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The potential of a circular grass refinery supply chain in the Netherlands

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Abstract

In this thesis work the potential of grass refinery in a defined agricultural region is investigated. The grass refinery is a component of a circular supply chain, which contains a dairy farm, a feed factory and a pig farm as well. Grass from grasslands on the dairy farm is transported to the refinery installation. This refinery delivers several products: a grass protein product, grass fibres, whey and a phosphate fraction. The grass fibres, whey and eventually the phosphate fraction can be used at the original dairy farm. The grass protein product is suitable as ingredient in pig feed, which is composed at the feed factory. Beyond the pigs at the pig farm digest this feed to meat, energy and manure. This manure can also be used as fertilizer at the grasslands. In the circular supply chain in this study grass, whey, fibres, grass protein product, feed and manure are transported between the different facilities. All these streams contribute to the circularity of the supply chain. Over the last years the circularity of systems has become an interesting topic in our economy due to the transmission from a linear economy to a circular one. Another important reason why the grass refinery is researched is the composition of the grass protein product from grass refinery. This grass protein product is a good alternative to replace the less preferable imported soybean meal in animal feed.

During this study a model is created and applied to a case study. In this case study an agricultural region is defined which represents a part of the Netherlands. Several scenarios are applied to investigate about the optimal organisation of that agricultural region. The first scenario is a reference situation with values for the parameters which are found in literature, from other researchers or from companies. Beyond the effect of the location of biorefineries is evaluated by placing possible biorefinery facilities at local and central places in the agricultural region. The optimization shows that the most potential belongs to local biorefineries.
Then the sizes of the biorefineries and the corresponding processing costs are investigated. Central and larger biorefineries could have lower processing costs but that advantage has to be equal or more than the advantage of less transportation costs at the smaller local biorefineries. Besides the effect of the soybean meal price is investigated. This price is fluctuating strongly and therefore a kind of a tipping point is found whereupon the grass protein product becomes more interesting to replace a part of the soybean meal in animal feed.

In general the conclusion is that grass refinery in the defined circular supply chain has certain potential in the Netherlands. However this study is just an initial evaluation which could be extended with several factors, like revenues for all products and investment costs for all facilities. The agricultural region which is defined in the case study is an average of the Dutch agriculture, but this could also be specified to one specific region to have more appropriate results.

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1 Introduction

1.1 Circular economy

The world population is growing fast and the living standards of people are increasing continuously (UN, 2015). Therefore the world has to obtain more feed, food and energy, which leads to a higher consumption of raw materials. Since there is already an exhaustion of the world's fossil resources (Giljum et al., 2009) it is necessary to eliminate inefficiencies in using raw materials. This can be achieved by closing loops of material flows, which is the aim of the concept called 'circular economy' (Preston, 2012). Waste materials in a circular economy are reused and therefore gain more value. Hence less input of raw materials is needed in a circular economy compared to a linear economy. The graphic view of both economies is presented in figure 1.

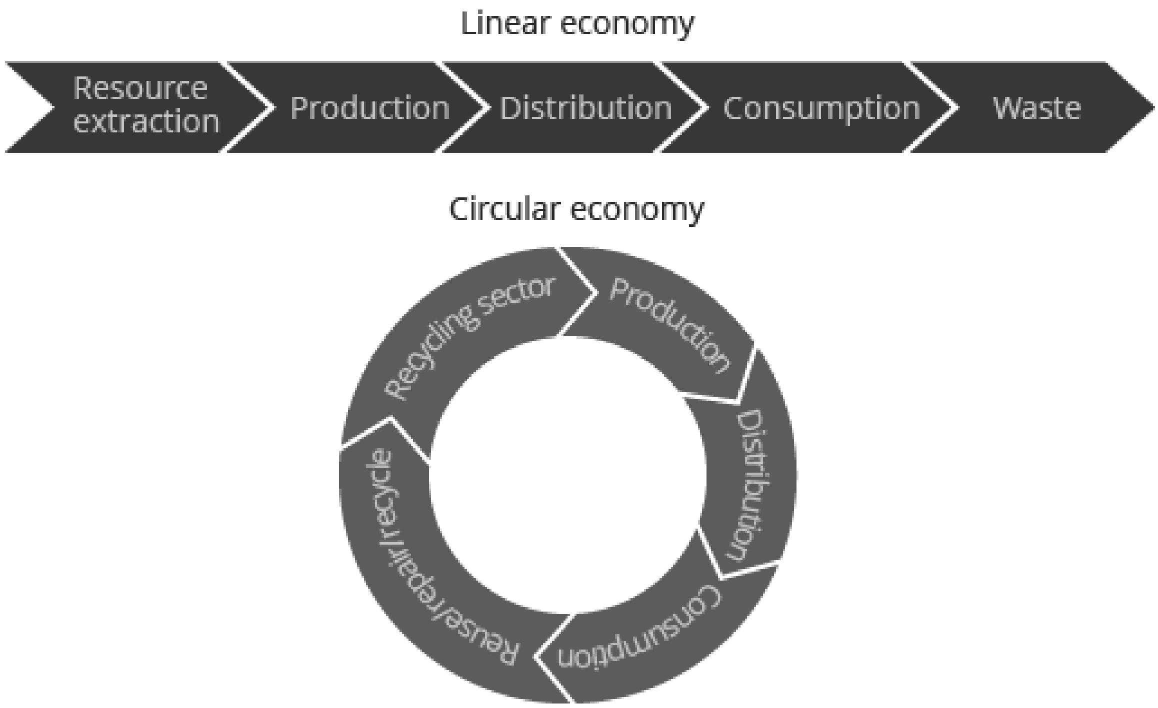

Figure 1: Graphic view of linear economy versus circular economy (AkzoNobel, 2016)

The idea of the circular economy fits to the strategy 'Europe 2020' from the European Commission. One of the seven initiatives of this strategy is called 'resource efficient Europe', which will help to decouple economic growth from the use of resources (EC, 2010). In the Netherlands the departments of Infrastructure & Environment and Economic Affairs recently made agreements to achieve a completely circular economy by the year 2050 (Rijksoverheid, 2016). Principally a lot of attention has been paid to the manufacturing industry but also the agricultural sector can contribute to the circular economy e.g. by reusing waste materials and by consuming local feedstocks. Accordingly the focus of this thesis work will be on a circular supply chain which can be applied to the Dutch agricultural sector.

1.2 Grass refinery

'Biorefining is the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials and chemicals) and energy (fuels, power and heat)' (de Jong et al., 2011). The refined fractions can be used more efficiently than the biomass and the waste- or by-streams are reused in circular systems. The circular supply chain in this study consists of certain biorefineries. The biomass is fresh grass and the products of the biorefinery are a protein product, fibres, whey and phosphate. Fresh grass consists of about 18 % dry matter, of which 20 % can be refined to a protein product, 66 % to fibres, 12 % to whey and 2 % to phosphate (Honkoop and Aarts, 2015).

The grass refinery is one of the facilities in the circular supply chain which is presented in figure 2. The other facilities are a dairy farm, a feed factory and a pig farm. Between these facilities the material flows are given by the drawn arrows and most of them will contribute to the circularity of the supply chain.

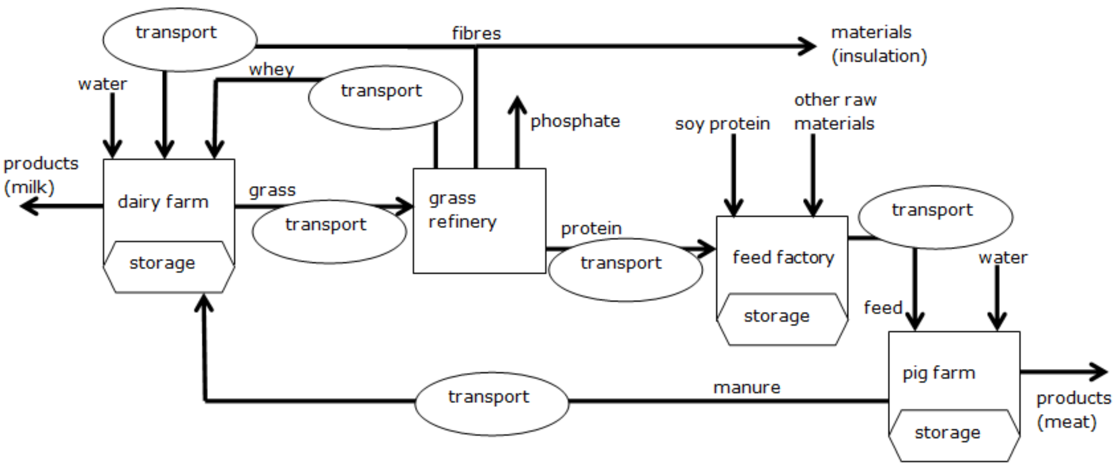

Figure 2: Circular grass refinery supply chain

The products of the grass refinery can have several purposes. The protein product can be used to produce protein rich animal feed, appropriate for cows, pigs or poultry. In this study the produced animal feed will only be consumed at pig farms. The whey and phosphate as products of the biorefinery are suitable as fertilizer and also the manure produced by the pigs can be used to fertilize agricultural soil. The grass fibre fraction can be sold to make new materials, such as insulation, or can be fed to dairy cows, because it has a good nutritional value for dairy cows.

Besides the use of grass protein product at the feed factory also other products can be used as ingredients for animal feed. To combine several ingredients into a good pig feed it is important to reach the required crude protein content, but it is even important which amino acids are included in what ratio. In figure 3 the composition of amino acids in grass protein product, soybean meal and rape seed meal is presented. The researchers of the corresponding study concluded that the amino acid composition of grass protein and soy protein are comparable and therefore grass protein product and soybean meal could substitute each other (Sanders et al., 2016).

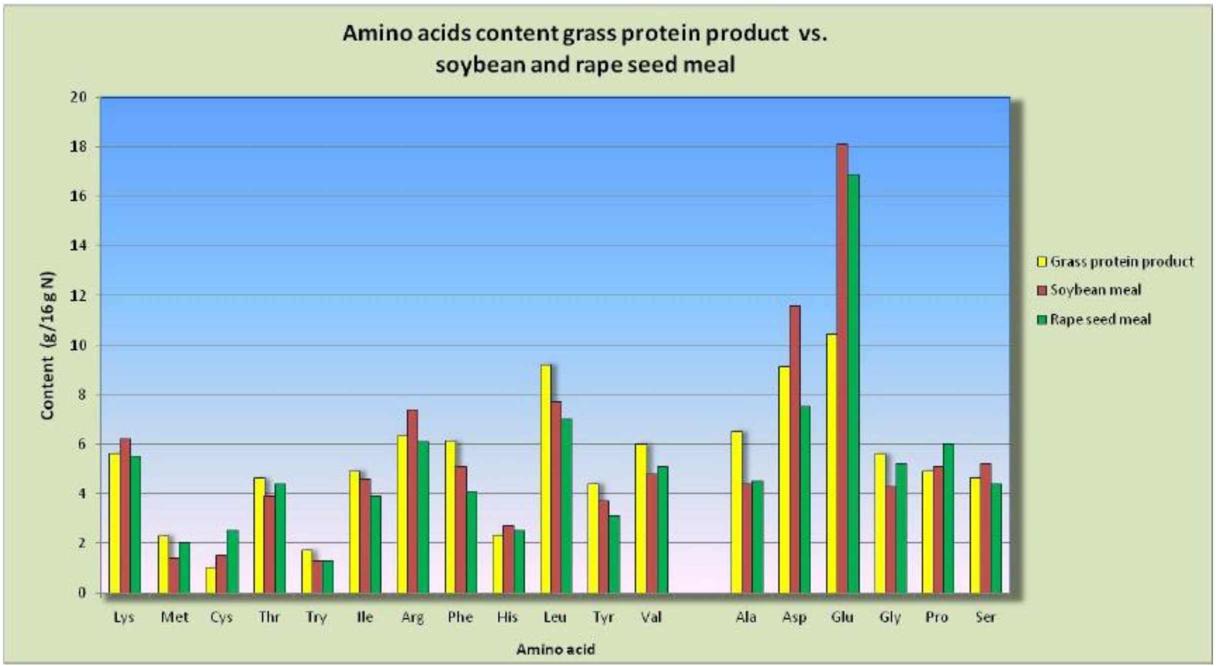

Figure 3: Amino acid content in grass protein product, soybean meal and rape seed meal (Sanders et al., 2016).

Nowadays much soy protein in the form of soybean meal is used to reach the protein demand in animal feed. Most of that soybean meal is imported from countries in South America. The soy industry in these countries is growing and causes social and environmental problems, for example deforestation and violence. Therefore it will be better to reduce the European import of soy products. This reduction can take place if some part of the soybean meal in animal feed will be replaced by the grass protein product from biorefineries.

1.3 Problem definition

The replacement of protein rich soy products with a protein fraction of grass can be a sustainable solution, but there is limited knowledge about the potential of the circular grass refinery supply chain in the Netherlands. Over the last years some important technological innovations have been proposed on parts of the circular supply chain of the grass refinery (Didde, 1999, 2012; Honkoop and Aarts, 2015; Klop et al., 2015; Koopmans, 2014; Sanders et al., 2016; van Doorn et al., 2013). However, strategic level decisions related to facilities and streams of materials must be optimised and logistical structures must be evaluated to improve the performance of the whole circular grass refinery supply chain. This can be achieved with advanced decision support tools.

1.4 Objectives

The objective of this work is to identify logistical configurations and relationships between inputs and outputs of the circular grass refinery supply chain and to evaluate the potential of these configurations in the Netherlands to replace imports of soy from South America.

The main research question is formulated as follows:

> *What is the potential of grass refinery in the Netherlands with respect to material flows and transportation in the circular grass refinery supply chain?*

To answer this question two sub questions are formulated:

1. *What is the optimal organisation of the circular grass refinery supply chain?*
2. *What is the potential of grass protein products in animal feed compared to imported soybean meal?*

The answers to these questions are found by using literature of other researchers in this subject and by describing the circular grass refinery supply chain in a mathematical model which is applied on a case study.

2 Background information

2.1 Grass refinery in the Netherlands

During the last twenty years grass refinery is widely explored especially in countries were a lot of grassland is located. Due to rainy springs and no dehydrated summers many farmers noticed a higher yield per hectare grassland over the last years (Didde, 2012). Basically it could be economically attractive when the additional yield could be sold. But when all farmers in the region have overflowing amounts of grass then the sale of fresh grass is not an option. Therefore some farmers, scientists and entrepreneurs started investigations towards other options. Some interesting developments are described in this section.

Avebe

During the 1990s researchers investigated on systems where grass could be transferred into several products without any use of cows. They wanted to exclude the cow from the system because the digestion of a cow is not very efficient (Koopmans, 2014). Many nutrients in grass will end up straight in the cow's manure. The result of those investigations was the first grass factory in the Netherlands at Avebe in Veendam in 1998 (Didde, 1999). Avebe is a manufacturer of potato starches for food, building, adhesives, paper, textiles and animal feed industries. The potato factory of Avebe is dependent on the harvest time of potatoes, i.e. the potato harvest campaign, and accordingly the factory will only be in operation between August and March (Avebe, 2015, 2016). A grass factory could be a solution to pad out the year. The capacity of that first installation was one tonne fresh grass per hour (Didde, 1999). The researchers were very enthusiastic about the obtained products, but unfortunately the grass factory did not fit in the policy of Avebe and the production had to stop (Reinshagen, 2011).

Grassa!

In 2006 some initiators started a test concerning the treatment of grass in Friesland. They fractionated the fresh grass and damaged the grass cells to split the protein juice from the fibres (Didde, 2012). The fibres could directly be used in the paper industry, but for the protein juice more research was needed. Gradually more amounts of protein product were separated through heating up the juice which leads to the coagulation of the protein (Bongen, 2014). This protein product has a neutral taste, which is very positive, because other protein sources such as soy or wheat have a foul taste (Didde, 2012), which have to be removed by food technologists. The protein product from the Grassa! installation is used in animal feed, but also other purposes could be possible in the future.

Figure 4: Grassa! mobile installation for biorefinery; introduced in 2016 (Ingenieur, 2016)

In recent years some new Grassa! refinery installations are introduced which are more efficient and mobile (Ingenieur, 2016). The newest installation is presented in figure 4. The big advantage of those mobile installations is that the biorefinery can take place wherever it is needed. This can decrease to number of inefficient movements of products and also small amounts of grass can be refined in an economically attractive way. Some pilots are running with the refinery of several kinds of biomass, such as reed and leaves of beets and cucumbers. If these pilots are completed successfully then the refinery installations of Grassa! could be widely used.

NIZO Food Research

NIZO Food Research in Ede is an independent company that develops food technologies for the global food industry and related markets. One of their businesses is about the proteins in grass and other biomass. Some of their researchers investigated the opportunities to isolate the protein Rubisco from the grass juice after biorefinery (Didde, 2012). Rubisco is an enzyme that incorporates CO_2 into plants during photosynthesis (Jensen, 2000). If this protein is isolated then it can be used in human food industries as ingredient in sauces, soups and desserts (Didde, 2012). In that way grass can be made available for human consumption which can increase the value of grass.

HarvestaGG

The company HarvestaGG in Lelystad works on processes to convert grass and other biomass to sustainable high-grade products. The company introduced a concept which is a closed cycle with sustainable products (HarvestaGG, 2016). Similar to the Grassa! concept HarvestaGG separates the grass juice from the fibres. The grass juice is further manufactured into animal feed as well, but the fibres are worked in a different way. First the fibres are mixed with fresh or ensilaged grass and then this mixture is dried for three weeks. Due to fermentation certain biogas is formed which can be upgraded to fuels or to CO_2 for greenhouse cultivation.

2.2 Pig feed

In the supply chain in this study the products of the refinery are protein product, fibres, whey and phosphate. The most important purpose is animal feed made from the protein product. The total demand for pig feed at all pig farms is the actuating force in the circular supply chain, i.e. if there is no demand for pig feed then the supply chain is not in operation in the defined form. To reach the demand for pig feed the feed factory has to produce enough nutritional feed. This feed has to meet certain requirements about protein and energy value. Currently, it becomes more important to know about the characteristics of possible ingredients for pig feed. This is due to the increasing number of possible ingredients for animal feed and there is more competition from other industries, e.g. biofuels and food (Noblet, 2013). At the feed factories in the defined circular supply chain the focus will be on the requirements for protein content in pig feed. Protein is an essential component of pig feed, because pigs need it for growth and development of muscle tissue.

2.3 Protein sources

Nowadays, soy is the main protein source for animal feed in the Netherlands. Nevertheless it is more sustainable to develop alternative protein sources for animal feed, because of negative environmental and social impacts of the soy production in South America, such as deforestation, violence and soil erosion. There are some different solutions for the replacement of soy, which will be described below. In this work only the solution concerning grass protein will be researched further.

- **Increasing protein content in existing crops**
  Cultivating crops in the Netherlands such as wheat and corn are suitable for animal feed. These crops are widely available and have a high energy content. When the protein content in those crops can be increased by for example changes in genetics, a higher amount of those widely available crops can be used for the production of animal feed. This could decrease the necessity for other protein rich materials such as soy.

- **Improved protein extraction from cultivated seeds**
  Seeds such as rapeseed and sunflower seeds are mainly cultivated for the production of oil. The residual product after the extraction of oil is protein rich. This product is already used in animal feed, but it is not suitable for all animal categories and therefore this may not be optimal at this point. When it becomes possible to extract the protein fraction from the residual product more animals can be fed with locally produced protein which will decrease the need for imported soy products.

- **Cultivation of protein rich crops in Europe**
  Despite the unsuitable European environmental conditions to cultivate soy, approximately an amount of 400,000 hectares of soy is grown in Europe today (Schreuder and de Visser, 2014). The quality of the soybeans from European soil are comparable with the imported soybeans, but the yield per hectare has to increase to make this cultivation more economic attractive.

There are also other protein rich crops such as peas, lupines and beans which can be grown in Europe. To increase the European production of these crops further improvement on the sensitivity to diseases and on the yield of these crops is necessary. It is important to investigate the perspectives of these crops to make it profitable enough for farmers to replace their current crops by these protein rich crops.

Grass is also a protein rich crop which is already cultivated in Europe for fodder purposes, especially for cows. The protein content of grass is about 15 % (Honkoop and Aarts, 2015), but cows are not able to digest that protein in an efficient way. They have a protein efficiency of 24 % (Koopmans, 2014), which is due to the high amount of rumen degradable protein in grass. To use the protein content of grass more efficient the cow can be excluded from the chain. An option to digest grass is to refine it into several products. After the refinement the protein fraction can be used in feed for pigs or poultry, which can have a protein efficiency up to 45 % (Koopmans, 2014). The cows will be fed with the fibres product that comes out of the refinery. The fibres still contain 10 % of protein which is now more efficiently accessible for the cow to digest (Sanders et al., 2016) i.e. their protein efficiency will rise slightly to 27 % (Koopmans, 2014).

- **Cultivation of crops outside the current European agricultural area**
  Another solution is the cultivation of crops which do not use arable area and which are therefore not competitive with arable crops. These cultivars, for example algae, duckweed and seaweed, are very productive and efficient in protein production. Currently the cultivation of these crops for animal feed needs further research. The processing step, i.e. the drying step, is too expensive due to the high water content in these protein sources (van Krimpen et al., 2013).

  Insects, which can grow without the use of arable area, are also a good protein source to replace soybean meal in animal feed, due to their high crude protein content of 42 to 63 % (Makkar et al., 2014). To make the production of insects for animal feed feasible, processing techniques need to be developed further and some legislative constraints need to be solved (Veldkamp et al., 2012).

3 Methods

3.1 Model description

In figure 5 the schematic overview of the studied circular grass refinery supply chain is presented. This supply chain is a reduced form of the earlier mentioned supply chain, which had more options and streams. Although in this study the supply chain from figure 5 is used which is more limited but still realistic for the Dutch agriculture. The extensive form could always be implemented in the model of this study.

Four different facilities are involved in the supply chain: dairy farms, grass refineries, feed factories and pig farms. Between these facilities several streams are drawn, which make three loops of recirculation: whey, fibres and manure. Besides there is an input of soy protein and an output of phosphate. The stream soy protein is equivalent to the input of imported soybean meal to this supply chain. The phosphate stream is formed due to the separation of phosphate from the remaining whey. Less phosphate in the whey is advantageous for the overflowing amount of phosphate in the Dutch soil. The phosphate fraction from grass refinery could be sold, however in this study only the amount of product is calculated.

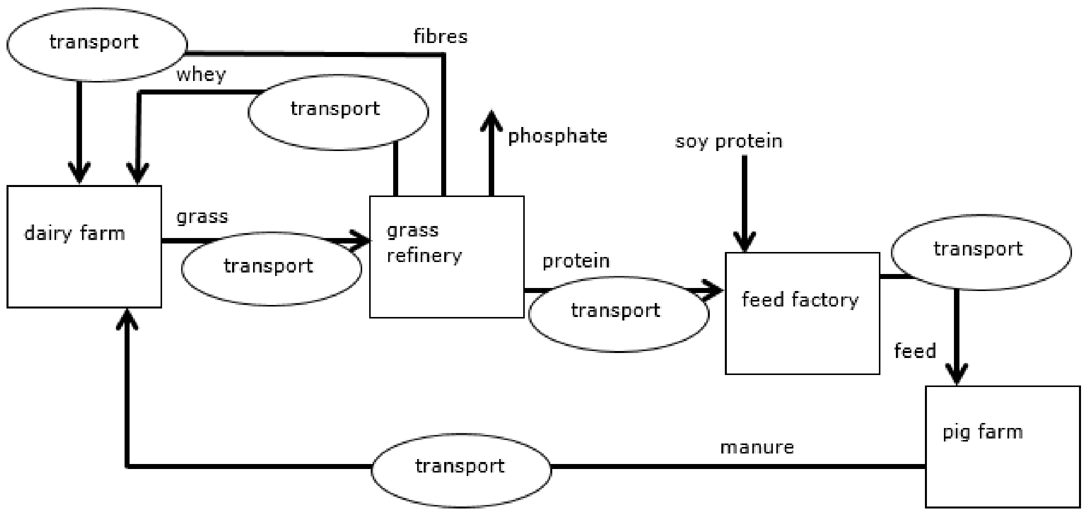

Figure 5: schematic overview of the studied circular grass refinery supply chain

The circular supply chain from figure 5 is transformed into a mathematical model with the option to include many dairy farms, grass refineries, feed factories and pig farms on certain locations in a certain region. The feasibility of the circular supply chain is explored by minimizing the total costs. These costs consist of processing costs made at different facilities, transportation costs for transport of products between different locations, and the acquisition costs for the input soy protein. The objective of minimizing the total costs is optimized with respect to many decision variables and constraints. The used indices, decision variables and parameters of the model are described in section 3.1.1 until 3.1.3.

3.1.1 Indices

The model consists of four different facilities which have their own indices, see table 1.

Table 1: Indices of the model

Index	Description
I	Index for dairy farms
J	Index for biorefineries
K	Index for feed factories
L	Index for pig farms

3.1.2 Decision variables

The decision variables of the model with their description are presented in table 2. The first six decision variables are about the optimal amount of a product (assigned with X, Y, Z, U, V and W) which is transported between two specific facilities (assigned with i, j, k and l). Then there is a binary variable (B_j) which decides whether a biorefinery will be operational or not. The last two decision variables involve the optimal level of used soybean meal in feed factory K and produced phosphate at biorefinery J. The lower bound of all decision variables is equal to 0, the upper bound is defined with several constraints for each decision variable.

Table 2: Decision variables with description

Variables	Description	Unit
$X_{i,j}$	Optimal amount of grass transported from dairy farm I to biorefinery J	[tonne]
$Y_{j,k}$	Optimal amount of protein product transported from biorefinery J to feed factory K	[tonne]
$Z_{k,l}$	Optimal amount of feed transported from feed factory K to pig farm L	[tonne]
$U_{j,i}$	Optimal amount of fibres transported from biorefinery J to dairy farm I	[tonne]
$V_{j,i}$	Optimal amount of whey transported from biorefinery J to dairy farm I	[tonne]
$W_{l,i}$	Optimal amount of manure transported from pig farm L to dairy farm I	[tonne]
B_j	Binary decision variable for open or close a biorefinery J	[-]
SOY_k	Optimal amount of soybean meal used in feed factory K	[tonne]
$PHOSPHATE_j$	Produced amount of phosphate at biorefinery J	[tonne]

3.1.3 Parameters

To calculate the optimal values for the decision variables several parameters are introduced in the model. These parameters concern the locations of the facilities and the distances between them, the transportation, processing and acquisition costs of the several parts of the circular supply chain, the conversions from one product to another and the capacities of the facilities. All parameters are presented in table 3. Values for these parameters are found in literature, from other researchers or from Dutch companies in the agricultural sector.

Table 3: Parameters with description

Parameters	Description	Unit
$DMDl_l$	Demand for feed at pig farm L	[tonne]
$DIJ_{i,j}$	Distance between dairy farm I and biorefinery J	[km]
$DJK_{j,k}$	Distance between biorefinery J and feed factory K	[km]
$DKL_{k,l}$	Distance between feed factory K and pig farm L	[km]
$DLI_{l,i}$	Distance between pig farm L and dairy farm I	[km]
TCtippertruck	Transportation costs with a tipper truck	[€/tonne/km]
TCbulktruck	Transportation costs with a bulk truck	[€/tonne/km]
PCgrass	Processing costs of grass per tonne grass	[€/tonne]
PCrefinery	Processing costs at a refinery per tonne grass	[€/tonne]
PCfeed	Processing costs of feed per tonne feed	[€/tonne]
PCmanure	Processing costs of manure per tonne manure	[€/tonne]
ICsoy	Acquisition costs of soybean meal	[€/tonne]
$Xdairyfarms_i$	X-coordinate of dairy farm I	[-]
$Ydairyfarms_i$	Y-coordinate of dairy farm I	[-]
$Xrefineries_j$	X-coordinate of biorefinery J	[-]
$Yrefineries_j$	Y-coordinate of biorefinery J	[-]
$Xfeedfactories_k$	X-coordinate of feed factory K	[-]
$Yfeedfactories_k$	Y-coordinate of feed factory K	[-]
$Xpigfarms_l$	X-coordinate of pig farm L	[-]
$Ypigfarms_l$	Y-coordinate of pig farm L	[-]
a	Conversion factor for grass into protein product	[kg/kg]
b	Conversion factor for grass into fibres	[kg/kg]
d	Conversion factor for grass into whey	[kg/kg]
e	Conversion factor for protein into feed	[kg/kg]
f	Conversion factor for feed into manure	[kg/kg]
g	Conversion factor for grass into phosphate	[kg/kg]
$CapDairyfarms_i$	Capacity of producing grass for biorefinement at dairy farm I	[tonne]
$CapBiorefinery_j$	Capacity of producing protein at biorefinery J	[tonne]
H	Required used fraction of biorefinery's capacity	[-]
$CapFeedfactory_k$	Capacity of producing feed at feed factory K	[tonne]
$CapManure_i$	Capacity of receiving manure at dairy farm I	[tonne]
$CapFibres_i$	Capacity of receiving fibres at dairy farm I	[tonne]

3.2 Mathematical model

Several equations are set up in the model with the decision variables and parameters supported by the indices. These equations are described in sections 3.2.1 and 3.2.2. The equations which belong to the part of constraints are indicated in section 3.2.3.

3.2.1 Calculation of the costs

In this study the goal of the optimisation is to minimize the considered total costs of the circular grass refinery supply chain. The item total costs contains three kinds of costs; transportation costs, processing costs and acquisition costs.

$$total\_costs = total\_transportation\_costs + total\_processing\_costs + acquisition\_costs \quad [€] \quad 3.1$$

Transportation costs

Transportation costs concern the amounts of transported products multiplied by the price for transport of one ton product over one kilometre multiplied by the distances. For the transport of grass a tipper truck is used, while the other products are transported with a bulk truck. The transportation costs for all product streams are summed to the total transportation costs.

$$\begin{aligned} total\_transportation\_costs &= \sum_{i,j} TCtippertruck * X_{i,j} * DIJ_{i,j} + \sum_{j,k} TCbulktruck * Y_{j,k} * DJK_{j,k} \\ &+ \sum_{k,l} TCbulktruck * Z_{k,l} * DKL_{k,l} \\ &+ \sum_{l,i} TCbulktruck * W_{l,i} * DLI_{l,i} \\ &+ \sum_{j,i} TCbulktruck * V_{j,i} * DIJ_{i,j} + \sum_{j,i} TCbulktruck * U_{j,i} * DIJ_{i,j} \end{aligned} \quad [€] \quad 3.2$$

Processing costs

The processing costs are made up of the amounts of produced products multiplied by the processing costs per ton input or output at the production facility. For all different facilities this cost item is summed to the total processing costs of the circular supply chain.

$$\begin{aligned} total\_processing\_costs &= \sum_{i,j} PCgrass * X_{ij} \\ &+ \sum_{i,j} PCrefinery * X_{i,j} + \sum_{k,l} PCfeed * Z_{k,l} + \sum_{l.i} PCmanure * W_{l,i} \end{aligned} \quad [€] \quad 3.3$$

Acquisition costs

The mentioned acquisition costs are for the acquisition of additional soybean meal coming from South America. This cost item is made up of the amount of imported soybean meal multiplied by the price for soybean meal.

$$acquisition\_costs = \sum_{k} SOY_k * ICsoy \quad [€] \quad 3.4$$

3.2.2 Calculation of the distances

Transportation is an important cost item in the circular supply chain. The costs for transportation are dependent on the distances between different facilities. These distances are calculated by using the Pythagorean theorem, presented in equation 3.5. The calculations of the distances in this study are specified in equation 3.6 till 3.9.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}a \qquad [\text{km}] \quad 3.5$$

$$DIJ_{i,j} = \sqrt{\left(Xdairyfarms_i - Xrefineries_j\right)^2 + \left(Ydairyfarms_i - Yrefineries_j\right)^2} \qquad \forall\, i,j \quad [\text{km}] \quad 3.6$$

$$DJK_{j,k} = \sqrt{\left(Xrefineries_j - Xfeedfactories_k\right)^2 + \left(Yrefineries_j - Yfeedfactories_k\right)^2} \qquad \forall\, j,k \quad [\text{km}] \quad 3.7$$

$$DKL_{k,l} = \sqrt{(Xfeedfactories_k - Xpigfarms_l)^2 + (Yfeedfactories_k - Ypigfarms_l)^2} \qquad \forall\, k,l \quad [\text{km}] \quad 3.8$$

$$DLI_{l,i} = \sqrt{(Xpigfarms_l - Xdairyfarms_i)^2 + (Ypigfarms_l - Ydairyfarms_i)^2} \qquad \forall\, l,i \quad [\text{km}] \quad 3.9$$

3.2.3 Constraints

It is important to define the limitations of the decision variables in a model. The lower bound in this study is always equal to 0, but the upper bound has to be defined with several constraints. The used constraints are about conversions, capacities and the ground for opening another biorefinery.

Conversions

Six different conversions are considered in the circular grass refinery supply chain in this study. Four conversions are performed at the biorefineries, one at the feed factories and one at the pig farms. For each conversion a corresponding factor is introduced (a, b, d, e, f and g). The constraints about conversions are specified in equations 3.10 till 3.15.

Conversion from grass to protein product:

$$\sum_k Y_{j,k} = a * \sum_i X_{i,j} \qquad \forall\, j \quad 3.10$$

Conversion from protein product and soybean meal to feed:

$$\sum_l Z_{k,l} = e * \left(\sum_j Y_{j,k} + SOY_k\right) \qquad \forall\, k \quad 3.11$$

Conversion from grass to fibres: $$\sum_i U_{j,i} = b * \sum_i X_{i,j} \quad \forall\, j \qquad 3.12$$

Conversion from grass to whey: $$\sum_i V_{j,i} = d * \sum_i X_{i,j} \quad \forall\, j \qquad 3.13$$

Conversion from grass to phosphate: $$PHOSPHATE_j = g * \sum_i X_{i,j} \quad \forall\, j \qquad 3.14$$

Conversion from feed to manure: $$\sum_i W_{l,i} = f * \sum_k Z_{k,l} \quad \forall\, l \qquad 3.15$$

Capacities

The different facilities in the circular supply chain have to work with some capacities which have to be added in the model. The dairy farms, biorefineries and feed factories have certain processing capacities and the dairy farms and pig farms have certain capacities for reception and consumption of products. The corresponding capacity constraints are presented in equations 3.16 till 3.21.

Capacity of producing grass for biorefinement at a dairy farm: $$\sum_j X_{i,j} \leq CapDairyfarms_i \quad \forall\, i \qquad 3.16$$

Capacity of processing grass at a biorefinery: $$\sum_i X_{i,j} \leq CapBiorefinery_j \quad \forall\, j \qquad 3.17$$

Capacity of producing feed at a feed factory: $$\sum_l Z_{k,l} \leq CapFeedfactory_k \quad \forall\, k \qquad 3.18$$

Capacity of receiving manure at a dairy farm: $$\sum_l W_{l,i} \leq CapManure_i \quad \forall\, i \qquad 3.19$$

Capacity of consuming fibres at a dairy farm: $$\sum_j U_{j,i} \leq CapFibres_i \quad \forall\, i \qquad 3.20$$

Demand for feed at a pig farm: $$\sum_k Z_{k,l} = DMDl_l \quad \forall\, l \qquad 3.21$$

Location of the biorefineries

In a certain region there are many options to locate a biorefinery and moreover the number of operational biorefineries is dependent on several issues. In the model the possible locations are set as an input together with some information about the capacity. The output of the model is at which location a biorefinery facility will be set. To make that output there is a choice at each possible location to have a biorefinery or not. This choice is assigned with a binary decision variable, B_j. If B_j is equal to 1 then that location will have an operational biorefinery, with B_j is equal to 0 no biorefinery will be set on that location. This part of the model is presented in equation 3.22. Besides another parameter was introduced, factor H in equation 3.23. This factor can be used to make sure that a certain part of the biorefinery's capacity is used for production, when you want to avoid that a biorefinery is not operating most time of the day. Only the processing of grass is assigned with the factor H. Constraint 3.23 can be excluded if H is set on 0.

Open or close a biorefinery: $$\sum_i X_{i,j} \leq CapBiorefinery_j * B_j \quad \forall j \qquad 3.22$$

Minimum of capacity: $$\sum_i X_{i,j} \geq H * CapBiorefinery_j * B_j \quad \forall j \qquad 3.23$$

Objective function

The objective function in this model is to minimize the total costs of the circular grass refinery supply chain in the Netherlands. The specification of the total costs is described above. Besides the total costs the objective function contains another small cost item. This is to denote that there are investment costs for opening a new biorefinery facility. With this part of the objective function only operational biorefineries will be located in the region.

$$minimize\ (total\_costs + 0.0001 * \sum_j B_j) \qquad 3.24$$

3.3 Data description

This section contains the description of the used values for each parameter. This data is from literature, other researchers or Dutch companies in the agricultural sector.

3.3.1 Conversion factors

Processes in the studied supply chain are working in accordance with the corresponding chemical and biological properties of those processes. The conversion factors that describe the ratio between inputs and outputs, i.e. to complete mass balances, are given in the next sections.

Grass refinery

The conversion of grass into the products of the grass refinery is studied by Honkoop and Aarts (Honkoop and Aarts, 2015). The grass they used for the biorefinement consisted of about 18 % dry matter, from which 20 % is refined to a protein product, 66 % to fibres, 12 % to whey and 2 % to phosphate (Honkoop and Aarts, 2015). With these values and the dry matter content of each product the conversion factors are calculated. Those conversion factors are used in this work to describe the processes at the grass refinery facilities and are presented in table 4.

Table 4: Conversion factors at the grass refinery

Product (conversion factor)	Percentage of 18 % DM grass	DM content product	Calculation	Conversion factor [kg product / kg grass]
Protein product (a)	20 %	25 %	0.18*0.20*100/25 = 0.144	0.15
Fibres (b)	66 %	35 %	0.18*0.66*100/35 = 0.339	0.35
Whey (d)	12 %	5 %	0.18*0.12*100/5 = 0.432	0.43
Phosphate (g)	2 %	5 %	0.18*0.02*100/5 = 0.072	0.07

Feed factory

Besides the biorefinery there are more conversions in the circular grass refinery supply chain which are important to consider in this study. The first conversion after the biorefinery takes place in the feed factory where a protein product and other ingredients will be assimilated into animal feed. In general pig feed about 20 % of the ingredients can be soybean meal (Ingels, 2013) and because the grass protein product is comparable to soybean meal the same applies for the grass protein product. Therefore the corresponding conversion factor in the model is equal to 5 kg feed per kg grass protein product, which means that one unit of protein product leads to five units of pig feed.

Pig farm

The last conversion which is considered in this study takes place at the pig farms. The pigs are fed with the pig feed and due to digestion they produce manure. In the Netherlands about 4.96 million tonne pig feed is consumed in 2015 (van Boekel, 2016) and some 9.877 million tonne pig manure was produced (CBS, 2016f). This brings us to a conversion factor of 2 kg manure per kg feed.

3.3.2 Coordinates and distances

In the circular grass refinery supply chain many dairy farms, biorefineries, feed factories and pig farms can be located somewhere. These locations are presented with X- and Y-coordinates which are set between a lower and an upper bound dependent on the size of the studied area and the distribution of different facilities.

The model can calculate the shortest distance by using the X- and Y-coordinates and the Pythagorean theorem (see equations 3.6 until 3.9). The distances are in a straight line and are presented in kilometres.

3.3.3 Total costs

The total costs of the circular supply chain consist of the total processing costs, the total transportation costs and the acquisition costs for soybean meal. The parameters, which are in the equations to calculate the costs, with their corresponding values are shown in table 5.

The total processing costs of the circular supply chain consist of the costs for producing grass at the dairy farms including labour, seeding and fertilizer (PCgrass); total costs for refining grass into protein, fibres, whey and phosphate (PCprotein), i.e. processing costs at a grass refinery;

costs for producing feed at the feed factories including labour and energy (PCfeed); and costs for the disposal of manure (PCmanure).

The usage of soybean meal from South America leads to acquisition costs which are presented as ICsoy. This is the total price a feed factory has to pay when buying soybean meal. Transport to the feed factory is included.

The total transportation costs consist of the costs for transporting grass, fibres, whey, grass protein, feed and manure. There are two kinds of trucks which can transport different products; the tipper truck (TCtippertruck) can transport only grass and the bulk truck (TCbulktruck) can transport the other products. The transportation of soy to the Netherlands is not included in the total transportation costs of the circular supply chain, but is included in the parameter ICsoy.

Table 5: Values for the costs parameters

Parameter	Description	Value
PCgrass	Processing costs of grass	19,62 [€/tonne]
PCrefinery	Processing costs at a refinery	23,76 [€/tonne]
PCfeed	Processing costs at a feed factory	27,30 [€/tonne]
PCmanure	Disposal costs for manure	20,00 [€/tonne]
TCtippertruck	Transportation costs with a tipper truck	1,73 [€/tonne/km]
TCbulktruck	Transportation costs with a bulk truck	1,85 [€/tonne/km]
ICsoy	Costs for buying soybean meal	350,00 [€/tonne]

PCgrass
Grass costs €0,109 per kilogram dry matter (KWIN-V, 2016). Then the costs per tonne of fresh grass are obtained by multiplication with the mass of dry matter (180 kg) in one tonne fresh grass and results in: €19,62 per tonne.

PCrefinery
The processing costs of refining grass into protein, fibres and whey are €120 per tonne dry matter in grass ((Sanders, 2014), Johan Sanders, personal communication, November 10, 2016). In the circular supply chain of this study we also have phosphate as a product. The estimated costs of the phosphate extraction from the whey are €12,- per tonne dry matter in grass, equivalent to the profit value of phosphate ((Sanders, 2014), Johan Sanders, personal communication, November 10, 2016). This results in operation costs of the grass refinery of €132,- per tonne dry matter in grass. Per tonne fresh grass only 18 % is dry matter so only 18 % of €132,- is equal to the price for refining one tonne fresh grass; €23,76 per tonne.

PCfeed
PCfeed is the factor for processing costs at a feed factory. About 12 % of the total processing costs is dedicated to energy consumption; this is equal to €40 million (Nevedi, 2015a). The total processing costs, equivalent to 100 %, are €333 million. The feed factories in the Netherlands produce 12.2 million tonne animal feed in total (Nevedi, 2015b). Accordingly the processing costs for feed are €27,30 per tonne.

PCmanure

Manure is a residual product at pig farms and therefore the greatest part of the processing costs at the pig farms are not a part of this study. But there are specific costs due to the disposal of the manure which are equal to 5 % of the total costs for pig production (Hoste, 2011). Though the price for manure disposal can fluctuate strongly a reference value is introduced; PCmanure, is set to €20,- per tonne manure (Sanders et al., 2016).

TCtippertruck / TCbulktruck

The total costs for transportation depend on the amount of transported product and the distances between different facilities. Transportation of one tonne product in a bulk truck over one kilometre costs €1,85 where transportation in a tipper truck costs €1,73 per kilometre (F. Beurskens, personal communication, November 3, 2016). Grass can be transported in the cheaper tipper truck, the other products will be transported in a bulk truck.

ICsoy

Most of the soy products are import products for the Netherlands. The production of soybeans is mainly located in North and South America (van Gelder and Kuepper, 2012). After harvesting the soybeans will be crushed into soybean meal and soy oil. The soybean meal is a protein rich product which can be used in animal feed. In the Netherlands the acquisition of soybean meal for animal feed costs €350,- per tonne (LEI, 2016).

3.3.4 Capacities

The different facilities in the circular grass refinery supply chain have certain capacities for production or consumption. These capacities can behave as limiting factors in the circular supply chain. In table 6 the corresponding values per day for each capacity parameter are presented.

Table 6: Parameters about capacities

Parameter	Description	Value [tonne/day]
CapBiorefinery	Maximum amount of refined grass	192
CapFeedfactory	Maximum amount of produced feed	200
DMDl	Required amount of consumed feed	3.45
CapDairyfarms	Maximum amount of grass for refinement	8.8
CapManure	Maximum amount of used manure per dairy farm	2.8
CapFibres	Maximum amount of consumed fibres	1.1

Grass refinery

Nowadays the newest grass refinery facility can process up to 8 tonne fresh grass per hour (Wagener, 2014), which leads to a capacity of 192 tonne per day when a 24-hours service is applied. Since the grass refinery facility needs some labour it makes sense to explore about the capacity for example in one shift of 8 hours. This is similar to 33 % of 192 tonne, which as a fraction, 0.33, is a possible value of the parameter H and is set as standard value. This value can be changed to identify the consequences eventually in cooperation with other kinds of biomass.

Feed factory
The feed factories in the model must have a production capacity which is large enough to reach the demand for feed in the defined region. Therefore this production capacity is not a limiting factor in the circular supply chain and is set on 200 tonne feed per day for each feed factory, equivalent to the average production capacity of feed factories in the Netherlands (Nevedi, 2015b; CBS, 2016b).

Pig farm
The capacity of a pig farm depends on the required amount of feed per pig and the number of pigs at a farm. In the Netherlands an average pig consumes 0.45 tonne feed in a year (CBS, 2016e; van Boekel, 2016). An average pig farm consists of 2800 pigs (CBS, 2016e). Therefore the consumption capacity of an average pig farm is 1260 tonne feed per year, which is 3.45 tonne per day. This capacity is equal to the demand for feed at an average pig farm; DMDl.

Dairy farm
At the dairy farms in the defined circular grass refinery supply chain several capacities play an important role; the capacity for production of grass for refinery, the capacity for using manure at grassland and the capacity for consumption of fibres by dairy cows.

The total area of grassland in the Netherlands in 2015 was 956000 hectare (CBS, 2016d). Divided over 18270 dairy farms (CBS, 2016e) this leads to a grassland area of 52.3 hectare per dairy farm. Last years the average annual yield of grassland is 11.1 tonne dry matter per hectare (Feenstra, 2015), which is 61.7 tonne fresh grass. The maximum available amount of grass for refinement is then 3227 tonne per dairy farm in a year, which is 8.8 tonne per day. It is important to keep in mind that this value is based on continuously harvesting during the full year.

In the Netherlands it is allowed to use on average 90 kg phosphate per year at one hectare grassland (EZ, 2014). Average pig slurry manure consist about 4.6 kg phosphate per tonne (den Boer et al., 2012). Therefore the capacity for using manure at dairy farms is 19.6 tonne manure per hectare. An average dairy farm has 52.3 ha grassland (CBS, 2016e, 2016d), which leads to an annual uptake of about 1000 tonne manure per year which is 2.8 tonne manure per day. Whey can also be used as fertilizer but it is not included in the phosphate-based capacity constraint of manure, since the phosphate fraction is separated from the whey. In this study the phosphate fraction will not be used as fertilizer at the defined dairy farms.

From research it is advised to feed cows with a maximum of 4 kg dry matter fibres per day (Klop et al., 2015). Fibres as a product from grass refinery consists for 35 % of dry matter (Honkoop and Aarts, 2015). This leads to a maximum capacity for feeding a cow with fibres of 11.4 kg fibres per day. An average dairy farm in the defined region has 97 dairy cows (CBS, 2016c) and therefore the capacity for feeding fibres at an average dairy farm is 1.1 tonne fibres per day.

3.4 Case study

The model has been applied to a case study which concerns the agriculture in the Netherlands. Several model runs were done to get insight into the potential of the circular grass refinery supply chain in the Netherlands. In these model runs several scenarios are evaluated.

3.4.1 Agricultural region

The potential of the circular grass refinery supply chain in the Netherlands is evaluated by determining a representing region. This region represents a part of the Netherlands as big as 225 km^2 with the relevant farming systems and some potential biorefineries. This specific area is based on the amount of feed factories in the Netherlands, which is 185 (CBS, 2016b) on a total area of 41543 km^2 (CBS, 2016a). The choice for one feed factory in the region of the case study leads to the area of 225 km^2 with the associated number of dairy farms and pig farms, 90 and 20 respectively (CBS, 2016c). The locations of these farms and the factory are randomly assigned to the region and shown in figure 6. The region is presented with X- and Y-coordinates, which are between 0 and 15, comparable to the dimension of 15 km times 15 km.

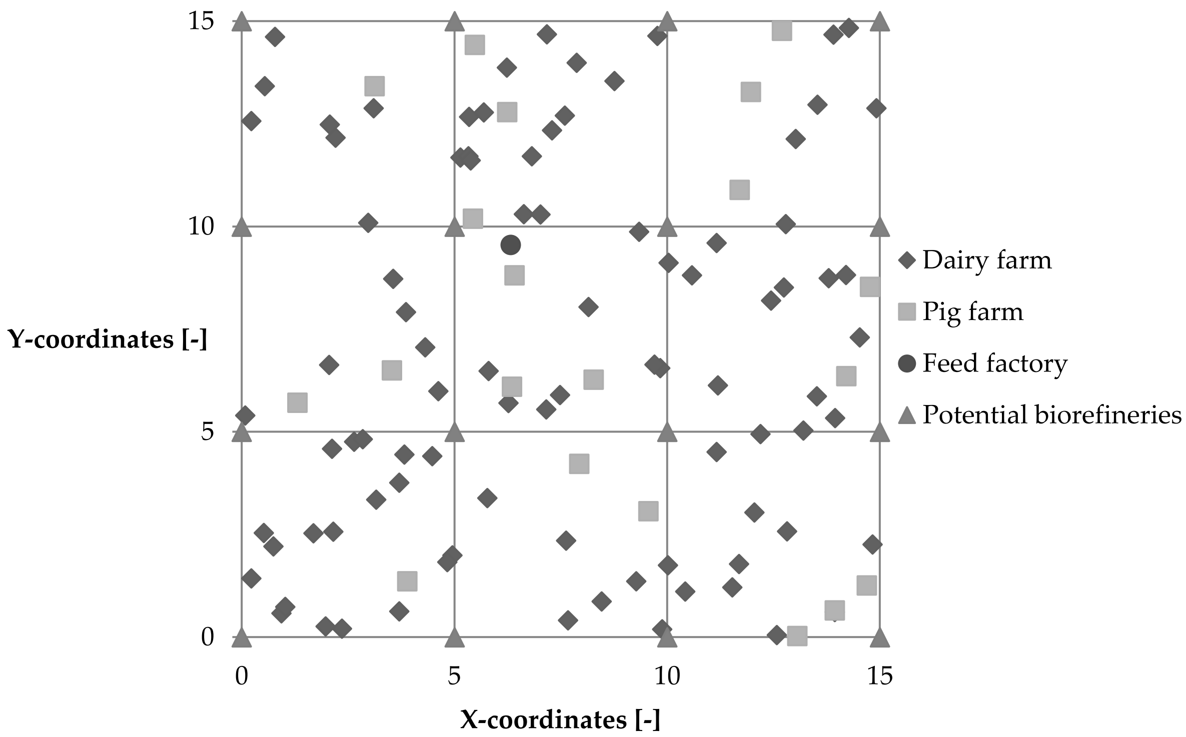

Figure 6: Agricultural region of 225 km^2 which represents a part of the agriculture in the Netherlands

In this region possible biorefinery locations are placed at the crossings of 5-kilometre-gridlines, assigned with triangles in figure 6. While optimizing the model a selection will be made which of these possible locations will have a biorefinery facility for the processing of grass, and which locations will not.

3.4.2 Scenarios

Several model runs were done to investigate the optimal organisation of the circular grass refinery supply chain in the defined agricultural region, evaluated with several scenarios. The specifications of each scenario are described in table 7.

Table 7: Description of the specifications of each scenario

Scenario	Specification of biorefineries
Basic scenario	16 central biorefineries with a capacity of 192 tonne fresh grass per day
Local biorefineries	90 local biorefineries with a capacity of 192 tonne fresh grass per day
Local small biorefineries combined with central large biorefineries	16 central and 90 local biorefineries with a capacity of respectively 1080 and 192 tonne fresh grass per day
Processing costs	16 central and 90 local biorefineries with a capacity of respectively 1080 and 192 tonne fresh grass per day with different processing costs
Soy price	16 local biorefineries with a capacity of 192 tonne fresh grass per day

Basic scenario

The first scenario was based on parameter values which are valid in the current agricultural sector in the Netherlands (listed in table 4, 5 and 6). The study of this scenario was done to know how the circular supply chain is set up under the current Dutch agricultural conditions. Behind this reference scenario some other interesting issues were implemented in the next scenarios.

Local biorefineries

A much-discussed issue in the biorefinery sector is about the location of biorefineries (Bruins and Sanders, 2012). Central located biorefineries could have higher yields and higher efficiency compared to local biorefineries. However local biorefineries could have less transportation, because many products could be used on the original dairy farm. To investigate about the best location two different model runs are applied. The first consists of a scenario where central biorefineries are located at each intersection point of the gridlines (see figure 6) and the second has the option to allocate a biorefinery to each dairy farm. All those biorefineries have the same size, i.e. a capacity of 192 tonne fresh grass per day.

Local small biorefineries combined with central large biorefineries

Central biorefineries work with grass from many dairy farms and therefore they need to be larger than local biorefineries. However local refineries could be technically simple and could have less transportation costs due to less transportation movements. The size difference of the biorefinery installations is investigated in this scenario, which is an extended version of the scenario 'local biorefineries'. At the intersection points of the gridlines large biorefineries could be placed and small biorefineries could be allocated at the dairy farms. As a result there are 106 possible locations for a biorefinery in an area of 225 km^2, 16 central and 90 local facilities. A local biorefinery has a capacity of 192 tonne fresh grass per day, a central facility processes 1080 tonne fresh grass per day. The processing costs of each installation are €23,76 per tonne grass, independent of the capacity.

Processing costs

In the scenario 'local small biorefineries combined with central large biorefineries' the processing costs of each biorefinery installation are set on €23,76 per tonne grass. Nevertheless, central located large refineries could have higher yields and therefore they could produce cheaper per amount of product compared to small local refinery installations. On that account the effect of the processing costs is investigated in this scenario. It is evaluated when it will be attractive to choose for either less transportation costs by using small local biorefineries, or for less processing costs by using large central biorefineries. This issue is investigated in several model runs by lowering the processing costs of the large central biorefineries. The local small biorefineries have processing costs of €23,76 per tonne grass. The parameter H is set on 0.00 in this scenario.

Soy price

The grass protein product is a substitute for imported soybean meal. Therefore the price of soybean meal is an important factor to concern about at the determination of the potential of grass refinery. The last ten years the soybean meal price of imported soy from South America fluctuated between €207,65 till €533,45 per tonne (LEI, 2016). This model run investigated the potential of grass refinery in the Netherlands at a soybean meal price in the range of €200,- and €600,- per tonne. The parameter H is set on 0.00. All other parameters are the same as in the scenario 'basic scenario'.

4 Results

Basic scenario

Figure 7 presents the number of operational central biorefineries in the defined agricultural region dependent on the required minimum used fraction of the capacity at a biorefinery. When the standard capacity constraint of H = 0.33 is applied only one biorefinery will open. If that constraint is relaxed, i.e. when the value for the parameter H is lowered, more central facilities will open.

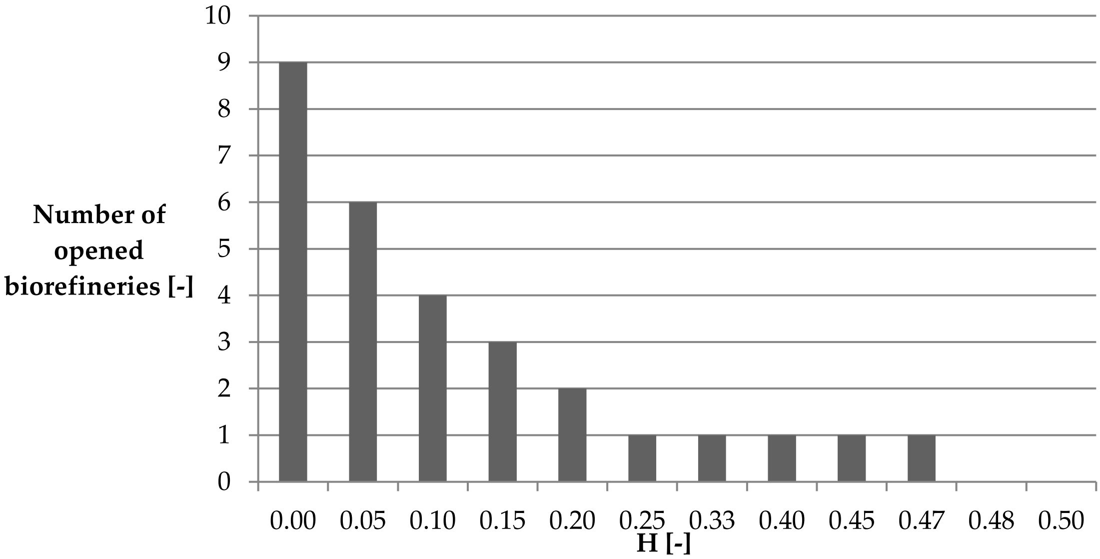

Figure 7: Number of opened central biorefineries as a function of H which is the required minimum used fraction of the biorefinery's capacity

In figure 8 is presented at which central locations a biorefinery will be operational when parameter H is equal to 0.00. At this capacity constraint 9 facilities will open their production.

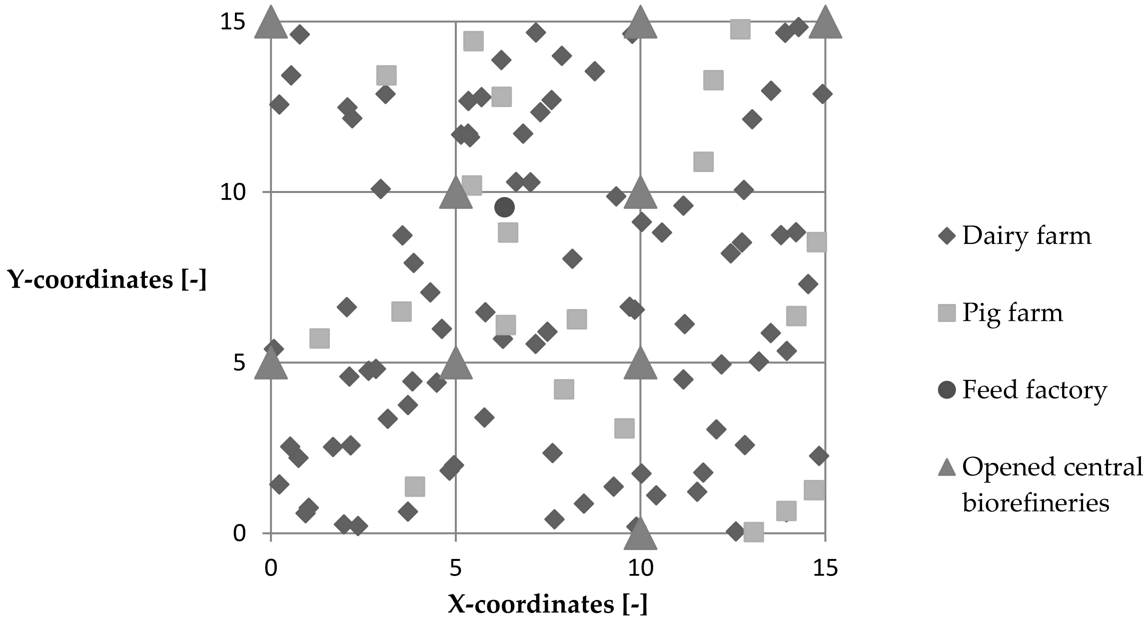

Figure 8: Presentation of the agricultural region at the basic scenario with all operational biorefineries; H = 0.00

Local biorefineries

Figure 9 presents the number of operationals local biorefineries in the defined agricultural region dependent on the required minimum used fraction of the capacity at a biorefinery. When the standard capacity constraint of H = 0.33 is applied only one local biorefinery will be opened, comparable to the basic situation. After decreasing the left hand side of capacity constraint 3.23 more local facilities will be operational.

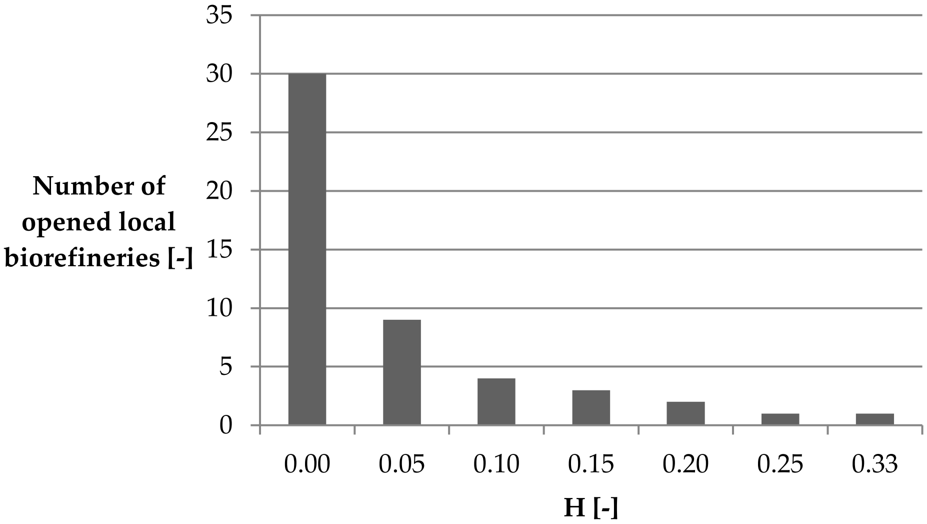

Figure 9: Number of opened local refineries as a function of H which is the required minimum used fraction of the biorefinery's capacity

In figure 10 the opened local biorefineries are presented in the agricultural region when parameter H is equal to 0.00. In this case 30 dairy farms in the agricultural region will have an operational biorefinery on their farmyard. As can be seen in the figure all those biorefineries are located in the middle of the region and nearby to the feed factory.

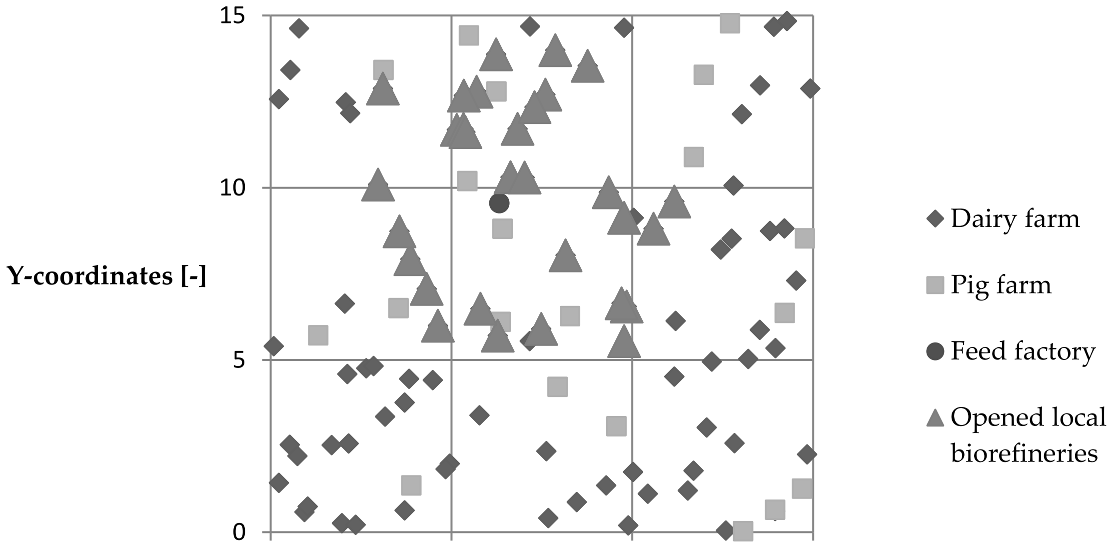

Figure 10: Presentation of the agricultural region especially with opened biorefineries on a dairy farm; H = 0.00

Small local biorefineries combined with large central biorefineries

Figure 11 presents the number of operational large central biorefineries and small local biorefineries in the defined agricultural region dependent on the required minimum used fraction of the capacity at a biorefinery. As can be seen in the graph the preference in the defined agricultural region is to open small local biorefineries above large central facilities.

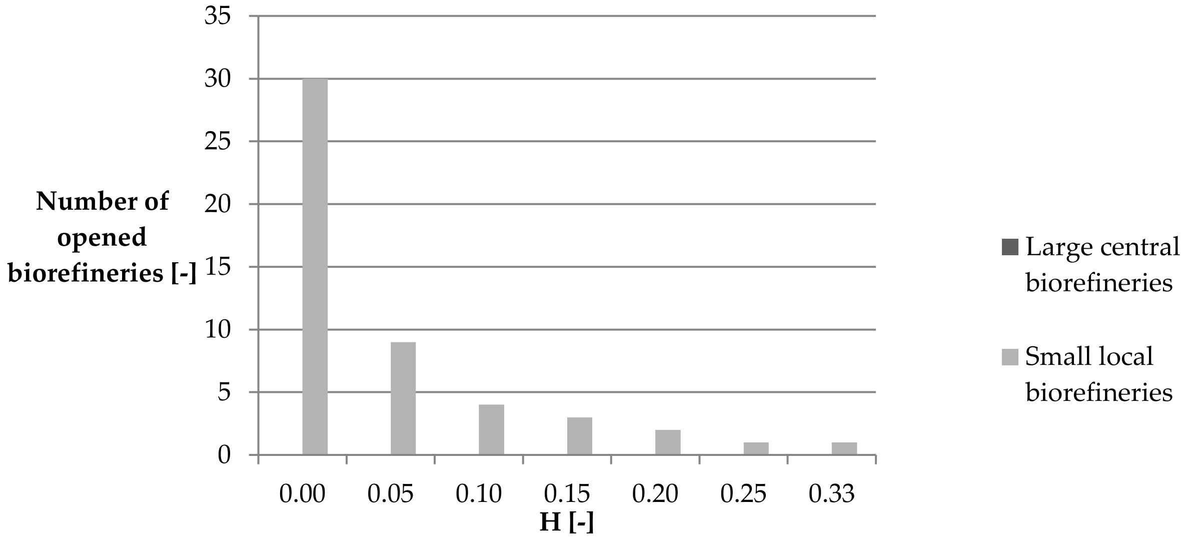

Figure 11: Ratio between opened large central biorefineries and small local biorefineries against the required minimum used fraction of the capacity at a biorefinery

In figure 12 the opened large central and small local biorefineries are presented in the agricultural region when parameter H is equal to 0.00. Only 30 small local biorefineries will be operational in this scenario. These facilities are located in the middle of the region and nearby the feed factory.

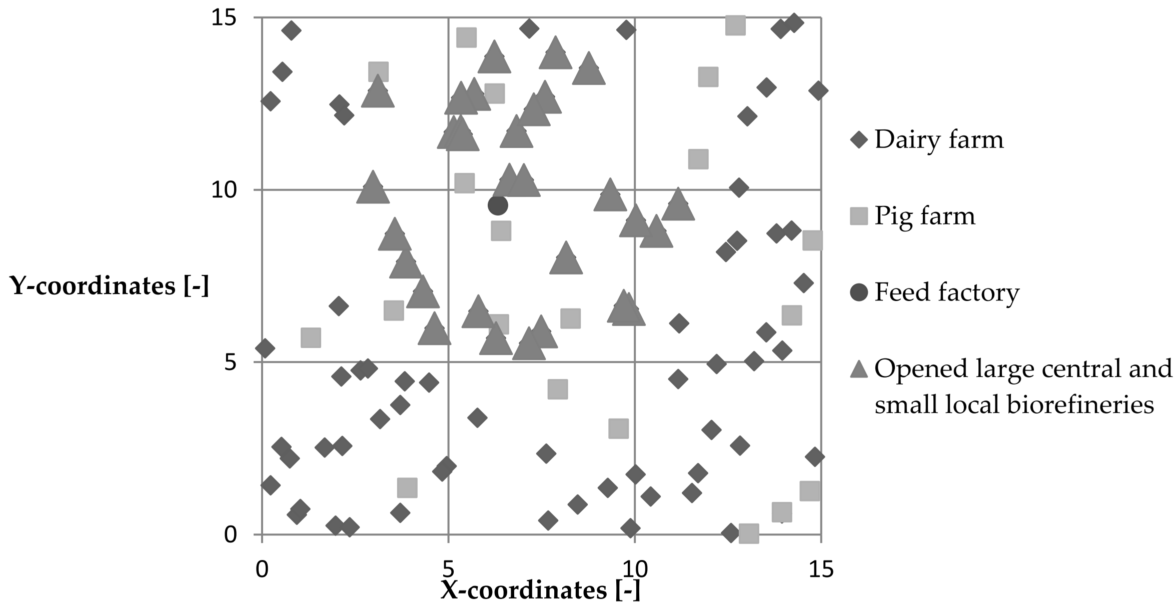

Figure 12: Presentation of the agricultural region where large central and small local biorefineries can be opened; H = 0.00

Processing costs
The processing costs at a standard small biorefinery are equal to €23,76 per tonne grass. However the efficiency of a large central installation can be higher than at small local refineries and therefore the processing costs per unit of product can be reduced compared to small local installations. Figure 13 presents the number of operational large central and small local biorefineries in the defined agricultural region dependent on the processing costs at the large central facilities.

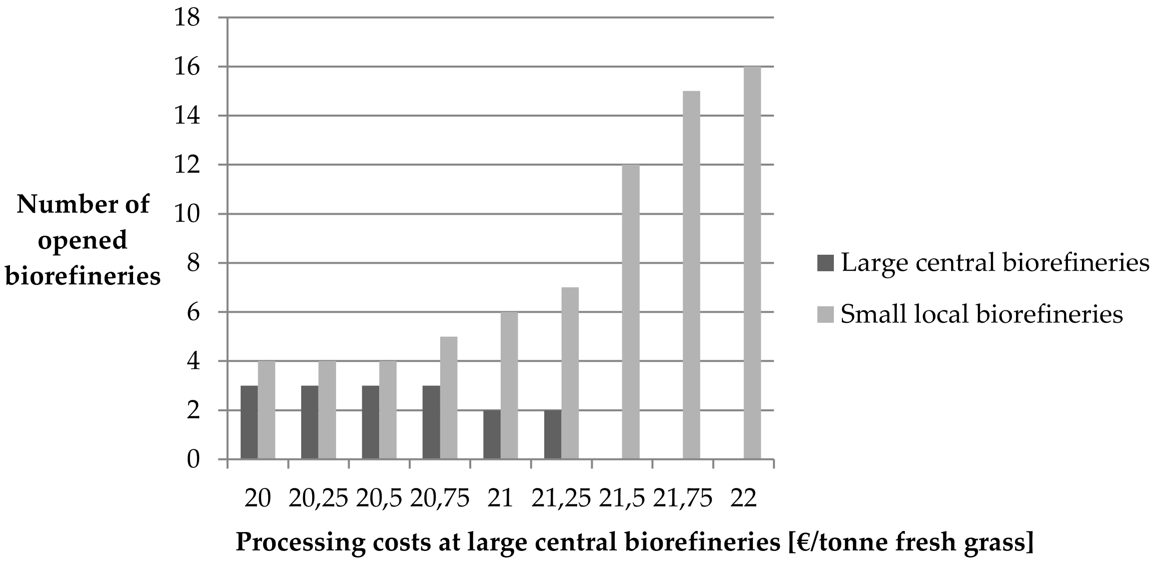

Figure 13: Ratio between large central and small local biorefineries dependent on the processing costs at central biorefineries; processing costs at small local biorefineries are equal to €23,76 per tonne; H = 0.00

As can be seen in the graph above it becomes interesting to open a few large central biorefineries in the defined agricultural region when the processing costs at those facilities are lower than €21,50 per tonne fresh grass. At processing costs of €21,50 per tonne or higher it is more advantageous to open only small local biorefineries which have a higher value for processing costs, €23,76 per tonne, but other costs, e.g. for transportation, are much less in that case.

Soybean meal price

In the defined region for this case study an average soybean meal price of €350,- is used to identify the potential of grass refinery. However the soybean meal price is fluctuating and therefore the potential of grass refinery is identified at different levels of soybean meal prices. The ratio between used grass protein products and soybean meal in the feed factory in this case study is presented in figure 14. The current price of soybean meal is also shown.

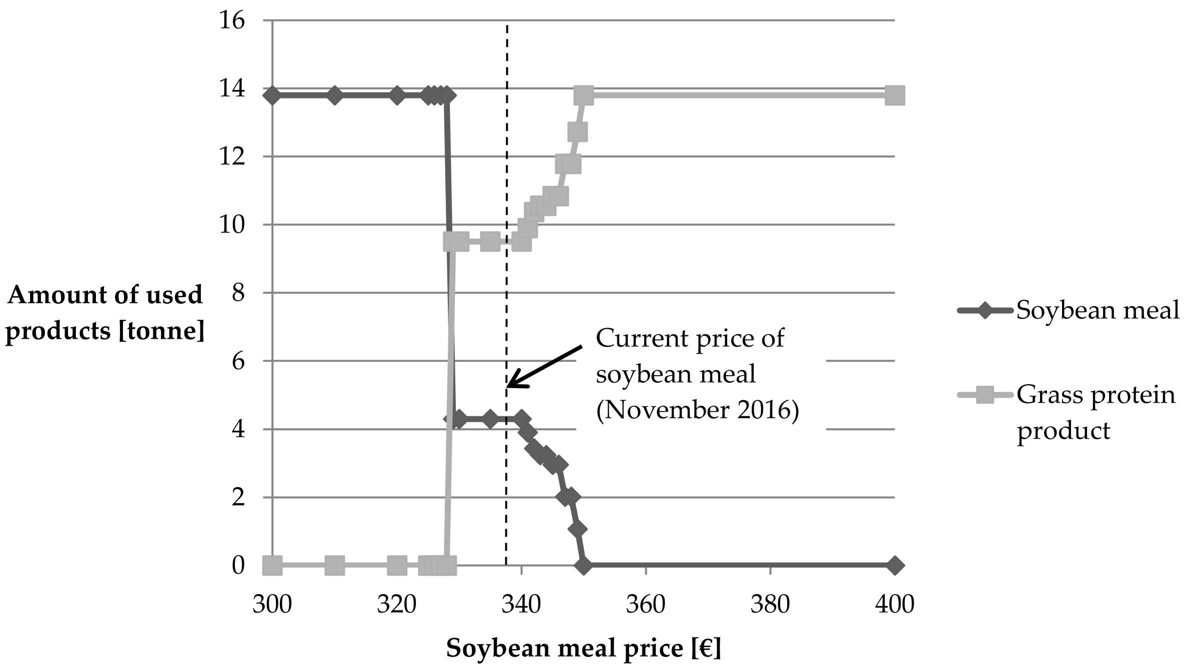

Figure 14: Ratio between grass protein products and soybean meal dependent on soybean meal prices in the Netherlands; H = 0.00

Figure 14 reveals a tipping point at the price of soybean meal whereupon it becomes more and more interesting to use grass protein product in animal feed instead of soybean meal. This point is located at a soybean meal price halfway €320,- and €340,- per tonne. The current price of soybean meal in the Netherlands is €337,45 per tonne which is behind the tipping point and therefore it is interesting to replace a part of the soybean meal in animal feed by grass protein product at this moment in the defined agricultural region.

5 Discussion

This thesis work concerns an initial evaluation of the logistics of the previously defined circular grass refinery supply chain. The material flows and transportation between dairy farms, grass refinery installations, feed factories and pig farms is described with a mathematical model. Several parameters are involved and data is obtained from literature, researchers and companies. Most of the parameters are fixed and are not changed during optimisation. When a parameter is changed during optimisation this is described in the chapter Methods. Something can be said about the differences in importance of parameters principally when the locations of the biorefineries are investigated, because then obviously the item transportation costs is the dominating factor. A sensitivity analysis to check which parameters are the most important and which data could be uncertain is not included in this study. To get insight into the sensitivity of the parameters such analysis should be performed.

In the scenario where both small local biorefineries and large central biorefineries are allowed, the result is that only small local refineries will be in operation. The number of opened facilities is equal to 30, which is the same in the model run called 'local refineries'. The dairy farms as close as possible to the feed factory are chosen to be the locations of a biorefinery, to have low transportation costs. After checking the coordinates of the opened biorefineries the conclusion is that in both model runs exactly the same dairy farms will have an operational biorefinery on their farmyard. Therefore the presentation of the agricultural region is exactly the same in figure 10 and 12. This outcome is due to the fact that the characteristics of both scenarios are basically the same. Central biorefineries are not operational in both scenarios and are therefore excluded from the results. This result is affirmative to the theory of Wageningen UR researchers Bruins and Sanders, who stated that small-scale biorefinery processes can be socially, ecologically and economically beneficial, due to the local re-use of involved materials (Bruins and Sanders, 2012).

In the model the parameter H was introduced to make sure that a biorefinery will only be operational if the production is equal to or more than a certain percentage of the biorefinery's capacity. This percentage or fraction only includes the refinement of grass. It is possible that other kinds of biomass will be processed during the rest of the day. During the optimization was cleared that when H is equal to 0.33, as in the basic situation, the corresponding constraint was severe. Therefore the parameter H was changed to lower values up to and including 0.00. This decrease leads to results with many operational biorefineries but it is important to notice that these installations work on a very low utilisation rate, which in practice may result to infeasible biorefinery installations. A solution could be that other kinds of biomass will be processed during the rest of the day.

The processing costs are investigated in a specific scenario because in practice there can be a difference in processing costs when the production capacity is differentiated. The large central biorefinery facilities in this scenario were not attractive as can be seen in previous scenarios. Therefore the costs for refining grass at a large central facility are lowered towards €20,00 per tonne fresh grass. There is no value for these processing costs from researches or companies but in this study the maximum processing costs for large central grass refineries amounts on €21,50 per tonne. This affirms the estimation that large-scale processing can be attractive when the processing costs are quite lower than at small-scale processing.

The result of the scenario where the soy price is concerned is that currently it is economically attractive to use more grass protein product in pig feed than soybean meal. The costs of all streams in the circular supply chain are involved. The processing costs at the feed factory, the disposal costs of manure and the transport costs of feed and manure are equal, regardless if grass protein product or soybean meal is used in the pig feed. But the differentiation is situated in the other streams. Soybean meal costs only contain the acquisition costs, but in the grass protein costs more units are involved; processing costs for grass and for refinery and transportation costs of grass, grass protein product, fibres and whey. If the grass refinery would be outside the boundaries of the system then the feed factory has to compare the acquisition costs of soybean meal and grass protein product. Nevertheless the current soybean meal price (November 2016) is €337,45 per tonne but grass protein product can be sold for €144,00 per tonne ((Sanders, 2014), Johan Sanders, personal communication, November 10, 2016). This means that if only the acquisition of the products are involved the grass protein product is economically more attractive than soybean meal.
In practice grass protein product is not already broadly used in animal feed instead of soybean meal. Probable other factors influences the choice of feed factories between both raw materials. At first in this study is assumed that the grass protein product can replace soybean meal, which is correct if you compare the protein content and composition. Nevertheless other nutritional values, such as energy content, sugars and lipids, can be various between both raw materials. And then when concerning the nutritional values over the prices feed factories maybe make other choices for useable raw materials. It would be interesting to evaluate the differences in prices and nutritional values of many alternative raw materials, which would be a study related to this work.
Another reason can concern the practical side of grass refineries in the current agricultural system. If there is not enough grass available to have an operational biorefinery, or the investment costs are too high compared to the revenues, or there is no market for all products, then there are negative factors which can counteract the possibilities of grass refinery as assumed in this study.

In the objective function of this model the main target is to minimize the considered total costs of the circular grass refinery supply chain. Costs for transportation, processing and acquisition were included, but this could be expanded with costs for investments or storage for example.
Another option to expand the model of the defined supply chain is to include the revenues, which could be earned when the phosphate fraction and the grass fibres from the biorefineries are sold to external companies.
The circular grass refinery supply chain as used in the model is a reduced version, which means that in further research more streams or options could be included, such as the option to make animal feed for more animals than only pigs. In this study not all options are included to reduce the size of the model, but it is interesting to try to take all options into account.
The defined region in the case study of this thesis work is an average of the Dutch agriculture,

but it is possible to define a region which specific characteristics of that specific region to have more appropriate results.

The focus in this study was on the whole defined supply chain and the total costs of that supply chain. Another way is to centralize the different stakeholders in the supply chain. All stakeholders would have different expectations and intentions and therefore the results could differ potentially. When focusing on stakeholders the system could be broadened by including all inputs and outputs of different links of the circular supply chain, e.g. as products from the farms like meat and milk. However in that case multiple objectives of the different stakeholders should be taken into account and it will be difficult to satisfy all stakeholders in the system.

The central biorefineries in the defined agricultural region are allocated at the intersections of the gridlines. In this study four gridlines are positioned over the X-axis and four over the Y-axis. These gridlines are even distributed at coordinates 0, 5, 10 and 15. Normally when using more gridlines a different outcome can be expected. However, in this study in most scenarios no central biorefineries will be operational, except in the basic situation where no other locations are available. Furthermore the distance between the gridlines is just 5 kilometres. Therefore it is not interesting to research the effect of more gridlines which will create more locations nearby the dairy farms. Then the whole effect of local and central biorefineries in the region will disappear.

6 Conclusion

This thesis work concerns an initial evaluation of the logistics of a defined circular grass refinery supply chain. The material flows and transportation between dairy farms, grass refinery installations, feed factories and pig farms is described with a mathematical model. Several parameters are involved and data is obtained from literature, researchers and companies. This optimization model is applied to a case study with several scenarios. One of the scenarios concerns the influence of the soybean meal price. With another scenario the effect of the location of biorefineries and the processing costs of biorefinery facilities are investigated.

Based on the results of the model runs it is concluded that the considered agricultural region in this study can work in an optimal way when some local biorefineries, with processing costs of €23,76 per tonne fresh grass, are in function. Large central possible facilities are only interesting for biorefinery in the defined agricultural region when the processing costs are below €21,50 per tonne fresh grass. If that is realised more large central biorefineries will be operational.

Currently it is interesting to replace a part of the soybean meal in pig feed by the grass protein product from grass refineries. The tipping point at the price of soybean meal whereupon the grass protein product becomes more economically attractive is allocated around €330,00 per tonne soybean meal. The current price in November 2016 is €337,45 per tonne and therefore the conclusion of this study is that the grass protein product has certain potential compared to imported soybean meal.

In general the conclusion of this thesis work is that grass refinery in the defined circular supply chain has certain potential in the Netherlands. It is an interesting concept regarding to the vision of the European Commission and the Dutch government about circular economies and it is probably a good option to reduce the problems due to soy import.
However when the options for a new grass refinery installation at a specific location are investigated more specific research has to be done in advance to make sure that the new installation can operate in an economically attractive way.

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