000000	705	846	1269
Haram	Vestrefjorden	1000000	66000000	28000000	94	113	169
Herøy	Moltustranda	5000000	330000000	140000000	470	564	846
Volda	Dravlaus	2500000	165000000	70000000	235	282	423
Volda	Steinsvik	7500000	495000000	210000000	705	846	1269
Sunndal	Sjølseng	480000	31680000	13440000	45	54	81
Total		68180000					11536

Table 6: Amount of fish sludge produced at each hatchery.

6.3.1.2. Dry substance and volatile solids content

The dry substance and volatile solids content in fish sludge varies throughout the year, as well as for each fish farm (Ytrestøyl, 2013). Since this is the case assumptions had to be made, and the used figures are displayed in Table 7. Data on DS and VS content in manure were generated from Carlsson and Uldal (2009, pp. 26).

	Primary fish sludge	Manure
Dry substance content	10%	9%
Volatile solids content	9%	7,2%

Table 7: Dry substance and volatile solids content in fish sludge and manure.

As previously explained the amount of digestate created at a biogas plant is assumed to be the same as the amount of biomass delivered to the plant. This means the digestate is used as is, and is not dewatered before transportation to agricultural land areas. The DS content of the digestate is therefore assumed to only depend on the DS content of the used biomasses. For each of the four models the DS content was calculated as shown in Table 8

.

	Biomass	Parameter T (in portion)
Model 1	Primary fish sludge	(1*0,10)= **0,10**
Model 2	Pre-treated fish sludge	(1*0,20)= **0,20**
Model 3	Primary fish sludge and manure	(0,875*0,10)+(0,125*0,09)= **0,09875**
Model 4	Pre-treated fish sludge and manure	(0,875*0,20)+(0,125*0,09)= **0,18625**

Table 8: Portion of dry substance in the produced digestate.

If co-digestion is used (both manure and fish sludge is used as biomass) to optimize the biogas production, the total VS content of the biomass should consist of 87.5% VS from fish sludge and 12.5% VS from manure. Parameter Γ was thus found using this as input data, and the following formula: *(% of total VS required to be from manure/ % VS in the used manure)/(% of total VS required to be from fish sludge/ % VS in the used fish sludge).* Calculations and parameter values are displayed below in Table 9.

	Parameter Γ (in portion)
Model 3	(0.125/0.072)/(0.875/0.09) **= 0,1786**
Model 4	(0.125/0.072)/(0.875/0.18) = **0,3571**

Table 9: Data used for parameter Γ.

6.3.1.3. Biogas plants

Ten potential biogas plant locations have been created. Only one of these is a real option, namely Aukra, or J-08 as it is presented as in Figure 11 in Section 3.1.7. This location is according to Ekanger et al. (2013) especially suitable, as a biogas plant located here can utilize waste heat from Nyhamna, a processing facility connected to the gas field Ormen Lange, to heat the used biomass. The other nine potential biogas plants are placed randomly.

Five different biogas plant sizes are used as input data. To determine investment cost for these, plant size estimations had to be made. According to Hagen (2011, Appendix Q) a biogas plant with daily capacity of 104 tons (mainly livestock manure) will cost between 15 and 20 million NOK. The same source suggest using the correlation $P_2=P_1*(C_2/C_1)^n$ when estimating price for different sized biogas plants. Here P_1 is the investment cost of a plant with capacity C_1, and P_2 is the investment cost of a plant with capacity C_2, while n is a scaling factor which is suggested to typically lie in the area 0.6-0.8. This approach was used to generate investment cost for the different plant sizes, and calculations are displayed in Appendix B. Yearly capital costs were then found using the annuity method. An interest rate of 6% and 15 years down-payment period was used for the calculations.

Production costs were calculated based on the findings of Nielsen et al. (2002). They found that plants with capacities of 300-, 550- and 800 m^3 biomass per day had production costs of 53-, 41- and 35 DKK per m^3 respectively. This data was used to find a logarithmic trend line and a logarithmic equation in excel, as displayed in Figure 10, and production costs in DKK for the five plant sizes were calculated. These were then converted to NOK (1DKK=1.11NOK). It has been assumed that 1m^3 biomass is equal to 1 ton biomass.

The capacities and costs of different plant sizes used for the scenario analysis are shown in Table 10.

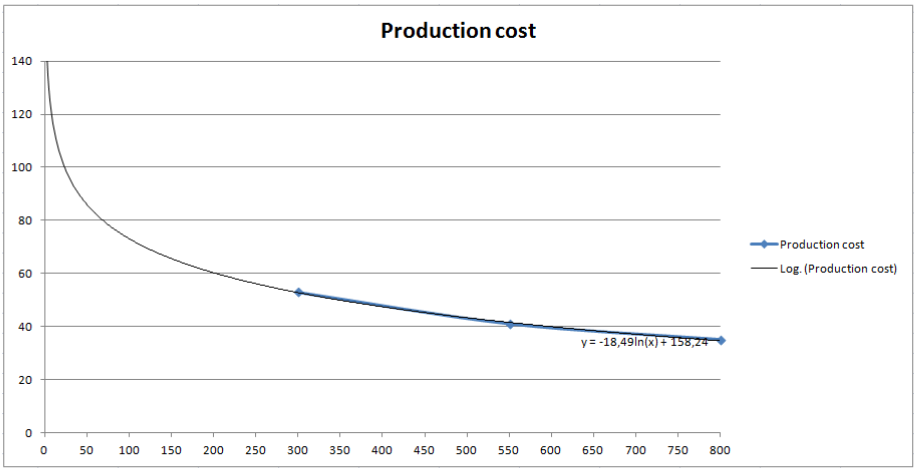

Figure 10: Production cost.

Sizes	A	B	C	D	E
Ton per day	9	12	18	35	44
Tons per year (330 operating days)	2970	3960	5940	11550	14520
Investment costs (in million NOK)	3,606	4,411	5,899	9,332	10,952
Investment cost per ton treated /year (in NOK)	1214	1114	993	808	754
Capital cost per year(NOK)	371284	454169	607377	960849	1127648
Production cost per ton biomass (in NOK)	129	123	115	103	85

Table 10: Capacities and costs for different plant sizes.

6.3.1.4. Pre-treatment facilities

Ten potential pre-treatment locations have been randomly placed in the county. In contrast to the biogas plants it is assumed that only one type of pre-treatment facility can be built, and this has a total capacity of 3800 ton primary sludge a year.

Since no such facility has yet been built in Norway, data on investment and production costs were not obtainable. The costs used as input data (see Table 11) were therefore made up, and can consequently differ substantially from reality.

Yearly capital cost (in NOK)	120000
Production cost per ton primary sludge (in NOK)	60

Table 11: Costs associated with pre-treatment.

The dry substance in pre-treated fish sludge is, as previously explained, assumed to rise from 10- to 20%, which corresponds to a 50% weight reduction. Hence parameter R is equal to 0.5.

6.3.1.5. Agricultural land areas and livestock farmers

Agricultural land areas and livestock farmers are assumed to be located at the same area, and only 10 locations are used as input data for the models. Each of these locations represents 10% of the total available agricultural land areas, as well as 10% of the manure production, in each municipality with potential biogas plant locations.

Data on operational agricultural land areas for each of the used municipalities was generated from Folstad and Rye (2012, pp.7). This source also provided data on total income from milk production in each area, as well as average income generated from each animal. These figures were used to calculate the total number of dairy cattle in each municipality.

On average one dairy cow produce 45 kg manure each day (Sandmo, 2009, pp.117), or 16,43 tones a year. By multiplying the yearly manure production per cow, with the total number of cattle in each municipality, the yearly manure production was found.

According to Blytt et al. (2011) 200-400 kg DS from manure is allowed to be used on one dekar of land each year. It is assumed that the same goes for digestate generated from biogas production, and a maximum of 300 kg DS per dekar is used to generate capacities for agricultural land areas. Since livestock farmers already use livestock manure as fertilizer on much of the land, only agricultural areas left untreated can utilize digestate. The used capacities of land areas as well as biomass production in each of the municipalities are displayed in Appendix C.

The computed capacities are assumed to be the same even if some of the manure is used as biomass in the biogas production.

6.3.1.6. Transportation costs

The initial transportation cost is set to 2.50 NOK /ton/km for all types of biomass as well as digestate, hence a linear relation between cost per ton and distance has been assumed.

6.3.1.7. Distances

All of the locations described above have been added to a customized Google Map, as shown in Figure 11. Shortest distance between each connected location was then found by adding a route between these. The shortest distance between each fish farm and Ecopro has been found in the same manner.

Figure 11: Location of potential biogas plants and pre-treatment facilities as well as location of fish farms. Land areas/Livestock farms used in the analysis is also shown. (Source: Google Maps).

All distances used for the scenario analysis are displayed in Appendix D.

6.3.2. Modifications made for Scenarios 2 to 5

Below all modifications made to the input data as well as an additional constraint added to the models are presented.

6.3.2.1. Reduced transportation cost

In Scenario 2 the transportation cost is lowered from 2.50 NOK/ton/km to 1.0 NOK/ton/km.

6.3.2.2. Increased smolt production

In Scenario 3 the total smolt production goes up from 68.18 million to 80.68 million. Small hatcheries which initially produced less than 1 million smolts still produce the same amount, while all others have increased their smolt production with 20%. Data for the increased smolt production can be found in Appendix E.

6.3.2.3. Pre-treatment at fish farms

In Scenario 4, the produced fish sludge is dewatered at each fish farm before it is transported directly to a biogas plant. No pre-treatment facilities have to be located and therefore only Model 1 and 3 are tested. The amount of fish sludge created at each fish farm (parameter S) is reduced by 50% ; however, since only the weight of the sludge has gone down, and not the actual production, the dry substance content in the fish sludge is simultaneously increased from 10- to 20%. This change affects parameter T, the portion of dry substance in the digestate, as shown in Table 12. In addition, it also affects the volatile solids content in the fish sludge, which leads to a change in parameter Γ (in Model 3).

	Model 1	**Model 3**	
Biomass	Primary fish sludge	Pre-treated fish sludge and manure	
DS content	20%	20%	9%
VS content	18%	18%	7,2%
Parameter T (in portion)	(1*0,20)= **0,20**	(0,875*0,20)+(0,125*0,09)= **0,18625**	
Parameter Γ (in portion)	-	(0.125/0.072)/(0.875/0.18) **= 0,3571**	

Table 12: Changes made to the dry substance portion of the produced digestate (parameter T) and the factor for determining the amount of manure to transport (parameter Γ).

6.3.2.4. Only one biogas plant

In Scenario 5 only one biogas plant should be built in Møre og Romsdal. An additional constraint has been added to each of the four models to enforce this.

Additional constraint:

$\sum_{j \in J} \sum_{k \in K} u_{jk} = 1$

6.4. Results

The four models were implemented in AMPL with IBM ILOG CPLEX Optimization Studio 9.0 as a solver. Ideally a later version of CPLEX would have been used; however this was the only version available to me during the research period.

All the problems were small enough to be solved to optimality within reasonable time and it was therefore not necessary to use heuristics. Computation times ranged from 0,52 to 4,71 seconds and varied between all models and for all scenarios as shown in Figure 12.

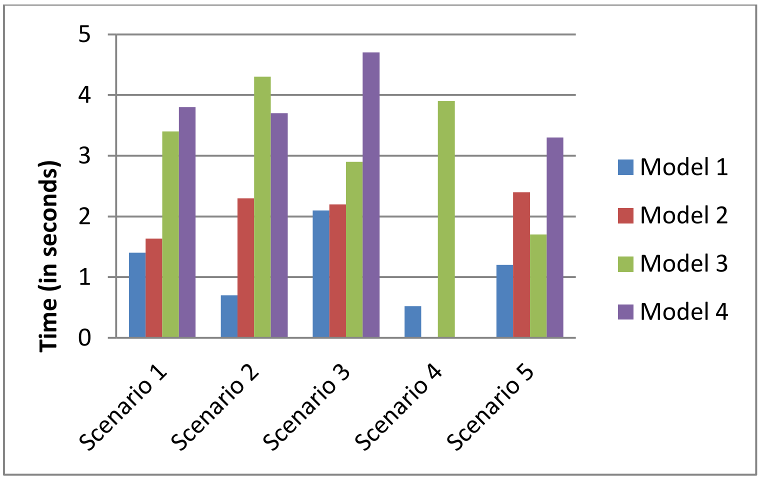

Figure 12: Computation times for different models and scenarios.

Below the results from each scenario is presented and explained. Scenarios 2 to 5 are compared to the baseline scenario, Scenario 1, and in addition several aspects are evaluated for each scenario. In the end the results are compared to the cost of delivering sludge to Ecopro and to the result of the financial analysis.

6.4.1. Scenario 1

In the initial scenario, Scenario 1, two biogas plant locations are used by all four supply chains, namely J-01 and J-06. These biogas plants are located in different parts of the county as depicted in Figure 11 (Section 3.1.7). Each supply chain does, however, utilize different biogas plant sizes and the assignment of fish farms vary between each alternative (see Table 13). The two supply chains with pre-treatment facilities are able to make use of smaller biogas plant sizes than the two without, as the two former chains deliver less biomass to the plants. Supply Chain 2 utilizes biogas plant sizes A and B, which together have a total capacity of 6930 ton biomass. Since the total amount of fish sludge left after pre-treatment is 5768 tons, this chain could potentially use the smallest biogas plant size, which has a capacity of 2970 ton biomass, at both locations. However, this would require changes in the assignment of fish and/or pre-treatment facilities as biogas plant location J-01 is currently receiving 3164 ton biomass. The result therefore suggests that any change in assignment of fish and/or pre-treatment facilities will increase the total cost.

The smallest cost is achieved by Supply Chain 1, which indicates that the cost of building and operating pre-treatment facilities is too high to compensate for the decreased biogas plant sizes and transportation costs. For all four supply chains the digestate is delivered to agricultural land areas in close proximity to the opened biogas plants. Livestock manure, which is needed in Supply Chains 3 and 4, is also transported from the closest livestock farms.

	Supply Chain 1		Supply Chain 2				Supply Chain 3		Supply Chain 4				
Fish farms	I-09, I-10, I-11, I-12, I-15, I-17, I-21, I-22, I-24, I-27, I-28, I-29, I-30	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, I-13, I-14, I-16, I-18, I-19, I-20, I-23, I-25, I-26, I-31	I-09, I-10, I-11, I-12, I-13, I-15, I-17, I-21, I-23, I-27	I-22, I-24, I-28, I-29, I-30	I-01, I-04, I-05, I-06, I-07, I-08, I-14, I-16, I-18, I-19, I-20, I-26	I-02, I-03, I-25, I-31	I-08, I-09, I-10, I-11, I-12, I-13, I-14, I-15, I-17, I-21, I-22, I-23, I-24, I-27, I-28, I-29, I-30, I-31	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-16, I-18, I-19, I-20, I-25, I-26	I-10, I-11, I-12, I-17, I-21, I-27	I-22, I-24, I-28, I-29, I-30	I-08, I-09, I-13, I-15, I-23	I-01, I-04, I-05, I-06, I-07, I-14, I-16, I-18, I-19, I-20, I-26, I-31	I-02, I-03, I-25
Pre-treatment location	-	-	P-02	P-03	P-06	P-07	-	-	P-02	P-03	P-04	P-06	P-07
Livestock farms	-	-	-	-	-	-	A-10	A-05	A-10			A-05	
Biogas plant location	J-01	J-06	J-01		J-06		J-01	J-06	J-01			J-06	
Biogas plant size	C	C	B		A		D	C	B			B	
Agricultural land area	L-10	L-05, L-06	L-10		L-05		L-10	L-05, L-06	L-10			L-05,L-06	
Total cost (NOK/year)	4096669		4222158				4703050		4800992				
Cost per ton DS (NOK/year)	3551		3660				4077		4162				

Table 13: Results from Scenario 1.

6.4.2. Scenario 2

In Scenario 2 the transportation cost has been lowered to 1 NOK per ton km and the total cost is, as a result, smaller for all four supply chains. While no other changes are seen in Supply Chains 1 and 3, the lowered transportation cost has enabled Supply Chain 2 to utilize the smallest biogas plant size at both locations. In addition, this chain now assigns some of the fish farms, as well as pre-treatment facility P-02, differently (see Table 14). If fish farms and pre-treatment facilities were assigned in the same manner while the transportation cost was 2,50 NOK per ton km, the total cost would have been 4228904 NOK, which is only 6746 NOK more than the total cost for Supply Chain 2, in Scenario 1. The cost reduction has also affected Supply Chain 4, which now locates four, instead of five, pre-treatment facilities. Despite these changes, the lowest cost is still achieved by Supply Chain 1.

	Supply Chain 1		Supply Chain 2				Supply Chain 3		Supply Chain 4			
Fish farms	I-09, I-10, I-11, I-12, I-15, I-17, I-21, I-22, I-24, I-27, I-28, I-29, I-30	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, I-13, I-14, I-16, I-18, I-19, I-20, I-23, I-25, I-26, I-31	I-22, I-24, I-28, I-29, I-30	I-09, I-10, I-11, I-12, I-13, I-15, I-17, I-21, I-27	I-01, I-06, I-08, I-14, I-16, I-19, I-20, I-23, I-26	I-02, I-03, I-04, I-05, I-07, I-18, I-25, I-31	I-08, I-09, I-10, I-11, I-12, I-13, I-14, I-15, I-17, I-21, I-22, I-23, I-24, I-27, I-28, I-29, I-30, I-31	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-16, I-18, I-19, I-20, I-25, I-26	I-09, I-10, I-11, I-12, I-13, I-17, I-21, I-27	I-22, I-24, I-28, I-29, I-30	I-01, I-07, I-08, I-14, I-15, I-16, I-18, I-19, I-20, I-23, I-26	I-02, I-03, I-04, I-05, I-06, I-25, I-31
Pre-treatment location	-	-	P-03	P-02	P-06	P-07	-	-	P-02	P-03	P-06	P-07
Livestock farms	-	-	-	-	-	-	A-10	A-05	A-10		A-05	
Biogas plant location	J-01	J-06	J-01	J-06			J-01	J-06	J-01		J-06	
Biogas plant size	C	C	A	A			D	C	B		B	
Agricultural land area	L-10	L-05, L-06	L-10	L-05, L-06			L-10	L-05, L-06	L-10		L-05, L-06	
Total cost (NOK/year)	3163504		3286841				3704768		3749537			
Cost per ton DS (NOK/year)	2742		2849				3211		3250			

Table 14: Results from Scenario 2.

6.4.3. Scenario 3

An increase in production at some of the fish farms has, in addition to higher cost, resulted in the use of larger biogas plant sizes or additional locations (see Table 15). The only exception is Supply Chain 2, which instead increase the number of pre-treatment facilities and thus reduce the transportation costs to these. The assignment of fish farms has changed for all alternatives to accommodate the increased biogas plant sizes at some of the locations. While only two biogas plant locations were utilized by all supply chains in Scenarios 1 and 2 a third is now used in Supply Chain 3, namely J-03 (see Figure 11, Section 3.1.7). The cheapest alternative in this scenario is to build and utilize pre-treatment facilities before transporting the fish sludge to biogas plants.

	Supply Chain 1		Supply Chain 2					Supply Chain 3			Supply Chain 4				
Fish farms	I-08, I-09, I-10, I-11, I-12, I-13, I-14, I-15, I-17, I-18, I-21, I-22, I-23, I-24, I-27, I-28, I-29, I-30	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-16, I-19, I-20, I-25, I-26, I-31	I-10, I-11, I-12, I-17, I-27, I-28	I-21, I-22, I-24, I-29, I-30	I-08, I-09, I-13, I-14, I-15, I-23, I-31	I-02, I-03, I-05, I-06, I-25	I-01, I-04, I-07, I-16, I-18, I-19, I-20, I-26	I-09, I-10, I-11, I-12, I-17, I-21, I-22, I-24, I-27, I-28, I-29, I-30	I-06, I-07, I-08, I-13, I-14, I-15, I-18, I-19, I-20, I-23, I-31	I-01, I-02, I-03, I-04, I-05, I-16, I-25, I-26	I-10, I-11, I-12, I-17, I-27, I-28	I-21, I-22, I-24, I-29, I-30	I-08, I-09, I-13, I-14, I-15, I-19, I-23, I-31	I-02, I-03, I-05, I-20, I-25	I-01, I-04, I-06, I-07, I-16, I-18, I-26
Pre-treatment location	-	-	P-02	P-03	P-04	P-07	P-06	-	-	-	P-02	P-03	P-04	P-07	P-06
Livestock farms	-	-	-	-	-	-	-	A-10	A-04	A-05	A-10			A-05	
Biogas plant location	J-01	J-06	J-01			J-06		J-01	J-03	J-06	J-01			J-06	
Biogas plant size	D	C	B			A		D	A	C	C			B	
Agricultural land area	L-10	L-05, L-06	L-10			L-05, L-06		L-10	L-04	L-05	L-09, L-10			L-05, L-06	
Total cost (NOK/year)	4900499		4865994					5531211			5608088				
Cost per ton DS (NOK/year)	3590		3565					4052			4108				

Table 15: Results from Scenario 3.

6.4.4. Scenario 4

In Scenario 4, fish sludge is dewatered at each fish farm before it is transported directly to a biogas plant; therefore only Supply Chains 1 and 3 are investigated. While Supply Chain 1 use the same biogas plant locations and the same assignment of fish farms as in Scenario 1, Supply Chain 3 assigns fish farms differently (see Table 16). Since the fish sludge is dewatered before transportation to biogas plants, the plant sizes as well as the total cost have decreased (Cost of building a pre-treatment facility at each fish farm has not been taken into account).

	Supply Chain 1		Supply Chain 3	
Fish farms	I-09, I-10, I-11, I-12, I-15, I-17, I-21, I-22, I-24, I-27, I-28, I-29, I-30	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, I-13, I-14, I-16, I-18, I-19, I-20, I-23, I-25, I-26, I-31	I-09, I-10, I-11, I-12, I-13, I-17, I-21, I-22, I-24, I-27, I-28, I-29, I-30	I-01, I-02, I-03, I-04, I-05, I-06, I-07, I-08, I-14, I-15, I-16, I-18, I-19, I-20, I-23, I-25, I-26, I-31
Livestock farms	-	-	A-10	A-05
Biogas plant location	J-01	J-06	J-01	J-06
Biogas plant size	A	A	B	B
Agricultural land area	L-10	L-05, L-06	L-10	L-05, L-06
Total cost (NOK/year)	2264277		3031346	
Cost per ton DS (NOK/year)	1963		2628	

Table 16: Results from Scenario 4.

While pre-treatment reduce the weight and volume of the sludge, the amount of DS in the fish sludge and the digestate is the same as in Scenario 1 for both supply chains. For that reason both chains still need to deliver digestate to three agricultural land areas each.

6.4.5. Scenario 5

Scenario 5 investigated if one common biogas plant location could be the best alternative for all four supply chains. This was not the case as the two supply chains with pre-treatment facilities located the biogas plant at location J-01, while the two other chains located it at J-03 (see Table 17). As depicted in Figure 11 (Section 3.1.7.), J-01 is located in Ørsta municipality near the southwest corner of Møre og Romsdal and J-03 is located further north in Gjemnes municipality. The different outcomes can be explained by the maximum distance restriction set on Supply Chains 1 and 3. Due to this, fish farms can only be assigned to biogas plants if these are located closer to the hatchery than Ecopro. However, if pre-treatment facilities are built and utilized these can deliver dewatered fish sludge to any opened biogas plant, regardless of where it is located. Compared to Scenario 1 the biogas plant sizes have gone up for all four supply chains, and the cheapest alternative is now Supply Chain 2, where the fish sludge is dewatered before transportation to a biogas plant. In addition to the results above this scenario also revealed that the models can be further improved. Instead of choosing biogas plant size D, a plant size large enough to handle all the primary sludge, Supply Chain 1 built a biogas plant of size E. This biogas plant size has a lower variable production cost than plant size D, which in this scenario was used to reduce the total cost of handling the fish sludge. In reality the variable production cost will only go down as the amount of biomass handled goes up, hence a larger plant size should only be built if it receives an adequate amount of biomass. To improve the models an additional restriction should therefore be added and all biogas plant sizes should not only have capacities, but also demand for biomass. This demand should preferably be higher than the capacity of smaller biogas plant sizes to avoid the outcome explained above.

	Supply Chain 1	Supply Chain 2				Supply Chain 3	Supply Chain 4			
Fish farms	All	I-08, I-09, I-10, I-11, I-12, I-13, I-14, I-15, I-17, I-21, I-23, I-27	I-22, I-24, I-28, I-29, I-30	I-01, I-03, I-04, I-05, I-16, I-25, I-26	I-02, I-06, I-07, I-18, I-19, I-20, I-31	All	I-08, I-09, I-10, I-11, I-12, I-13, I-14, I-15, I-17, I-21, I-23, I-27	I-22, I-24, I-28, I-29, I-30	I-01, I-02, I-04, I-05, I-16, I-25, I-26	I-03, I-06, I-07, I-18, I-19, I-20, I-31
Pre-treatment location	-	P-02	P-03	P-06	P-08	-	P-02	P-03	P-06	P-08
Livestock farms	-	-	-	-	-	A-04	A-10			
Biogas plant location	J-03	J-01				J-03	J-01			
Biogas plant size	E	C				E	D			
Agricultural land area	L-03, L-04	L-09, L-10				L-03, L-04	L-08, L-09, L10			
Total cost (NOK/year)	**6559588**	**5324632**				**7021865**	**6059053**			
Cost per ton DS (NOK/year)	**5686**	**4616**				**6087**	**5252**			

Table 17: Results from Scenario 5.

6.4.6. Alternative costs

If central biogas plants and pre-treatment facilities are not built in Møre og Romsdal all fish sludge can alternatively be delivered to Ecopro. The total cost of utilizing this disposal alternative has been calculated for each of the five scenarios and the result is displayed in Table 18. As can be seen, these costs are significantly higher than the cost of utilizing any of the investigated supply chains.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total cost of delivering to Ecopro (NOK/year)	24942585	18282954	29540120	12471293	24942585
Cost per ton DS (NOK/year)	21622	15849	21640	10811	21622

Table 18: Total cost of delivering fish sludge to Ecopro, for all 31 hatcheries. (Assuming a gate-fee of 1200 NOK/ton fish sludge)

Supply Chains 1 and 2 have been compared to the cheapest option from the financial analysis, which was Value Chain 4. Scenarios 1 and 5 are used in the comparison and the results are displayed in Table 19. The same transportation costs and DS content were used in both scenarios and the financial analysis.

While two biogas plants are built in both supply chains in Scenario 1, Scenario 5 shows the cost of building only one centralized biogas plant in each supply chain. Compared to the least cost option from the financial analysis the results indicate that two centralized biogas plants built in Møre og Romsdal will decrease the fish sludge recycling cost for Smøla

Klekkeri og Settefiskanlegg AS. However, it should be noted that costs of building storage tanks and ventilation systems at the hatcheries are not taken into account in the location analysis.

Cost per ton DS (NOK/year)		
	Scenario 1	**Scenario 5**
Supply Chain 1	3551	5686
Supply Chain 2	3660	4616
Value Chain 4	4040	4040

Table 19: Results from the two analyses.

7. Conclusion and further research

Two analyses have been used to evaluate different fish sludge recycling alternatives. A financial analysis was used to look into four different internal value chains for Smøla Klekkeri og Settefiskanlegg AS. This analysis showed that the hatchery could potentially reduce the cost of fish sludge recycling by investing in a small scale biogas plant and a Salsnes Filter system. Further, it also suggests that another good alternative could be to invest in the latter as well as the Global Enviro Technology. However, some of the data used in the analysis was based purely on assumptions or generated randomly. Therefore, a more thorough analysis should be performed as more accurate data becomes available.

A facility location analysis was used to determine if cooperation among fish farmers on one or more centralized biogas plants could benefit the industry. Four linear mathematical models were developed and used to look into four different supply chains. A scenario analysis was then used to investigate how changes in input data affected the location and size of biogas plants, as well as the assignment of fish farms. This analysis showed that pre-treatment at the fish farms, or a decrease in transportation cost did not affect the location of biogas plants. An increase in salmon smolt production showed similar results, however an additional biogas plant location was used in one of the investigated supply chains. While little changes were seen on biogas plant locations, the assignment of fish farms and biogas plant sizes more or less varied for each scenario. Compared to the cost of delivering to an already established waste facility, the results suggest that fish farmers can reduce the cost of fish sludge disposal by cooperating and building one or more biogas plants. Furthermore, it also implies that two centralized biogas plants could potentially be more beneficial to the fish farmers than investing in internal fish sludge treatment methods.

Much of the data used in the facility location analysis has, as in the financial analysis, been based on assumptions or randomly created, and thus, the results could consequentially be misleading. While this might be the case, the models developed have been shown to work well and they can therefore, with more accurate data, be used as a decision tool and provide valuable results.

In future research several modifications can be made to further improve the developed models. First of all, the scenario analysis revealed that each biogas plant size should have a demand for biomass. By adding a demand restriction on each biogas plant size the associated variable costs would be assigned correctly in all situations. The developed models also use a linear relation between transportation costs per ton biomass and distance. This linear relation might not give an appropriate allocation of transportation costs and a different approach, where number of transportation units is used instead, should be considered. In the developed models all hatcheries are either assigned directly to pre-treatment facilities or biogas plants. An additional model should also be developed to consider a situation where fish farms can be assigned to pre-treatment facilities or biogas plants, depending on which of these facilities are located closest.

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9. Appendices

Appendix A: Data used in the financial analysis

	Investment costs (in NOK)	O&M costs
Global Enviro	1300000	160-200 kWh/day + Service cost: 50000 NOK
Salsnes Filter	1000000	Assumed to be the same as for Global Enviro
Biogas plant	1000000	Personnel cost, 30min/day
Storage tanks:	Value Chain 1: 100000	-
	Value Chain 2: 75000	-
	Value Chain 3: 50000	-
	Value Chain 4: 75000	-
Ventilation system	50000	-

Table A1: Data on investment and operation and maintenance costs for fixed assets. Data provided by participants in the Slam-Bep project are shown in black, while assumed data is shown in red.

Amount of fish sludge	846 tons
DS content	10 %
VS content	9 %
DS content after pre-treatment with Salsnes Filter	20 %
VS content after pre-treatment with Salsnes Filter	18 %
DS content after pre-treatment with Global Enviro	90 %
Transportation cost	2,5 NOK/ton/km
Electricity cost	0,31 NOK/kWh
Methane yield	560m^3/ton VS
Personnel cost	400 NOK/hour
Distance from Smøla Klekkeri og Settefiskanlegg AS to Ecopro	294 km
Distance from SKS to appropriat agricultural land areas	15 km
Gate-fee	1200 NOK/ton

Table A2: Additional data used in the financial analysis.

Appendix B: Investment costs for different plant sizes

Biogas plant size	**Daily capacity (in tons)**	**Scaling factor**	**Investment cost**
-	*104*	*-*	*20 million NOK*
A	9	0,7	20mill NOK*$(9/104)^{0,7}$= **3,606 mill NOK**
B	12	0,7	20mill NOK*$(12/104)^{0,7}$= **4,411 mill NOK**
C	18	0,7	20mill NOK*$(18/104)^{0,7}$= **5,899 mill NOK**
D	35	0,7	20mill NOK*$(35/104)^{0,7}$= **9,332 mill NOK**
E	44	0,7	20mill NOK*$(44/104)^{0,7}$= **10,952 mill NOK**

Table B1: Investment cost for different plant sizes. The first row contains the input data used to retrieve investment costs for different biogas plant size. This data was generated from Hagen (2011, Appendix Q).

Appendix C: Availability of manure and capacities for agricultural land areas

Municipality	**Income from milk production (in mill. NOK)**	**Number of milking cows**	**Produced livestock manure (in tons)**	**Yearly available manure at each location (10% of total) (in tons)**	**Amount of available DS from manure (in tons)**
Rauma	27,9	1280	21030	**2103**	189
Aukra	4	183	3007	**300**	27
Fræna	60,1	2757	45298	**4529**	408
Gjemnes	28	1284	21096	**2109**	190
Aure	19,9	913	15000	**1500**	135
Surnadal	35,3	1619	26600	**2660**	239
Sunndal	18	826	13571	**1357**	122
Vestnes	14,1	647	10630	**1063**	96
Vanylven	16,3	748	12290	**1229**	111
Ørsta	32,7	1500	24645	**2464**	222

Table C1: Available manure at each livestock farm. (Data on income from milk production was adapted from Folstad and Rye, 2012).

Municipality	Total operational agricultural land areas (in dekar)	Yearly available agricultural land areas for each location. (10% of total) (in dekar)	Maximum amount of DS from manure and digestate on each land area (in ton DS)	Maximum amount of digestate on each land area (in ton DS)
Rauma	35880	3588	1076	**887**
Aukra	9310	931	279	**252**
Fræna	58480	5848	1754	**1346**
Gjemnes	25750	2575	772	**582**
Aure	23010	2301	690	**555**
Surnadal	35440	3544	1063	**824**
Sunndal	21920	2192	658	**536**
Vestnes	20310	2031	609	**513**
Vanylven	23440	2344	703	**592**
Ørsta	35870	3587	1076	**854**

Table C2: Capacities for agricultural land areas. (Data on operational agricultural land areas was adapted from Folstad and Rye, 2012, pp. 7).

Appendix D: Distances

	J-01	J-02	J-03	J-04	J-05	J-06	J-07	J-08	J-09	J-10
I-01	222	155	80	109	63	10	253	127	132	257
I-02	259	192	117	171	124	47	290	164	169	294
I-03	259	192	117	171	124	47	291	164	169	294
I-04	231	164	88	118	72	18	262	135	140	265
I-05	238	171	96	106	60	26	269	142	147	273
I-06	226	159	84	104	57	44	258	131	136	261
I-07	200	133	57	91	44	55	231	104	109	234
I-08	134	67	19	74	97	78	165	46	44	169
I-09	126	122	131	185	209	190	188	125	97	151
I-10	21	140	133	187	211	192	88	127	99	56
I-11	26	134	127	182	205	186	95	121	93	63
I-12	30	158	167	222	245	226	146	161	133	109
I-13	127	35	84	163	162	143	158	78	50	162
I-14	180	24	63	110	153	122	211	64	103	215
I-15	123	39	81	167	158	139	155	75	48	158
I-16	251	184	108	168	121	49	282	155	160	286
I-17	98	107	116	170	194	175	159	110	82	123
I-18	200	133	58	50	54	81	231	104	109	235
I-19	182	115	40	68	56	63	213	86	91	217
I-20	199	132	56	64	67	80	230	103	108	233
I-21	42	155	147	202	225	206	56	141	113	67
I-22	30	189	182	236	259	240	30	176	148	33
I-23	111	50	68	122	145	127	142	62	34	145
I-24	28	187	180	234	258	239	70	174	146	9
I-25	259	192	117	172	126	47	290	164	169	294
I-26	217	150	75	135	72	5	248	121	126	252
I-27	91	100	80	135	158	139	123	74	36	126
I-28	45	168	161	215	238	220	47	155	127	70
I-29	23	182	175	229	252	233	47	169	141	16
I-30	36	195	188	243	266	247	62	182	154	1
I-31	203	129	80	5	48	130	234	115	113	238

Table D1: Distance between fish farms and potential biogas plant locations (in km).

	A-01	A-02	A-03	A-04	A-05	A-06	A-07	A-08	A-09	A-10
J-01	169	147	153	164	229	210	218	105	47	4
J-02	14	88	86	97	162	142	144	70	192	165
J-03	84	68	46	11	75	56	85	55	187	160
J-04	128	120	113	75	109	70	10	107	239	212
J-05	171	135	103	88	62	23	58	130	262	235
J-06	140	116	84	70	16	51	140	111	243	216
J-07	200	178	184	195	260	240	249	136	14	73
J-08	83	3	50	76	133	114	130	47	179	152
J-09	91	57	62	73	138	119	127	18	151	124
J-10	204	182	187	199	264	244	253	140	50	41

Table D2: Distance between potential biogas plant locations and agricultural land areas (in km).

	P-01	P-02	P-03	P-04	P-05	P-06	P-07	P-08	P-09	P-10
I-01	27	202	244	125	84	11	31	67	103	174
I-02	89	239	281	162	120	48	11	104	148	211
I-03	88	240	281	163	121	48	11	104	148	211
I-04	36	211	252	134	92	19	40	75	111	183
I-05	24	218	259	141	99	26	30	57	83	190
I-06	21	206	248	130	88	45	58	55	80	178
I-07	18	180	221	103	61	55	69	28	54	152
I-08	71	114	156	37	5	81	119	41	78	87
I-09	183	117	134	77	116	193	231	153	189	69
I-10	184	1	42	79	118	195	233	155	191	36
I-11	179	28	49	73	113	189	227	149	185	30
I-12	219	50	45	113	153	229	267	189	226	88
I-13	134	107	148	28	68	146	184	106	142	79
I-14	114	160	202	81	48	125	163	85	121	132
I-15	131	104	145	25	65	142	180	102	139	76
I-16	85	231	272	154	112	52	90	95	132	203
I-17	168	69	105	62	101	178	216	138	174	41
I-18	48	180	221	103	61	84	99	28	13	152
I-19	30	162	204	85	43	66	81	10	31	134
I-20	46	179	220	102	60	83	97	27	27	151
I-21	199	61	54	94	133	209	247	169	206	57
I-22	233	48	7	127	167	243	281	203	240	84
I-23	118	91	132	12	52	130	167	90	126	63
I-24	232	47	34	126	165	242	280	202	238	83
I-25	90	239	281	162	121	48	11	104	149	211
I-26	36	197	239	120	78	6	40	62	98	169
I-27	132	71	113	40	66	142	180	102	138	50
I-28	211	61	54	105	144	222	260	183	219	70
I-29	226	42	11	121	160	236	274	197	233	77
I-30	240	55	26	134	173	250	288	210	246	91
I-31	83	183	225	106	67	133	133	77	45	155

Table D3: Distance between fish farms and potential pre-treatment locations (in km).

	J-01	J-02	J-03	J-04	J-05	J-06	J-07	J-08	J-09	J-10
P-01	205	138	63	83	36	37	236	110	115	240
P-02	20	141	134	188	211	192	87	128	100	55
P-03	23	182	175	230	253	234	36	169	141	26
P-04	100	62	57	111	134	116	131	51	23	134
P-05	139	72	15	71	93	74	170	51	48	174
P-06	216	148	62	133	73	3	246	120	125	250
P-07	254	186	100	133	87	41	284	158	163	288
P-08	176	108	22	77	60	57	206	80	85	210
P-09	212	145	58	45	49	93	243	116	121	247
P-10	56	113	108	160	183	164	186	100	72	91

Table D4: Distance between potential pre-treatment locations and potential biogas plant locations (in km).

	J-01	J-02	J-03	J-04	J-05	J-06	J-07	J-08	J-09	J-10
L-01	169	14	84	128	171	140	200	83	91	204
L-02	147	88	68	120	135	116	178	3	57	182
L-03	153	86	46	113	103	84	184	50	62	187
L-04	164	97	11	75	88	70	195	76	73	199
L-05	229	162	75	109	62	16	260	133	138	264
L-06	210	142	56	70	23	51	240	114	119	244
L-07	218	144	85	10	58	140	249	130	127	233
L-08	105	70	55	107	130	111	136	47	18	140
L-09	47	192	187	239	262	243	14	179	151	50
L-10	4	165	160	212	235	216	73	152	124	41

Table D5: Distance between livestock farmers and potential biogas plant locations (in km).

	Ecopro
I-01	236
I-02	227
I-03	227
I-04	245
I-05	233
I-06	216
I-07	241
I-08	294
I-09	406
I-10	408
I-11	402
I-12	564
I-13	424
I-14	385
I-15	428
I-16	294
I-17	391
I-18	265
I-19	253
I-20	269
I-21	422
I-22	456
I-23	439
I-24	575
I-25	228
I-26	245
I-27	355
I-28	436
I-29	449
I-30	583
I-31	280

Table D6: Distance between fish farms and Ecopro (in km).

Appendix E: Increased smolt production

Municipality	Local name	Yearly production	Spring smolts (110 grams each)	Fall smolts (70 grams each)	Weight of smolts	Feed factor	Sludge factor
			60 %	40 %		1,2 kg feed/kg smolt	1,5 kg sludge/kg feed
		Number of smolts	Total (in grams)	Total (in grams)	Total (in tons)	Total feed used (in tons)	Total sludge (in tons)
Aure	Sagosen	2400000	158400000	67200000	226	271	406
Aure	Leddalsvatn	1800000	118800000	50400000	169	203	305
Aure	Kjørsvikbugen	1800000	118800000	50400000	169	203	305
Aure	Fuglvåg	200000	13200000	5600000	19	23	34
Aure	Storvik	200000	13200000	5600000	19	23	34
Halsa	Botn	3000000	198000000	84000000	282	338	508
Halsa	Hønsvikgulen	1200000	79200000	33600000	113	135	203
Molde	Hjelset	500000	33000000	14000000	47	56	85
Norddal	Tafjord	1200000	79200000	33600000	113	135	203
Ørsta	Storelva	800000	52800000	22400000	75	90	135
Ørsta	Standal Y	3000000	198000000	84000000	282	338	508
Ørsta	Urke	6000000	396000000	168000000	564	677	1015
Rauma	Reistad	500000	33000000	14000000	47	56	85
Rauma	Hamre	300000	19800000	8400000	28	34	51
Rauma	Hjelvik	1200000	79200000	33600000	113	135	203
Smøla	Aunvågen	6000000	396000000	168000000	564	677	1015
Stranda	Opshaugvik Land	750000	49500000	21000000	71	85	127
Tingvoll	Rimstad	500000	33000000	14000000	47	56	85
Tingvoll	Tveekrem	600000	39600000	16800000	56	68	102
Tingvoll	Torjulvågen	2400000	158400000	67200000	226	271	406
Ulstein	Flø	850000	56100000	23800000	80	96	144
Vanylven	Videild	2400000	158400000	67200000	226	271	406
Vestnes	Sætre	2400000	158400000	67200000	226	271	406
Volda	Dale	6000000	396000000	168000000	564	677	1015
Aure	Tjeldbergodden biopark	6000000	396000000	168000000	564	677	1015
Aure	Sagvikvatnet	9000000	594000000	252000000	846	1015	1523
Haram	Vestrefjorden	1200000	79200000	33600000	113	135	203
Herøy	Moltustranda	6000000	396000000	168000000	564	677	1015
Volda	Dravlaus	3000000	198000000	84000000	282	338	508
Volda	Steinsvik	9000000	594000000	252000000	846	1015	1523
Sunndal	Sjølseng	480000	31680000	13440000	45	54	81
Total		80680000					13651

Table E1: Increased salmon smolt production.