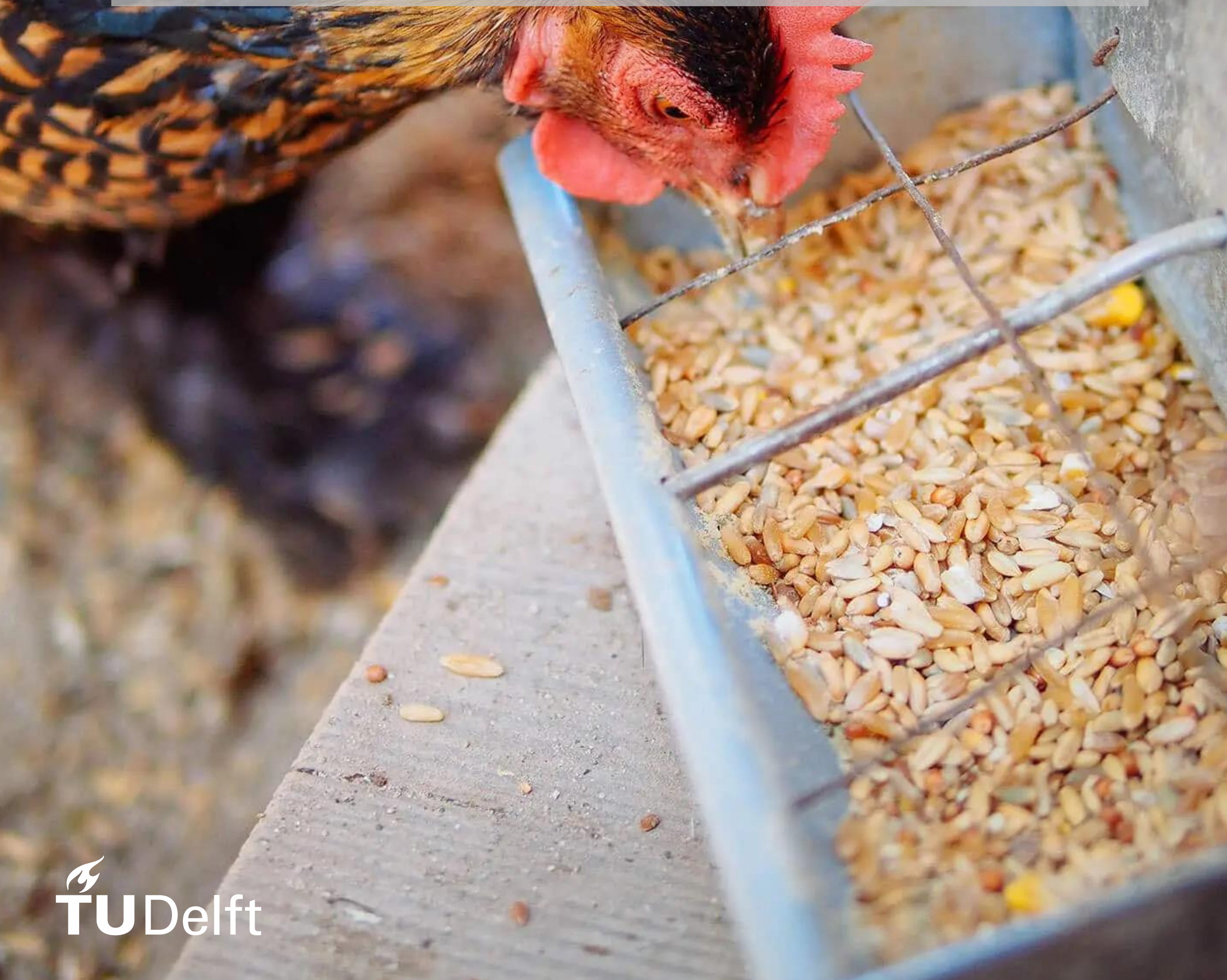
J. N. M. Russell

Measuring the environmental performance of the feed production of the livestock industry

Constructing an environmental performance index from an economic perspective

Delft University of Technology



Measuring the environmental performance of the feed production of the livestock industry

Constructing an environmental performance index from an economic perspective

by

J. N. M. Russell

Thesis

in partial fulfilment of the requirements for the degree of

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Supervisors:	Dr. W.W.A. Beelaerts van Blokland	Delft University of Technology
	Prof. Dr. R.R. Negenborn	Delft University of Technology
	S. Lestiboudois	Deloitte
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Preface

This report is the result of my graduation thesis of the MSc Mechanical Engineering with a specialization in Multi-Machine Engineering at Delft University of Technology. This thesis is written in collaboration with Deloitte. During the graduate internship, I was given the opportunity to explore the future of food and, in particular, the world of livestock feed. The aim of this master thesis project was to contribute to academic literature as well as to practice through a performance measurement study. The study contributes to academics by filling an identified research gap concerning the optimization of livestock feed with regards to environmental sustainability while including both GHG emissions and carbon capture.

Deloitte gave me the opportunity to contribute to research on livestock feed. The livestock industry contributes to global warming massively. This is an extremely relevant topic and I am grateful that they let me dive into this complex and challenging topic.

Naturally, I could not have completed this thesis without the help of others. I would like to express my gratitude and appreciation for this help. Especially, I want to thank Sean Lestiboudois for the opportunity to conduct my thesis internship at Deloitte Supply Chain and Network Operations. His knowledge of the food industry, his enthusiasm and his feedback helped me to get the most out of the project. Futhermore, I would like to thank Agrifirm for sharing their view on circularity and regenerative agriculture in the livestock feed industry. Also, Agrifirm shared their vision on nutritional values of livestock feed and provided the benchmark feed composition for the environmental performance index.
I would like to thank the experts in the feed industry, Agrifirm, Blonk Consultants and Joost Vogtländer, for their contribution to the verification of the model.

I would like thank my graduation committee of the Delft University of Technology for providing excellent guidance throughout the project. First, I would like to express my appreciation for my supervisor, Dr. W.A.A Beelaerts van Blokland. He guided me throughout the whole research in a great way and helped me with the research approach and with his knowledge on performance measurement. Next, I would like to thank Prof. Dr. R.R.Negenborn for the critical feedback during the meetings which helped me greatly to make this research both relevant for science as for practice.

Finally, I would like to thank my friends and family for their support and willingness to listen to my 'thesis-talk' for the past months.

Enjoy reading,

J. N. M. Russell
Delft, June 2022

Executive summary

A transformation of the global food system is necessary to make it more environmentally sustainable and durable. The demand from both the European Union (EU) and society to mitigate the Greenhouse Gas (GHG) emissions associated with food has risen over the past decade. Within the food industry, the livestock industry is the biggest contributor to climate change.
The livestock industry in the Netherlands is one of the most densely packed livestock industries in the world. It imposes significant effects on the environment. The production of livestock feed is a big contributor to the overall emissions of the industry. A transformation, including many innovations, is necessary to reduce the high amount of GHG emissions from livestock feed. The transformation from this complex and sustainable unconscious system towards a more safe, efficient and sustainable system brings along significant challenges. There is a knowledge gap on how to produce more environmentally sustainable livestock feed.
Livestock feed consists of a mixture of different commodities. To determine the appropriate proportions of every commodity in the mixture, current optimization models are based on cost and nutritional values. To mitigate the emissions, feed compositions should not only be optimized against cost and nutritional values, but also against environmental sustainability.

This study focuses on proposing a new method for performance measurement of the livestock feed production industry from an environmental and economic perspective. An environmental performance index is created to assess feed compositions in terms of environmental sustainability as well as from an economic perspective. This index should support the decision-making process of livestock feed companies to produce environmentally sustainable livestock feed at as low as possible costs. Based on insights obtained from the index, livestock feed companies can determine their strategy to comply with the environmental regulation and demands.
The main research question is: "*How could an environmental performance index be created that balances GHG emissions with carbon capture for the feed production of the livestock industry from an economic perspective?*".
This question is answered by assessing the findings on five sub-questions. The answers to the different sub-questions cover several topics. The GHG balance of the feed production for the livestock industry is discussed. Techniques to construct an environmental performance index are outlined and the creation of a sector-specific environmental performance index for livestock feed industry is proposed. The technical feasibility of the environmental performance index is investigated by bringing the model into practice; different scenarios are quantitatively compared to a benchmark feed composition. The index is verified and validated to ensure it reflects the intended purpose and it produces accurate results.

No prior research is done on a GHG balance, that includes GHG emissions and carbon capture, in combination with the optimization of feed compositions. A literature study on the GHG balance of livestock feed is presented. Livestock feed production consists of three parts; crop cultivation, transportation and storage, and feed processing.
First, crops need to be cultivated. During this cultivation process, there are several sources of emissions; land use, land use change, the use and production of synthetic fertilizer and the use of organic fertilizer. Land use is the occupation of land to produce crops. High occupation of land means less land is available to produce crops for bio-energy or human consumption or to grow new forests to capture carbon. Land use change is the change of the designation of land and the replacement of forests with agricultural land. Especially deforestation is associated to the release of GHG emissions, since the carbon stored in the soils of forests is released when forests are cleared. During crop cultivation, emissions are also released due the production and use of synthetic fertilizers. Fertilizers stimulate the growth of crops. Next to synthetic fertilizers, manure can act as a fertilizer as well. A circular process within the livestock industry is created when manure, organic fertilizer, is used.
Secondly, crops need to be stored and transported. The amount of GHG emissions that are released depend on the mode of transport, the origin of the crop and the type and length of storage. All emis-

sions are due to the use of energy and fossil fuels.
The third part is processing. There are two sources of processing. First, there is processing to obtain different products from a crop. And second, the processing of all crops to create compound feed. Both types of processing involve the use of energy and fossil fuels.
Besides the GHG emissions that are emitted during this first stage, crop cultivation, there is a possible opportunity to capture carbon. The inclusion of regenerative agricultural practices during the crop cultivation, offers the opportunity to capture carbon from the atmosphere in the soil. Regenerative agriculture is the practice of restoring degraded soils to improve soil organic carbon stocks. This sequestration process has been ignored for a long time, but research has proven it can no longer be neglected. Even the European Commission announced the Farm to Fork Strategy, a program that has the goal to stimulate carbon farming within the EU to capture carbon in order to reach a carbon-neutral economy.

A literature survey is done on the construction of an index, also referred to as a Composite Indicator (CI), in order to create an environmental performance index for livestock feed. Literature on the construction of a CI showed that it is relevant to review the performance of a company, an industry or a product. It is a recognized tool that allows decision-makers to compare a set of indicators with different units of measurements to review the performance systematically with a comparative quantitative scoring system.
The construction of a CI consists of five phases. In the first phase, the variables that should be included to measure the performance must be selected. Secondly, the variables should be scaled to get normalized values that can be combined in an index. In the third phase, the variables are weighted. Weights are assigned to the different input variables. In the fourth phase, the different variables with the accompanied weights are combined into a CI, this is called the aggregating phase. Finally, in the last phase the CI is post analyzed. It is important to conduct the post analysis to constantly improve the quality of the CI and ensure the robustness and transparency.
For every phase different methods can be used and the right method should be selected based on the nature of the CI. It is important that a CI is sector-specific, because the appropriate variables should be included with accurate data and the right choices to get a correct result.

After knowledge from literature is gained on the construction of indices and the methods that could possibly be used, the environmental performance index for livestock feed is constructed. The goal of the CI for livestock feed is to be able to systematically compare feed compositions in terms of environmental sustainability performance and economic performance.
As described in the literature on CIs, the environmental performance index for livestock feed consists of five phases. First, the input variables are determined. The literature on the GHG balance of the livestock industry is used as the input for the environmental performance index for livestock feed. Next, the variables are scaled using the min-max transformation. In the third phase, weights are assigned to all variables with the analytical hierarchy process. Expert opinions can be well reflected with the analytical hierarchy process, but the weights are computed through statistical models. The scaled variables and the weights are aggregated with simple additive weighting. This is a widely used method that is easy to understand, which is important for a CI. In the last phase, the constructed CI is validated with an uncertainty analysis and sensitivity analysis.
With experts from the livestock industry, the created index is verified to confirm that the intended purpose of the model is accurately incorporated in the environmental performance index for livestock feed.

Next, the technical feasibility is proven by bringing the created environmental performance indicator into practice; nine scenarios, which all represent a feed composition, are compared to a benchmark feed composition. The results generated with the environmental performance index for livestock feed indicate that the index is technically feasible and effective to measure the performance of the livestock feed industry from an environmental and economic perspective.
The constructed environmental performance index is validated to ensure the models is right. The validation is done with an uncertainty analysis and sensitivity analysis.
A verified and validated environmental performance index is created for the feed production of the livestock industry. The constructed environmental performance index can serve as a decision-making tool for livestock feed companies.

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List of Acronyms

AHP Analytical Hierarchy Process

CI Composite Indicator

EC European Commission

EU European Union

FAO The Food and Agriculture Organization of the United Nations

GHG Greenhouse Gas

GWP Global Warming Potential

LCA Life Cycle Analysis

LST Linear Scaling Transformation

LU Land use

LUC Land use change

SA Sensitivity Analysis

SAW Simple Additive Weighting

SOC Soil Organic Carbon

UA Uncertainty Analysis

1 Introduction

A food system is established to provide every human being with food. The global food system has become extremely complex due to the globalization of the world economy and the rising globalization to meet the demands of society. This highly complex system is responsible for a significant amount of Greenhouse Gas (GHG) emissions. In modern society, there is a growing tendency towards environmentally sustainable food. To fulfil this need, the global food system needs to be transformed.
This transformation from this complex and sustainable unconscious system towards a more safe, efficient and sustainable system brings along significant challenges.

In this Chapter, the field of research is outlined. This is followed by the problem statement, the research objective and the research questions. Finally, the scope of this research and the structure of the report is elaborated on.

1.1. Field of research

Every day, every human being needs to have access to food, a fundamental human right. Besides a basic need, food is an important aspect of social activities in almost every culture. The global food system needs to be expanded by 50% in 2050 to feed the world population of, by then, approximately 10 billion people [93]. The challenges that come with providing the growing population with sufficient, healthy and safe food, while ensuring this is done in a sustainable way with a system that can be maintained long-term, are significant.
When taking up these challenges, the system should be transformed and this offers the opportunity to contribute to a better, healthier and more sustainable world.

This study focuses on the environmental sustainability of the food system. The food industry is responsible for almost 30% of the total global GHG emissions. An environmental sustainable system that can be maintained long-term is needed to reduce the GHG emissions to comply with the regulations from the EU. Ultimately, net-zero emissions should be reached and global warming should be limited to 1.5°C compared to pre-industrial levels [49, 53, 93].

The livestock industry is the biggest contributor to global warming within the food industry. This industry is responsible for almost 50% of all GHG emissions within the global food system [66]. The livestock industry is responsible for 14.5% of the global GHG emissions [24, 29, 66, 71]. This research will focus on the environmental sustainability of the livestock industry, and especially on the Dutch livestock industry.

The livestock industry in the Netherlands is very productive per unit of land [86]. The Netherlands is a world leader in the area of agricultural and animal science and technology [86]. This high level of knowledge has resulted in a good market position and high export rates of livestock products. Meat is the second most lucrative agricultural good exported by the Netherlands, followed by dairy and eggs [41].

The value of the total Dutch export of agricultural products in 2020 is estimated at 95.6 billion euros. Despite the COVID-19 pandemic, this is 1% higher than 2019 [41]. When considering re-export, the Dutch export is composed of 68.3 billion euros of exported goods of Dutch origin and 27.3 billion euros of re-exported foreign agricultural products [41]. It is essential to include re-export to prevent a distorted export overview. Including re-export is especially important for the Netherlands since a large number of commodities are imported through the port of Rotterdam and Schiphol, and are directly re-exported [86].
The Dutch success is not only due to the high level of knowledge development, but also because of the good climate and soil conditions, high cost-efficiencies and imports of agricultural materials such as livestock feed [86].

The Dutch livestock sector is responsible for 9% of the country's total GHG emissions. Research done by Post et al. [58] emphasizes that the GHG emissions released by the Dutch livestock industry are almost double as high when both national and international emissions related to the Dutch livestock industry are taken into account [58]. The Netherlands have a very high import rate of livestock feed. The emissions associated with feed production are often allocated to the country of origin.
Approximately 70% of the agricultural land in the Netherlands is dedicated to the production of feed for livestock. Agricultural land includes both crop and grazing land [58]. To put this in perspective, the Netherlands consists of 33,893 km^2 land area [85, 94], 54% of the Dutch land area is covered by agricultural land [94]. This amount of land is not enough to supply the high amount of livestock in the Netherlands with enough feed. More feed needs to be imported from abroad [58].

The livestock industry in the Netherlands is one of the most densely packed livestock industries in the world [58]. The system imposes significant effects on the environment. A transformation, including many innovations, is necessary to reduce the high amount of GHG emissions.
The Netherlands has committed to the climate regulations of the EU. The commitment is made to have net-zero emissions by 2050. This commitment is in line with the European Green Deal and the Paris Agreement [21].

1.2. Problem definition

A transformation of the global food system is necessary to make it more environmentally sustainable and durable. The environmental sustainability of livestock feed is an important topic. More research should be done since the intake of proteins by eating animal products has risen tremendously over the past 80 years. In developed countries, such as the Netherlands, the protein intake increased by 33%. In under-developed and developing countries, the daily availability, and therefore, the intake of protein rose by 116% [83]. Livestock products provide 17% of the kilo-calorie intake worldwide and they provide 34% of the global protein intake [66, 83]. It is expected that the overall worldwide demand for livestock products will keep growing. This puts even greater pressure on the environment and the need for a transformation becomes even more clear [14, 72, 83].

The GHG emissions of the livestock industry can be divided into different sources: energy consumption, manure management, enteric fermentation and feed production. Energy consumption is responsible for 5%, manure management for 10%, enteric fermentation for 44% and feed production for 41% of the total GHG emissions. This is visualized in Figure 1.1. It can be concluded that feed production is among the two major contributors to GHG emissions and, therefore an important part of the livestock industry to focus on [28].

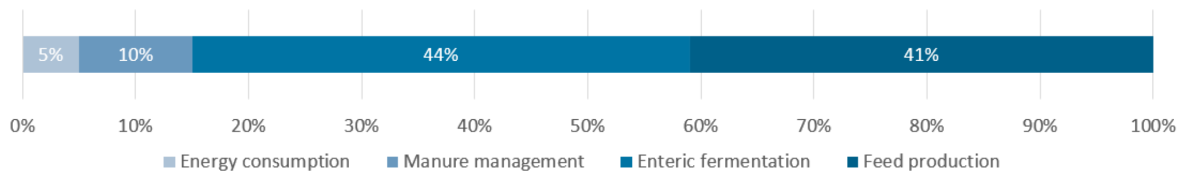

Figure 1.1: Overview of sources of GHG emissions livestock industry

During the past decades, the growing tendency towards more environmentally sustainable products can be observed. Retailers and customers have started focusing more on, and are even demanding, sustainable products. Besides this market pull, the need to reduce GHG emissions is not just a demand from society. The EU has committed to reaching net-zero GHG emissions by 2050. This commitment is in line with the European Green Deal and the global climate action under the Paris Agreement. As a part of this commitment, the EU wants to reduce the emissions by 55% compared to 1990 [21].

Both consumers and the EU demand this reduction of emissions. Farmers are mainly held accountable for the transformation and actions to reduce emissions. Consumers want their food to be more environmentally sustainable, but prefer not to pay extra for this. Food retailers need to sell environmentally sustainable products to meet the growing demand of society. However, they do not want to increase the prices because they do not want to lose costumers. Food retailers ask farmers to deliver products with increased environmental sustainability, without a rise in payment. Otherwise, they will switch to another farmer. The transformation of the current farming system to a more sustainable one, costs a lot of time and money. Besides this, knowledge should be gained on how the current farming system can be transformed in a more sustainable farming system. This knowledge gain should not just be the responsibility of the farmers, but of all players in the market.

It is essential to do more research in the area of optimizing livestock feed. Currently, optimization models for livestock feed focus on costs and nutritional values. There is much to gain since limited research has been done on optimizing livestock feed with regards to environmental sustainability and on the opportunity to include carbon capture during crop and grass production in the emission overview.
A literature study on this showed a gap in the literature [67]. A GHG balance that includes carbon emissions and carbon capture is never investigated in combination with the optimization of feed compositions in terms of environmental sustainability [67]. In Appendix A the literature matrix is shown.

This study focuses on this gap in the literature by proposing a new method for performance measurement of the livestock feed industry from an environmental and economic perspective. Livestock feed producing companies need to have more insight in the overall performance of feed compositions, which includes the effect of carbon capture on the performance, to be able to produce environmentally sustainable livestock feed. Currently, this is just based on costs and nutritional values.
In order to do this, a composite indicator should be created to assess feed compositions in terms of environmental sustainability from an economic perspective. To assess the environmental sustainability, carbon emissions and carbon capture should be included. An economic perspective is included since maximizing profits is in the end an important, or the most important, business objectives. The trade-off between environmental sustainability and economics is made, with a strong focus on mitigating GHG emissions.

1.3. Research objectives

In this study, knowledge is gained on the combination of a GHG balance and the optimization of feed compositions for the livestock industry in terms of environmental sustainability and from an economic perspective.
This research aims to create an environmental performance index with an economic perspective for the feed production of the livestock industry to reduce GHG emissions and ultimately reach net-zero emissions while keeping the economic performance as good as possible. It is expected that this environmental performance index give insights into the environmental sustainability of livestock feed and could contribute to solving the problem of high GHG emissions of livestock feed.
Next to creating an environmental composite indicator for the livestock feed, this is a hypothesis-building study. A composite indicator is created with different variables. The relationship between these variables is investigated and hypotheses about these relationships are set up. In further research, these hypotheses should be tested [19].

In the study, first background information on the GHG balance of feed production is gathered. Next, theory on constructing a composite indicator is elaborated on. After information on the GHG balance and the creation of composite indicators is gathered, this is combined to construct an environmental composite indicator from an economic perspective for the livestock feed industry. Now, the created index is verified to afterwards bring it into practice with data from Agrifirm, the use-case, and other data sources. Results on the performance of feed compositions are obtained and the index is validated. A benchmark feed composition is compared to feed compositions that represent different scenarios. A conclusion is drawn based on the results, the validation and the verification.

1.4. Research questions

A research question is formulated to find an answer to the proposed problem. Five sub-questions are formulated to find an answer to the research question.

Research question: How could an environmental performance index be created that balances GHG emissions with carbon capture for the feed production of the livestock industry from an economic perspective?

Five sub-questions are formulated to answer the research question.

Sub-question 1: What can be found on the GHG balance of the feed production of the livestock industry?
The GHG balance of the livestock should be well understood to get a clear understanding of what variables are important to determine the environmental sustainability performance of livestock feed. The GHG balance of the livestock industry is elaborated on on the basis of a literature survey.

Sub-question 2: What are the techniques for constructing an environmental performance index?
Literature on the construction of environmental performance indices is investigated. Based on these findings, a sector-specific environmental performance index for the livestock feed industry can be created.

Sub-question 3: How can an environmental performance index for livestock feed be constructed from an economic perspective?
An environmental performance index from an economic perspective for the livestock feed industry is created based on the information obtained from sub-question 1 and 2.

Sub-question 4: Can the created environmental performance index be proven to be technically feasible by comparing the benchmark feed composition to alternative feed compositions?
The created environmental performance index is brought into practice by comparing different feed compositions to each other to validate if the index is technically feasible and can be used by livestock feed companies.

Sub-question 5: Can a verified and validated conclusion be drawn on the environmental performance of feed compositions based on the outcome of the created environmental performance index?
To draw a conclusion on the performance of feed compositions, the results should be found. If a verified and validated conclusion can be drawn, this means the environmental performance index is a useful tool to support the decision-making of livestock feed companies.

1.5. Scope of the research

This study focuses on creating an environmental composite indicator for the feed production of the livestock industry in the Netherlands. The Dutch feed production industry is in scope, this includes the import and transportation of raw materials from all over the world. This is visualized in Figure 1.2.
The carbon balance is considered from crop cultivation to feed production. GHG emissions from pesticides are out of scope, since the emissions are negligible. This is based on a previously done literature study on "Carbon balancing in the feed production of the livestock industry" [67]. Manure management and enteric fermentation are out of scope. Land use change (LUC) as a result of the high demand for livestock feed is in scope.

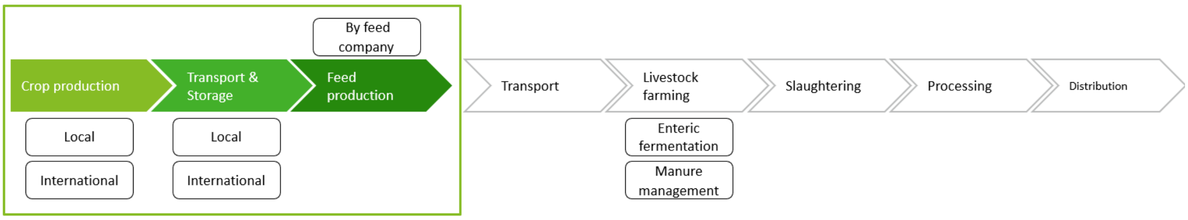

Figure 1.2: Overview of the scope of the research

In the Netherlands, different kinds of livestock are held. In Table 1.1 an overview of the different types of livestock and the numbers present in the Netherlands in December 2020 is shown [11].

Livestock	**Number of livestock** (x1000)
Cattle	3,691
Pigs	11,541
Sheep	710
Rams	27
Bulls	11
Goats	557
Chickens	89,515*
Ducks	568*
Turkeys	568*

Table 1.1: Dutch livestock numbers Dec 2020, *data from April 2021 [11]

This Table makes clear that cattle, pigs and chickens are the predominant Dutch livestock types. Therefore, these three categories are in scope. Livestock refers to cattle, pigs and chickens. This means livestock products refer to meat, eggs and dairy products.

In this study, the GHG emissions that are taken into account are the GHG emissions that contribute to global warming. This is measured in CO_2 and CO_2-equivalents. So, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These GHG emissions are expressed in CO_2-equivalents. This is done following the 100-year Global Warming Potential (GWP) value [39]. The Fifth Assessment Report AR5 of GWP values relative to CO_2 is used, since this is recommended by the IPCC [39]. This is shown in Table 1.2.

GHG	**GWP value**
CO_2	1
CH_4	28
N_2O	265

Table 1.2: Global Warming Potential values for a 100-year time horizon AR5 [39]

1.6. Outline of the report

The defined sub-questions are answered to draw a conclusion and answer the main research question. Every chapter handles a sub-question and in the last chapter, the conclusion and discussion, the research question is answered and recommendations for further research are made.
In Figure 1.3 the structure of this report is shown. In Chapter 2 and 3 theory from literature is explored. In Chapter 2, sub-question 1 is answered. In Chapter 3, literature on the construction of composite indicators is evaluated and the second sub-question is answered. The theory gathered from the literature is used to construct a sector-specific composite indicator for livestock feed. Next, the sub-question 4 is handled in the Chapter 5 where the created environmental composite indicator for livestock feed is brought into practice with data from the use-case. The results are shown in Chapter 6 and sub-question

5 is answered. Lastly, the research question is answered in Chapter 7. A conclusion, discussion and recommendations for future research are outlined in the last Chapter.

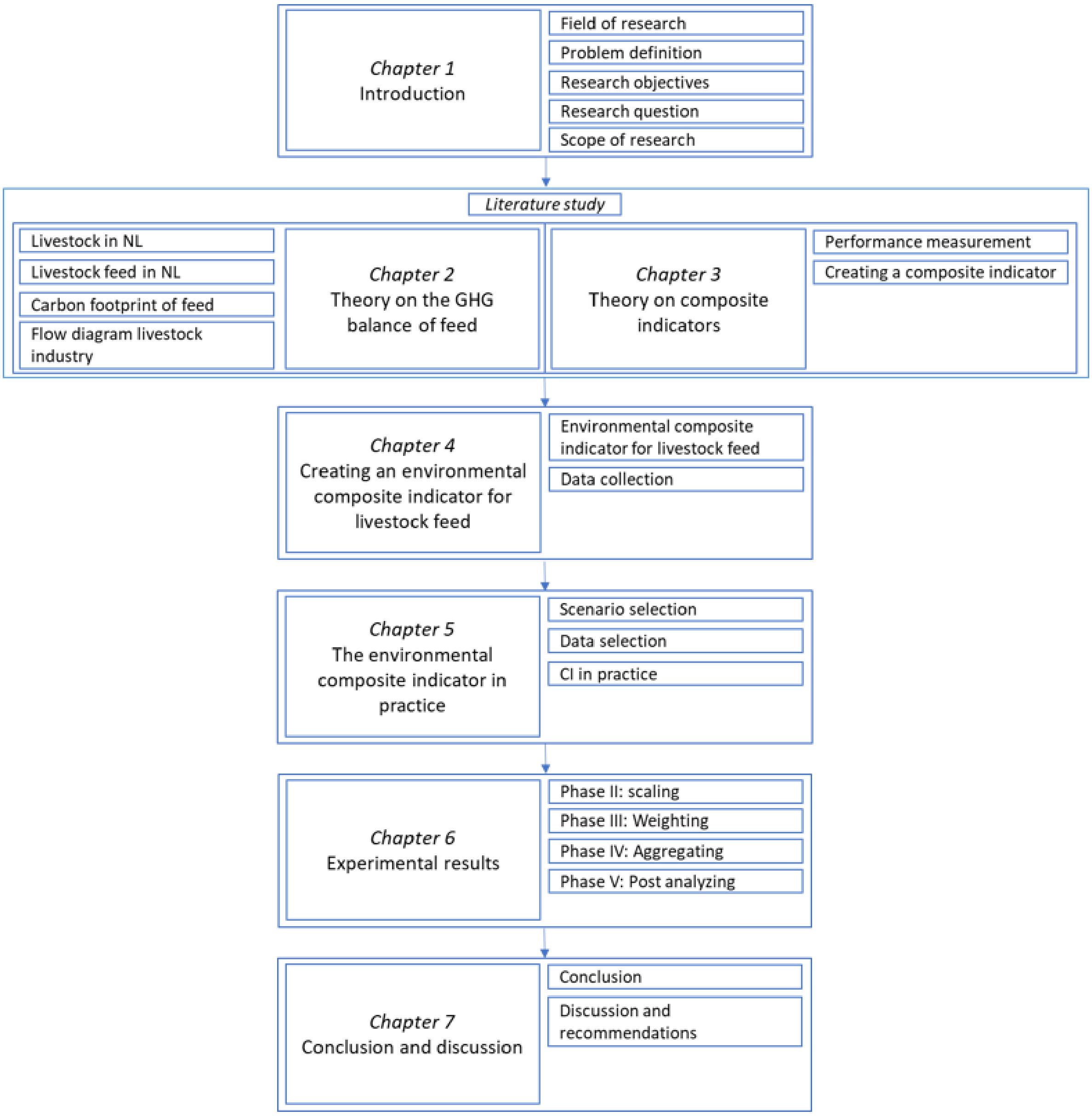

Figure 1.3: Overview of the structure of the report

2

Theory on the GHG balance of feed

The GHG footprint of the feed production of the livestock industry can be assessed by balancing GHG emissions and carbon capture. All assets of this GHG balance should be reflected in the performance index. To provide a background to assess this, knowledge is gained on the feed production for this sector. This information gives a firm foundation for determining the key drivers of the GHG balance. Sources of GHG emissions and possibilities to capture carbon are discussed.

2.1. Livestock in the Netherlands

The livestock industry in the Netherlands is one the most densely packed livestock industries in the world [58]. To assess the GHG emissions of the Dutch livestock industry it is important to determine whether the livestock numbers have increased or decreased over the years. It is important to evaluate the growth because the numbers on emissions in literature should be interpreted differently if the numbers have varied over the years. In Figure 2.1 the growth of the cattle market is shown from 1980 to 2020.

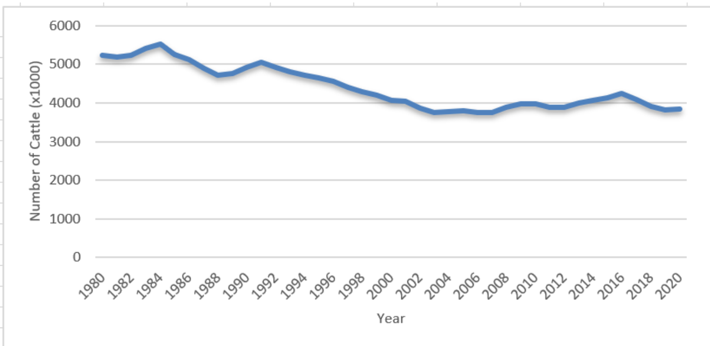

Figure 2.1: Evolution of cattle in the Netherlands [62]

In this Figure, there can be seen that the number of cattle in the Netherlands has deccreased with almost 27% over the past 40 years, with a stabilization in the past 20 years. The sudden decline of cattle numbers in 1984 is the result of the introduction of the milk quota by the EU [62].

In Figure 2.2 the growth of the numbers of pigs in the Netherlands is shown.
From this Figure it becomes clear that the the number of pigs in the Netherlands has grown over the past 20 years. An increase of almost 18% is realized over two decades. In 1997, a decline in the number of pigs can be seen. This is the result of a swine fever [62].

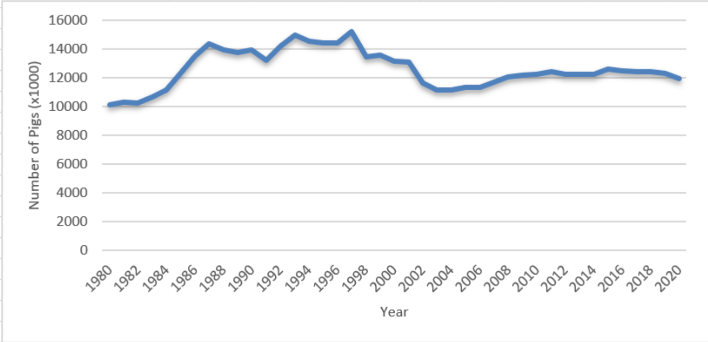

Figure 2.2: Evolution of pigs in the Netherlands [62]

In Figure 2.3 the number of chickens in the Netherlands is shown. It shows an increase of almost 26% between 1980 and 2020. The steep decline in 2003 is the result of the avian influenza [62].

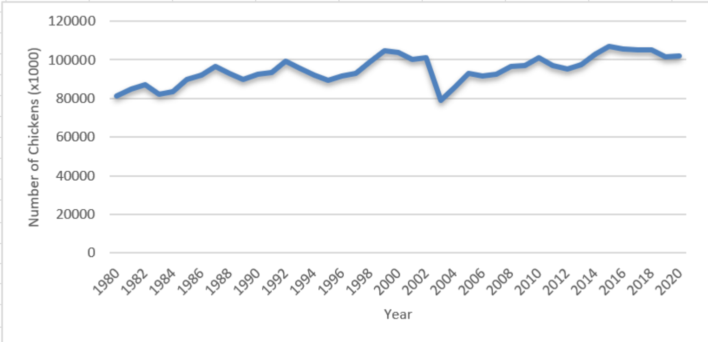

Figure 2.3: Evolution of poultry in the Netherlands [62]

The findings of the Dutch livestock market are partially in line with the European livestock market. In Europe, the number of cattle has been declining since 1980 [45]. This is in line with the Dutch market, as shown in Figure 2.1. This reduction is visible in all countries in Western-Europe and is the consequence of new environmental policies, agricultural land change and market developments [45].
Pig numbers have been stable since the mid 1980s in Europe [45]. In Figure 2.2 it becomes clear that when comparing 2020 to the mid 1980s the number of pigs is stable, but almost the two decades after the mid 1980s, a growth of number of pigs was visible on the Dutch market. From 2004 and forward, the Dutch pig market stabilized.
Finally, the number of poultry in the European market is in line with the numbers of the Dutch market, the numbers have been increasing over the last 40 years [45].

Livestock products are an export product of the Netherlands. Meat is the second most lucrative agricultural good exported by the Netherlands followed by dairy and eggs [41].
The value of the total Dutch export of agricultural products in 2020 is estimated on 95.6 billion euros. Despite the Covid-pandemic, this is 1% higher than 2019 [41]. Research done by van Grinsven et al. [86] emphasises that re-export should be considered to prevent a distorted picture of gross export, especially in the Netherlands since some commodities are imported through the port of Rotterdam and through Schiphol and are directly re-exported [86]. A more accurate overview of the Dutch export is that the overall export is composed of 68.3 billion euros of exported goods of Dutch origin and 27.3 billion euros of re-exported foreign agricultural products [41].
78.8% of the total agricultural products is exported to countries within the EU, still including the United Kingdom (UK). The export to neighbouring countries, Germany, Belgium, the UK and France, is the most significant with respectively an export rate of 26%, 11%, 9% and 8% of the total export [41]. It can be argued that export to neighbouring countries from the Netherlands is regional transport, because the goods are exported but the chain is relatively short.

The high level of knowledge development in the area of agricultural and animal science and technology are a driving force of the Dutch success. Besides this, the good Dutch market position is due to the good climate and soil conditions, high cost-efficiencies and imports of agricultural materials such as livestock feed [86].
The high level of development is not just reflected in the livestock industry, but in the agricultural sector overall. The Netherlands is from all EU countries the most productive per unit of land. However, this high productivity and efficiency go hand in hand with high GHG emissions. Van Grinsven et al. [86] compared the Dutch agriculture to other European countries expressing it in eco-efficiency. The research defines eco-efficiency as: "*Economic value added per unit of environmental damage or pressure*". This makes the quantification of the gross value added per unit of environmental degradation possible. The Netherlands was ranked first, so the country with the highest eco-efficiency. However, they also ranked the Netherlands as the country with the highest environmental pressure per unit of land.

2.2. Livestock feed in the Netherlands

The Netherlands belongs to the most intensive producers of cattle, pigs and poultry in Europe [45]. For the intensive production of livestock, a constant supply of feed is required. A high amount of feed needs to be produced to meet this high demand of the Dutch livestock market.
The total area of land dedicated to agricultural purposes in the Netherlands is smaller than the amount of land necessary to supply the livestock industry with enough feed. To compensate for this, livestock feed needs to be imported from abroad. It is estimated that in 2015 14,000 km^2 of land within the Netherlands, and 26,000 km^2 of land outside of the Netherlands, was used for the feed production for the Dutch livestock [58].

Feed for the livestock in the Netherlands is typically composed of grass, cereals, maize and crops rich in proteins such as soy. The land area within the Dutch borders is mainly used to grow grass and maize. On the land outside of the Netherlands, cereals and protein-rich crops are grown [58].

Livestock feed consists of a composition of various raw materials. A mixture of different raw materials is made for the production of feed. A flow diagram of this production process is shown in Figure 2.4 [74].

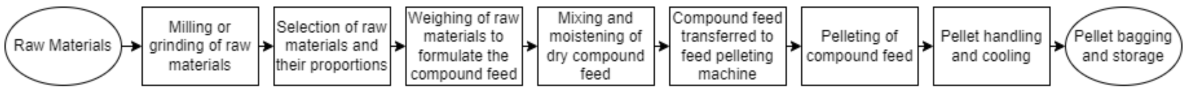

Figure 2.4: Flow diagram of feed production [74]

In this flow diagram, it is assumed that the feed is stored and transported in the form of pellets. A study done by Shrinivasa and Mathur [74] states that a pellet is the preferred form to store and transport compound feed. A pellet prevents the segregation of the feed and, therefore, ensures a homogeneous mixture.
As shown in the flow diagram, a selection of raw materials for the compound feed is formulated. The composition of feed for the Dutch livestock industry varies per sort of livestock and is composed of different raw materials. The feed composition has consequences for the final properties of the compound feed. The nutritional values, the costs and the environmental sustainability of the compound feed are influenced by the choice of commodities and their proportions in the feed mixture. These three objectives, the nutritional values, the cost and the environmental sustainability, should be taken into account when determining an optimal feed composition,

The nutritional value of feed is an important objective [10, 46, 56, 61, 71, 74]. The nutritional values affect the growth rate of livestock. This influences the conversion ratio of feed (feed/kg product) [45]. A low feed conversion ratio means less feed is required per unit of the livestock product [6]. Feed additives can be added to feed to improve the quality and nutritional values [7, 27].

Secondly, the costs of feed are influenced by the choice of commodities for the feed mixture [4, 10, 46, 61, 74]. First of all, raw materials have different prices. These commodity prices fluctuate throughout the year. Next to this, the transportation from the country of origin to the Netherlands differs per commodity. The distance and the mode of transport influence the price. Lastly, the type of processing is different per commodity and is accompanied by different costs.
The cost of feed is the most significant influencing factor on the final price of food [14, 48, 56].

Thirdly, the environmental sustainability of compound feed is a property that is influenced by the choice of commodities. The contribution to global warming of products is getting rising attention. GHG emissions associated with commodities differ per crop and, thus, per feed mixture [10, 46, 56, 66, 71].
The emissions from production vary per raw material. This variation is due to different processes in the supply chain of feed crops. The intensity of the use of fertilizers can differ per crop, climate and farm management. The required processing differs per crop. Often used processes in the Netherlands are dry-milling, wet-milling and crushing. Processing requires the use of fossil fuels [24, 46]. Furthermore, the emissions from transportation differ per country of origin and per transport mode [46, 89, 92]. Altering the country of origin and transport modes can bring down GHG emissions [7]. Land use change is a major source of GHG emissions. Land use change is associated with certain crops, mainly originating from South America. The emissions from land use change depend on the type of crop used in the feed mixture [6, 43]. The different sources of GHG emissions are further discussed in Section 2.3.1.

Currently, the formulation of feed compositions is often just based on nutritional values and costs [4, 46, 61, 74]. The interest in environmental sustainability is rising. Due to regulations and a market pull this objective is getting more important when determining an optimal feed composition for livestock feed [46, 56].
Feed is responsible for 41% of the GHG emissions of the livestock industry. The choice of commodities and their proportions in a feed composition should be optimized toward environmental sustainability to reduce this high number. Reducing the GHG emissions should be done while keeping the nutritional values and costs in mind. In order to construct a model to optimize livestock feed in terms of environmental sustainability while maintaining the nutritional values and costs at an acceptable level, the carbon footprint of feed should be investigated. In the next Section, the GHG emissions and possibilities to capture carbon are elaborated on.

2.3. Carbon footprint of feed

The livestock feed industry needs to be transformed into a more sustainable and environmentally conscious production system. The feed system releases an extremely high amount of GHG emissions into the atmosphere. This same system has the great possibility to sequester GHGs from the atmosphere and capture these GHGs in the soil. This way, a GHG balance could be created. GHG emissions are released and have a negative influence on the balance. With carbon capture, GHGs are sequestered from the atmosphere and, thus, have a positive influence on the balance.
In Figure 2.5 the GHG balance is shown. The top GHG balance shows that the release of GHGs into the atmosphere is bigger than the GHGs sequestered from the atmosphere. The lever is pushed down by release of GHGs. The bottom lever of the Figure shows the possible balance that could be reached. The release of GHGs into the atmosphere can be balanced with the sequestration of GHG from the atmosphere into the soil.

In this Section, the different sources of GHG emissions in the livestock feed industry are discussed and also the possible opportunities to capture carbon are elaborated on.

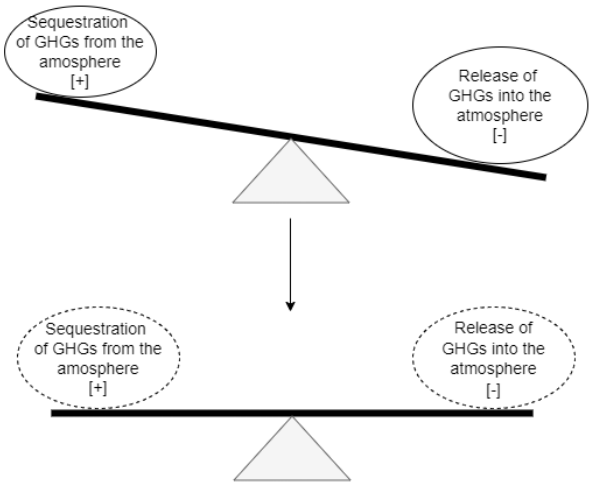

Figure 2.5: GHG balance

2.3.1. GHG emissions

In the livestock feed industry, there are different sources of emissions that contribute to global warming. In Figure 2.6 the sources of GHG emissions are shown. The different sources of emissions are assigned to a part of the production process. The production process can be split into three parts; crop cultivation, transportation and storage and feed processing.

In the crop cultivation stage, GHG emissions are released due to Land use (LU) and Land Use Change (LUC), the production and use of synthetic fertilizers and the use of organic fertilizers. In the second part there are GHG emissions due to energy and fossil fuel use during transportation and storage. In the last stage, feed processing, GHG emissions are released due to the processing of the crops to produce compound feed. These emissions come from energy and fossil fuel use as well.
The different sources of emissions are elaborated on one by one.

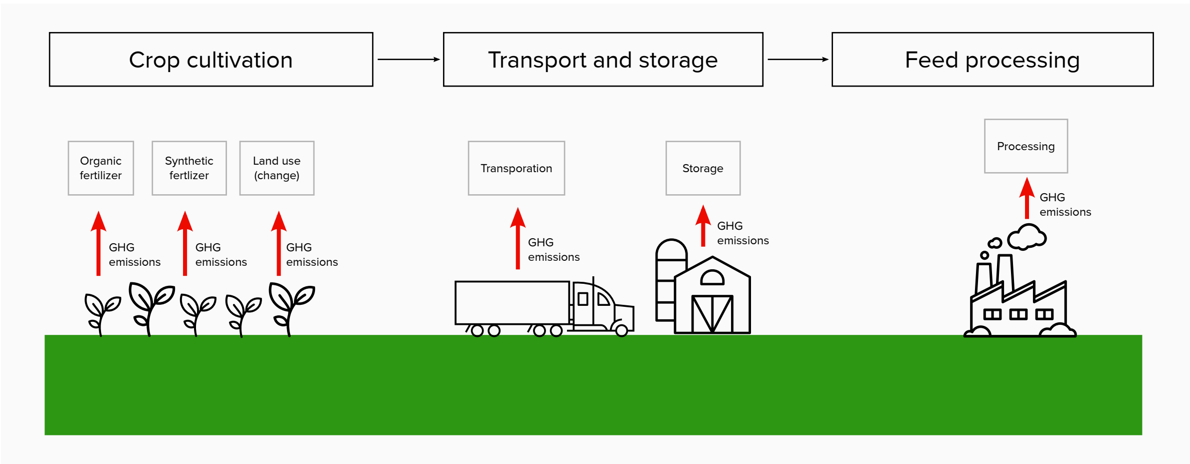

Figure 2.6: GHG emissions in the livestock feed industry

Land use and land use change

Worldwide, approximately 80% of the agricultural land area is dedicated to the livestock industry [36, 63]. The amount of land use to produce feed for the livestock industry puts a high pressure on land area [58]. This high strain put on available land results in changes in the designation of land. Land use refers to the amount of land necessary to grow crops. Changes in the designation of land and the replacement of forests with agricultural land is referred to as land use change.

The LU for cultivating feed crops is in direct competition with crop cultivation for human consumption. Furthermore, there is competition from crop production for bio-energy [6]. This is known as the food-feed-fuel competition [48]. The mitigation of LU results in higher availability of land to grow crops for human consumption, for bio-fuels or to grow new forests to capture carbon [6, 48]. The yield per area of land differs per crop and, thus, influences the emissions. The life-cycle of a crop, the number of production cycles per year, should be reflected in emission calculations [24, 80].

LUC, also known as deforestation, is known for the high contribution to the emissions of GHGs [6, 71]. GHG emissions from land use change are released because forests function as a carbon sink. The stored carbon in the soils is partially released with deforestation [6, 43]. The natural carbon cycle of the soil is disrupted due to deforestation and the carbon sequestration of the soil decreases when changing forests into crop- or grassland [66]. The clearing of forests to replace this with agricultural land mainly happens in South America and is primarily connected to the cultivation of soy [6, 29, 92]. Thus, high import rates of protein-rich feed such as soy are connected to high emissions due to LUC. The Dutch livestock system is known for importing a high amount of high protein feed such as soy [6].

The impact of deforestation is major and should therefore be taken into account when assessing the GHG emissions related to the livestock feed industry. Colomb et al. [15] argues that deforestation accounts for 11% of the worldwide emissions. The findings of Gerber et al. [29] on this matter are that 9.2% of the emissions of the livestock industry can be allocated to LUC. These findings are not in line with each other. This inconsistency of the findings is recognized by Gerber et al. [29], Bellarby et al. [6] and The Food and Agriculture Organization of the United Nations (FAO) [24]. They argue this is caused by the unclear and still disputable allocation rules for the emissions of LUC and the exact drivers are unknown. Despite the discussion on the exact numbers, the high impact of LUC on the release of GHG emissions is recognized by all.

Synthetic fertilizers
Synthetic fertilizers stimulate the growth of crops. They consist of either nitrogen (N), phosphorus (P) or potassium (K), or a combination of the three [25]. Emissions from fertilizers are built up of emissions from the production, the transportation and the on-farm emissions [6, 58].
Synthetic fertilizers are produced with energy; natural gas is most commonly used [66, 88]. To produce nitrogen fertilizers, raw materials ammonia and nitric acid are required [88]. The Haber-Bosch process is the commonly used production method. Under extremely high pressure, a catalyst consisting of mainly of iron and other chemicals N fertilizers are made. This method requires a high amount of energy [44, 91]. Both phosphorus and potassium are sourced through mining. For phosphorus, rocks are chemically treated to obtain P.

Phosphorus (P) is only mined in a few countries. Findings from the United States Geological Survey (USGS) [84] show China is the biggest producer, followed by Morocco and the United States. The same applies to potassium (K), it is only produced in a small number of countries. Canada is the biggest producer, with a 30% market share, followed by Russia, Belarus and China. The last three countries are all responsible for around 15% of the production of potassium. Nitrogen, however, (N) is produced in many countries around the world [91]. This means that for the supply of P and K often long distances have to be travelled, which leads to emissions from transportation. However, Walling and Vaneeckhaute [91] found that the transport of fertilizers is responsible for an extremely small amount of the overall emissions related to synthetic fertilizers. Therefore, emissions from the transport of fertilizers can be neglected [91].

On-farm emissions are the most significant part of the emissions due to the use of fertilizers. Sources of emissions are energy used to apply the fertilizers, the (de)nitrification process and anaerobic conditions. Besides high emissions, a particular share of fertilizers applied to crops runs off in the soil. This leaking leads to the contamination of the soil and groundwater [44].

Organic fertilizers
Manure can be used as a fertilizer. It is referred to as an organic fertilizer. Emissions from organic fertilizer are the result of storage of manure, the transportation and on-farm emissions. During storage,

methane is emitted because of anaerobic decomposition. Nitrogen is converted into ammonia (NH_3) and becomes nitrous oxide (N_2O) [29, 91].

Organic fertilizers are not transported over long distances. This has both technical and economic reasons. The maximum transportation distance is around 30 kilometres. Emissions due to transport are therefore not a significant source of emissions and can be neglected [91].

On-farm emissions consists of energy use to the distribute the manure on the land and also the (de)nitrification process and anaerobic conditions.

Transportation and storage
Crops are transported and stored before and after they are processed. The mode of transportation and the distance between the origin and the destination of the commodity influences the amount of GHG emissions. GHG emissions are generated due to fossil fuel use during transportation and during the transshipment of the commodities. Energy use is necessary to maintain suitable environmental conditions during transportation and storage [97].

Processing
Raw materials need to be processed before they are ready to be included in a feed mixture. Commonly used processing techniques are dry-milling, wet-milling and crushing. Maize is typically processed using wet-milling. For the processing of all cereals, dry-milling is applied. GHG emissions are released due to energy and fossil fuel use during these production processes [24]. After the individual raw materials are processes, there are emissions from the mechanical mixer that is utilized to produce the feed mixture [74].

2.3.2. GHG capture

During the production of feed crops, there is a possibility to capture GHGs. To be more specific, the capture of GHGs is the sequestration of CO_2 from the air [58, 79]. In this study, the sequestration of CO_2 is called carbon capture. In Figure 2.7, the GHG balance that is created by including carbon capture is shown. During the crop cultivation stage, CO_2 sequestration is added to the GHG emissions overview, creating a GHG balance.

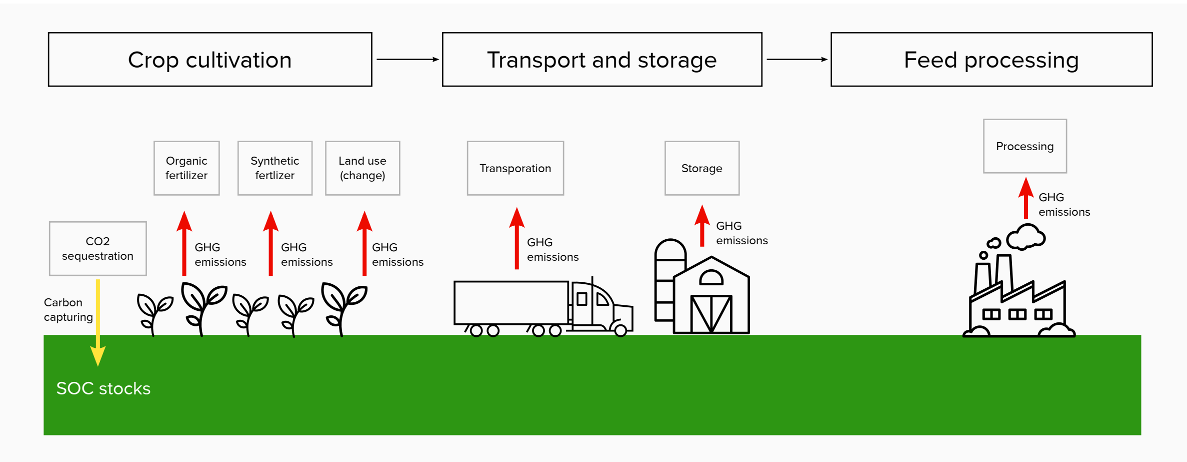

Figure 2.7: GHG balance livestock feed industry

Carbon capture can be increased by implementing regenerative agricultural practices. Furthermore, GHG emissions can be mitigated by introducing circular processes in the supply chain. Both regenerative practices and circular processes bring the GHG balance down.

Regenerative agriculture
Regenerative agriculture is the practice of restoring degraded soils to improve the Soil Organic Carbon (SOC) stocks [43, 109]. The FAO [25] defined SOC as: "*Organic carbon present in the fraction*

of soil that passes through a 2 mm sieve". SOC stocks in soil function as a carbon sink; these stocks sequester carbon from the atmosphere. The carbon sequestered by soil is improved by optimizing the regenerative agricultural practices.

The goal of regenerative agriculture is not just increasing SOC in soil. It has other benefits as well [43, 109]:

- Improvement of soil fertility
- Stimulation of biodiversity
- Availability of water
- Prevention of wind and water erosion

It has been ignored for a long time that the management of soil could increase the sequestration of capture from the atmosphere [90]. Research has proved that carbon capture cannot be ignored anymore [109]. Even the European Commission (EC) announced in December 2021 the Farm to Fork Strategy. This strategy includes short- to medium-term actions to assess the challenges of carbon farming. Also, a reward strategy to stimulate land owners to adopt carbon capture measures is included [22].

The amount of carbon capture depends on various factors. The primary influence factors are the type of land, the raw material grown on the land, the temperature, the precipitation, the use of manure and fertilizers and the management of the farming system.

Different types of land have different rates of carbon capture. Grassland has the ability to sequester more carbon than cropland [24, 25, 58, 79]. Thus, grassland is of greater importance for carbon capture since they have more SOC stocks than cropland [25]. Forests are the greatest carbon sinks, and they capture significantly more carbon than crop- and grassland. With deforestation these major sinks are lost and the captured carbon is released into the atmosphere [6, 43].
The type of crop grown on land influences the SOC stocks in the soil and, thus, the carbon capture. A study done by Mathew et al. [50] argues that land with grass or maize has the greatest ability to capture carbon in the soil. They unexpectedly found remarkably high SOC stocks in soil where maize and soy were rotated. This is, however, also influenced by the temperature and participation.
Besides all this, the SOC stocks are influenced by the use of synthetic and organic fertilizers. Nutrients in fertilizers contribute to the increase of SOC. Organic fertilizers have a greater contribution to SOC stocks than synthetic fertilizers [66, 88, 91, 109]. With synthetic fertilizer, the N fertilizers stimulate SOC stocks the most. Besides the nutrients, the increased biomass due to the use of fertilizers results in higher amounts of SOC stocks [25].

An extensive literature survey is done on regenerative agriculture and can be found in Appendix C. The different influence factors are further elaborated on per type of land.

Circularity
The inclusion of circular processes in the feed chain can help mitigate the release of GHG emissions. The goal of circularity is to create a loop of materials to reduce resource consumption and GHG emissions [87]. In the livestock feed industry, circularity can be reached in various ways. Firstly, by-products and waste streams, also known as secondary streams, from other industries, or the livestock industry itself, can be included as a source of feed. Secondly, secondary streams of the livestock industry can be used by other industries. Lastly, manure produced by livestock can be used as an organic fertilizer to stimulate the growth of feed crops.

Using secondary streams of other industries could help mitigate the GHG emissions of the livestock feed industry. Waste streams and by-products are usually more locally sourced products [71]. Using secondary streams means fewer primary crops are required and they could potentially replace soy products. This could help avoid the potential contribution to land use change, a process that is associated with significantly high GHG emissions. Research done by Pinotti et al. [56] states that there is a research and knowledge gap on the nutritional potential, the logistic processes and the life-cycle cost of using former food products and bakery by-products. Based on current findings, Pinotti et al. [56] hope to raise awareness and increase the interest in the potential of reducing emissions by using secondary streams. Research done by Mackenzie et al. [46] argues that the GHG footprint is not necessarily mitigated since the use of secondary streams often results in feed compositions with a lower energy density. The GHG emissions are therefore not always brought down.

Next, other industries can use the waste- and by-products of the livestock industry. Selling secondary streams could generate income for farmers which they can use to invest in systems to increase the environmental sustainability of their farming system. For example, residual wheat straw and corn husk biomass could be used as thermal isolation material for sustainable buildings in the construction industry [65]. This circular use does not only contribute to the mitigation of the GHGs of the livestock feed industry, but the high GHG emissions that are associated with the fabrication of insulation materials are reduced as well [65]. Another application of wheat straw is the possibility to produce cement from it. Thermal, acoustic, mechanical, and microstructural measurements already showed promising results for the use of wheat straw in cement [55].

The third possibility to introduce circularity is to use the manure from livestock as an organic fertilizer. The use of manure is already widely applied and is not a newly introduced form of circularity. It is, therefore, already discussed in Section 2.3.1.
The use of organic fertilizers could help reduce the GHG emissions of livestock feed because it could (partly) replace synthetic fertilizers. The GHG emissions associated with the production of synthetic fertilizers can be mitigated [24].

It should be further investigated whether introducing different options to increase circularity can help reduce GHG emission. The current situation should be compared to the newly created situations.

2.4. Flow diagram livestock industry

It is important to get a clear understanding of the current supply chain and flows within the livestock industry. New situations can be compared to the current situation. In this study, the current situation is used as the benchmark or reference case. The answer to the first sub-question, "what can be found on the GHG balance of the feed production of the livestock industry?", is summarized in a flow diagram. In Figure 2.8, the as-is situation of livestock industry is shown in a flow diagram with the associated GHG emissions.

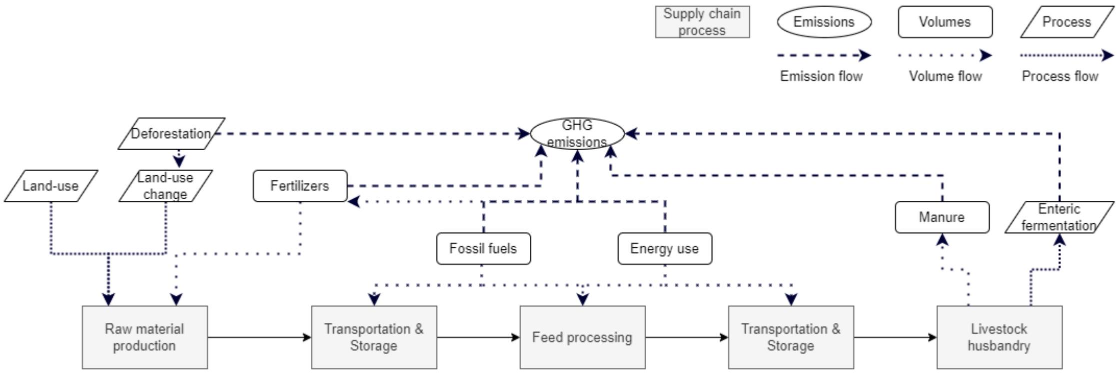

Figure 2.8: Flow diagram of the livestock industry as-is situation

In the grey boxes, the supply chain processes are shown. The emissions, volumes and processes influencing this supply chain processes are shown in the flow chart. In the circle sized boxes, GHG emissions are shown. Emission flows are marked with dotted lines as shown in the legend. In rectangular boxes volumes are shown, volume flows are indicated with thin dotted lines (see the legend). Processes are displayed in stretched rectangle-shaped boxes. Process flows are referred to in dense small dotted lines.

From the diagram, it becomes clear that the flow in the current livestock industry is horizontal. Feed production starts with the production of raw materials. To grow crops and grass, a high amount of land is required. Due to the growing demand for feed, there is a high rate of land use change. This results in the loss of carbon sinks [15, 35]. Besides this, during the raw material production, fertilizers are applied to crops to stimulate the growth, but are accompanied by GHG emissions [44].

After harvesting, the raw materials are transported, stored and processed. Fossil fuels and energy are used during these processes.

Finally, compound feed is transported to the livestock husbandry to feed the animals. During this stage of the livestock industry flow, there are emissions from manure and enteric fermentation. This part is, however, out of scope in this research.

In Section 2.3, the principles of circularity in the livestock feed industry are discussed, as well as the regenerative practices to increase the sequestration of CO_2 to capture carbon during crop cultivation of the livestock feed industry. A new flow diagram can be composed when considering these factors. A new flow diagram of the livestock industry is shown in Figure 2.9. In the new diagram, more circular flows and carbon capture are included. By plotting the release of GHG emissions against the capture of carbon, a GHG balance is created.

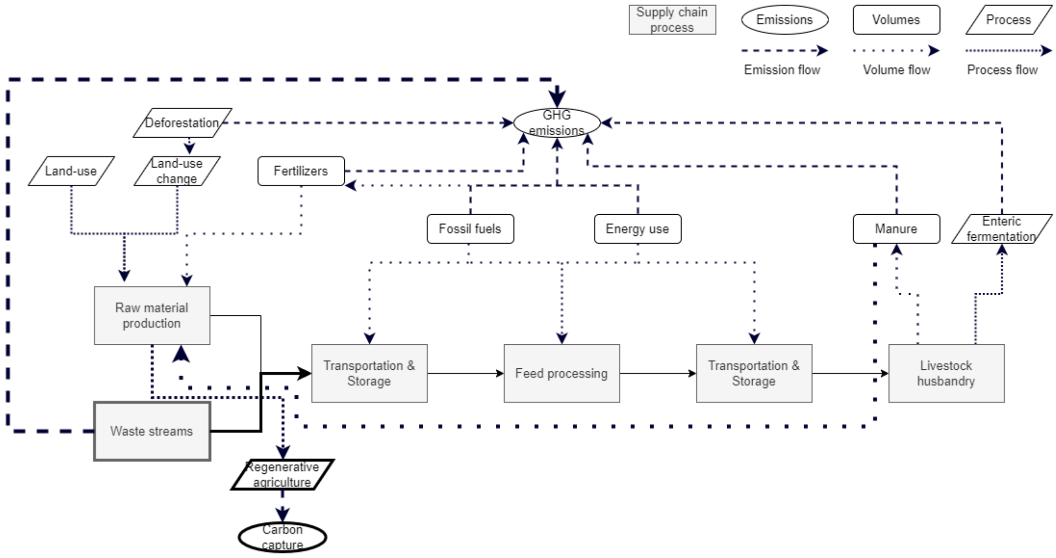

Figure 2.9: Circular flow diagram of the livestock industry including carbon capture

The newly added flows, processes and emissions are shown in bold. First of all, it can be seen in the flow diagram that not just crops from raw material production but also waste streams are the input for feed processing. The waste streams are responsible for a new source of emissions, but the amount of raw material that should be produced is brought back. The use of secondary streams is the first form of circularity that is introduced to the new flow diagram.
Secondly, the circular flow of manure from livestock husbandry is introduced. Manure is re-used as an organic fertilizer for raw material production.
Thirdly, GHG capture is newly introduced to the flow diagram as well. The sequestration of carbon from the atmosphere to capture carbon can be stimulated by introducing regenerative practices during raw material production.

In this study, the circular use of secondary streams, the circular use of manure and the potential of carbon capture are further investigated. The potential of all three processes to mitigate the GHG emissions is investigated.

3

Theory on composite indicators

The theory on a CI, or referred to as index, should be well researched to be able to construct an environmental performance index for livestock feed. The structure of a CI should be investigated as well as the possible methods that can be used. The theory gives a foundation for the construction of a sector-specific index for livestock feed. In this Chapter, the theory on the construction of CIs is outlined and the possible methods are elaborated on.

3.1. Performance measurement

Measurement of performance is relevant for decision-makers to assess the current performance to plan the next steps and future innovations [103]. Yildiz et al. [98] defined performance measurement as "the process of regular and systematic data collection, analysis and reporting to be used by a firm to follow up the resources it uses, the results it obtained with the produced goods and services".

Company performance measurement evolved from purely financial frameworks to frameworks that include both financial performance indicators and non-financial indicators. To reflect real-life situations and complex business environments, performance measurements is further developed over the years with more variables [100]. Zeng [100] concludes that the next step in performance measurement is the development of quantitative company performance measurement frameworks from an economic and an environmental perspective.

There is a rising demand for the inclusion of environmental indicators in performance measurement because environmental sustainability is becoming increasingly relevant as a strategic move for companies to boost customer success and employee satisfaction. Besides this, laws and regulation oblige companies to further enhance their environmental sustainable practices. A measurement system that tracks the implementation of environmental sustainability is required to determine the success of the implementation process [81]. An index or composite indicator is a recognized tool that allows decision-makers to compare a set of indicators to review the performance systematically. With an index, a set of indicators with varying units can be combined into a comparative quantitative scoring system [75, 81, 103, 104]. Azevedo et al. [3] proposed a definition of a composite indicator based on OECD (Organisation for Economic Co-operation and Development), Glossary of Statistical Terms: "A CI is formed when individual indicators are compiled into a single index by an underlying model of the multi-dimensional concept that is being measured.

3.2. Creating a composite indicator

A CI measures the multi-dimensional performance of a set of indicators by comparative quantification [75]. To create a CI different steps have to be taken. It involves selecting the underlying variables, scaling, weighting and aggregating these variables to finally post analyze the CI [3, 73, 101, 105]. The five phases are illustrated in Figure 3.1.

In every phase of the construction of a CI there exist different methods to complete it [105]. For every phase the possible methods are discussed below. For every application the appropriate method should be chosen [101].

In the process of creating a CI some choices and actions can be subjective and imprecise [73, 100,

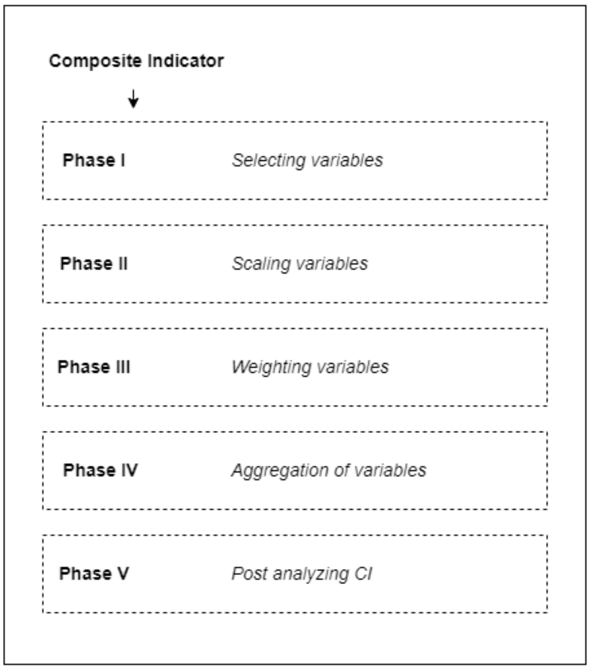

Figure 3.1: Construction CI

101]. Often it is argued that the subjective choices that have to be made when constructing an index bring uncertainty along. Subjectivity comes forward during different stages of creating a CI such as determining the relevant indicators, selecting the data, making assumptions on errors or data or during selecting weights and aggregation methods [73, 75]. It is important to ensure the choices made are justified and correct [75]. The quality and reliability of a CI is extremely important. A poorly constructed CI gives unreliable results and the outcome of the CI is misleading and incorrect [100].
A CI should be sector-specific, it is not possible to make a generalized CI for all sectors. To measure the performance of a company in a certain sector, the CI should include the appropriate variables for that sector to create an as accurate as possible CI [98]. The quality of data need to be good to ensure the CI is applicable for the sector. In case of lacking data, alternative methods can be implemented such as means substitution, correlation results or time series. It should be determined what the influence of the use of the alternative methods has on the finale result [75].

3.2.1. Phase I: Selecting variables

In the first phase a framework should be created that maps the components that should be assessed to measure the overall performance of a company, industry or product. Singh et al. [75] describes these components can be defined based on a combination of theory, empirical analysis, pragmatism, experts' opinion or intuition, or just one of these.
Theory that could be used with selecting variables is the following:

- Principle Component Analysis (PCA)
- Factor Analysis (FA)
- Cluster Analysis (CLA)

Principle Component Analysis (PCA) shows the correlation between different variables with a correlation matrix. This is a method to reduce the number of variables. PCA is further elaborated on in Section 3.2.3 [103].

The next method to select the different variables is Factor Analysis (FA). This method determines based on statistics whether the balance of the various variables is correct. Underlying factors describe the set of variables to reduce the dimensions and to clarify the relations between the variables [101].

Cluster Analysis (CLA) could be used to bring down the dimensions of an extensive amount of variables and data. This is done by clustering the information into piles based on the similarities between the different variables [73, 101]

3.2.2. Phase II: Scaling

The second phase consists of scaling. Scaling is the transformation or normalization of variables [13]. This should be done because the various variables do not have the same unit of measurement. By scaling the different variables the data can be compared to each other [3, 73]. There are different techniques to scale:

- Standardization
- Min-max Transformation
- Conventional Linear Scaling Transformation (LST)

The standardization (z value) is a normalization technique where all the values are standardized with an average of 0 and a standard deviation of 1. The standardized values can be positive and negative [75, 101]. A downside of standardization is that variables with extreme values could affect the CI in a greater way [3].

Another technique to scale variables is the min-max transformation, also know as re-scaling. This method is not based on the standard deviation but on the range. With min-max transformation the scaled variables are all expressed in values between 0 and 1. This method could be of worth when data are within a small range, min-max transformation could widen the intervals between the various variables. This widening of the range could, on the other hand, also be a possible downside. Extremes could become unreliable outliers [3, 30, 73, 101].

With the conventional Linear Scaling Transformation (LST) method variables are scaled relative to a reference. For this reference often the minimum and maximum value of the variable should be explored [75, 101].

3.2.3. Phase III: Weighting

A weighting system should be determined in the third phase. The weights are allocated to different variables and offer the opportunity to prioritize variables over others. The weights are used in the aggregation phase to combine all variables into one index value [75]. There are several methods to assign weights to variables:

- Principle Component Analysis (PCA)
- Fuzzy Logic (FL)
- Analytical Network Process (ANP) & Analytical Hierarchy Process (AHP)
- Shannon Entropy (SHE)
- Regression Analysis
- Delphi method

Principle Component Analysis (PCA) is a known multi-variate method to determine weights. The variables are weighted against a principle component with the proportion of variance in the set of variables [75]. This way dimensions of the data are reduced, while retaining the variation as much as possible. This is an appropriate method when the data consists a many correlated variables. Principle components are obtained, the high number of correlated factors are transformed into a a smaller amount of uncorrelated variables [73]. This method does not provide the statistical precision of the outcomes. This is especially important with a small sample size. This is a shortcoming of PCA.

Fuzzy Logic (FL) is an intelligent operational decision-making tool that makes it possible to include vagueness and subjectivity. Fuzzy logic provides the opportunity to represent a system in a more 'human' way. Normally, decision making by computers is done with a boolean code, this means the outcome is either 0 or 1. Fuzzy logic makes it possible to have a grey, non-bounded, area in the decision-making process.

Another technique that is widely used for determining weights is the Analytical Network Process (ANP) and the Analytical Hierarchy Process (AHP). ANP is a more general form of AHP, but the characteristics are quite similar. Both are rather subjective methods, the opinion of experts can be well reflected, the opinion is converted into a numerical value of importance [70, 101]. Both quantitative and qualitative factors are weighted based on the relative importance. The consistency of the comparison is verified by calculating the eigen values of a comparison matrix [101]. The difference between the ANP and AHP is that with ANP the multi-decision problem is modelled as a network and with AHP the problem is modelled as a hierarchy, so with different layers. The goal, the decision variables and the alternatives are structured in a hierarchy.

A more objective weighting method is the Shannon Entropy (SE) method. This technique has a higher accuracy. As the name indicates, this technique was first introduced in thermodynamics. Now it a widely used method across different sectors. This technique measures the uncertainty of an event when information is subjective of partially incomplete. A downside is, however, that it sometimes is not consistent with the real-life situation [101].

Regression analysis is based on statistics, it is independent of experts' opinion. This statistical method that is used to show the relationship between dependent variables and one or more independent variables [105].

Lastly, the Delphi method is technique used for weighting variables. This technique is based on information of a panel of experts. The formalized method extracts information by communicating with experts and obtaining a maximum amount of unbiased information. The uncertainty of the information can be quantitatively assessed [3, 100, 101]. This method is only appropriate to use when the experts are carefully selected [3].

There can also be decided to assign Equal Weights (EW) to all variables. This indicates all variables have the same importance in the composite indicator [3, 108]. Azevedo et al. [3] argues the choice for the EW approach is usually made due to simplicity reasons. Zeng et al. [101] confirms the simplicity of this method, but argues that it is hard to reflect on real-life situations with EW.

3.2.4. Phase IV: Aggregating

All the variables that are included in the CI are aggregated after a weight is assigned to the different variables. The aggregation of variables is the consolidation of different variables and the associated weights into an overall score of indexation [75]. Commonly used methods for aggregation are:

- Linear Aggregation Technique (LIN)
- Simple Additive Weighting (SAW)
- Weighted Geometric Aggregation (WGA)
- Grey Relational Analysis (GRA)

Linear Aggregation Technique (LIN) is a technique where a linear weighted sum combines the different variables into an index. With this method there is total compensation among the different variables. This means that a extremely bad performing variable can be compensated by a good performance of another variable [31].

Simple Additive Weighting (SAW) technique is also known as weighted sum method. This technique is widely used because the method is easy to understand and use. It is appropriate to use SAW when the assumption is made that the different variables in the CI are mutually preferentially independent [105].

This means the poor performance of one variable can be compensated by the good performance of another variable. Independency of the different variables is crucial for the application of linear methods, so this applies to SAW, but also to LIN [3, 101]. For SAW, however, research has shown that even if the independency assumption of the variables is not met, the SAW method still shows results that approaching the ideal value in an extremely close way [3].

Weighted Geometric Aggregation (WGA) is a method that aggregated by taking the product of weighted variables. Weighted product is a well-known multi-criteria decision-making (MCDM) [101]. This method handles partial compensability. This method can be used to have better reflections on situations where a limitation of one variable cannot be compensated by the other variables [105]. This method cannot be used when 0 is present in the dataset [101].

Another method for aggregation is Grey Relational Analysis (GRA). Both quantitative and qualitative variables can be analyzed and can be used in a non-linear model, which is a benefit compared to other correlation analysis techniques. Grey relation represents uncertainty about relationships among different variables of a system [101].

3.2.5. Phase V: Post analyzing

In the last phase, the CI should be validated. Continuous validation and adjustment results in an optimized CI [75]. This validation can be done with Uncertainty Analysis (UA) and Sensitivity Analysis (SA). Often one of the analysis techniques is chosen to post analyze the CI. However, the combination of the two techniques, make the biggest contribution to the transparency and the robustness of the CI [23, 101].

UA gives an insights on how the uncertainties of the input data are translated in the output of the CI [101]. In the ideal case, the uncertainties of every phase are investigated. This is, however, a time intensive process. [23].

SA is an important part of the validation of the CI. This analysis measures the sensitivity of input variables by evaluating the correlation ratios and sensitivity measures [101]. Sensitivity measures are assessed by evaluating the uncertainty of the overall CI per company, industry or product as a result of the a single source of uncertainty [23].

In general, the results of the uncertainty analysis are outlined per company, industry or product with the associated uncertainty bounds. The results of the sensitivity analysis are usually displayed as the sensitivity measure for each uncertainty input, so per input variable.

3.3. Summary

Performance measurement is relevant for decision-makers to assess the performance of a company to identify the problems and plan the next steps. A composite indicator is a recognized tool that could help review the performance. A CI makes it possible to systematically compare a set of indicators with different units of measurements. To reflect real-life situations and complex business environments a wide set of variables should be included. Over the years there has been a rising demand for the inclusion of environmental indicators next to financial indicators in performance measurement.

The construction of a CI consists of five phases. In the first phase the variables that should be included to measure the performance must be selected. Secondly, the variables should be scaled to get normalized values that can be combined in an index. In the third phase, the variables are weighted. Weights are assigned to the variables. In the fourth phase, the different variables with the accompanied weights are combined into a CI, this is called the aggregating phase. Finally, in the last phase the CI is post analyzed. It is important to conduct the post analysis to constantly improve the quality of the CI.

For every phase different methods can be used and the right method should be selected based on the nature of the CI. It is important a CI is sector-specific, because the appropriate variables should be included with accurate data and the right choices to get a correct result.
A literature matrix is created to get an overview of the methods used in other studies. The papers in the literature matrix are selected based on two criteria. The first criterion is that the paper has to discuss and research composite indices from, amongst other, an environmental perspective. The second criterion is that in the paper company or farm performance is measured. Performance measurements of countries is left out of scope of this matrix. Country performance measurement is very often done with Data Envelopment Analysis (DEA). This weighting technique makes it possible to find optimized weights per country to optimize the performance in the CI relative to other the other countries [64]. This technique does not contribute to the construction of a CI with the aim of this paper. The matrix is shown in Table 3.1. In the matrix, on x-axis the different methods are shown per phase. On the y-axis papers are listed that construct environmental composite indicators.

Table 3.1: Literature matrix composite indicator

	Selecting KPIs				Scaling			Weighting						Aggregation				Post	
	Expert/lit.	PCA	FA	CLA	Stand.	min-max	LST	PCA	FL	ANP/AHP	SHE	Reg.	Delphi	LIN	SAW	WGA	GRA	SA	UA
Zeng et al. 2020 [105]	x					x						x			x	x		x	
Seidel et al. 2019 [73]	x			x		x		x						x					
Zeng et al. 2018 [102]	x					x			x	x	x					x			
Azevedo et al. 2017 [3]	x					x							x		x				
Salvado et al. 2015 [70]	x					x				x				x					
Gómez-Limón and Sanchez-Fernandez 2010 [31]	x			x		x		x		x				x		x		x	
Gómez-Limón and Riesgo 2009 [30]	x					x		x		x					x	x			

In the literature matrix there can be seen that in the first phase, selecting variables, all papers made use of expert knowledge and literature studies to determine the important variables. Two papers brought the dimensions of the identified variables and data down with CLA. During the scaling phase, it is striking all papers used min-max transformation for the normalization of the variables. In the third phase, it can be seen that ANP/AHP and PCA are the most commonly used. FL, SHE, regression and the Delphi method are all used in one paper in the matrix. For the aggregation of the variables into an index there can be seen the choice for the method is equally distributed over LIN, SAW and WGA. The last phase, post analysis, is only conducted by two studies. Zeng et al. [102] and Azevedo et al. [3] recognize this phase should be carried out. Although in many studies the post analysis is left out of consideration, this was raised to do further research on. It is important to ensure the robustness and transparency of the CI [3, 23, 101, 103].

4

Creating an environmental composite indicator for livestock feed

The pressure on all parties in the livestock industry is increasing due to their enormous contribution to climate change. In fact, literature shows there is a rising interest in the optimization of feed mixtures from an environmental perspective. The necessity is even acknowledged that the traditionally used feed optimization models that include costs and nutritional values should be enhanced with environmental sustainability [46, 56].
Therefore, an environmental composite indicator should be created for the livestock feed industry to support better decision-making. The environmental CI should provide insights on the ingredient mix of feed compositions to livestock feed companies. Livestock feed companies can easily see the effects of changes in the feed composition on the environmental sustainability and economic performance. The index could also help with the decision-making process of farmers. Farmers that (partly) produce their own crops to feed their livestock could use the CI. Also, the CI could help farmers to assess the environmental performance of different feed producers to determine the most suitable producer of livestock feed.

4.1. Environmental performance index for livestock feed

The goal of an environmental performance index for livestock feed, or referred to as a composite indicator for livestock feed, is to be able to systematically compare feed compositions in terms of environmental sustainability performance and economic performance. The literature shows that traditional optimization models that include economic and nutritional performance should be enhanced with environmental sustainability performance. Therefore, an environmental performance index for livestock feed is created from an economic perspective. A trade-off is made between the economic performance and the environmental sustainability performance. The focus is put on mitigating the GHG emissions from livestock feed, while keeping the costs as low as possible.
The feed compositions that are inserted in the CI should comply with the nutritional values standards. Feed compositions are a mixture of different commodities from different origins. The proportion of every commodity in the mixture is known. A sector-specific environmental CI for livestock feed should be constructed that is able to compare different feed compositions to each other.

In Chapter 3 the construction of a CI is outlined including the different methods that could be used. To create a sector-specific CI for the livestock feed industry the appropriate methods should be selected. As described in Chapter 3 the construction process consists of five phases and for every phase a method should be chosen. Mazziotta and Pareto [51] made a framework to identify the right methods for an application. According to their framework, in the first phase, the selection of variables, there should be determined whether the indicators are substitutable or not. Variables are substitutable when compensation between different variables is possible. This is the main criterion that determines the method used in this phase. Next, the method for aggregation is determined in the framework. It distinguishes simple and complex aggregation methods. The choice of aggregation is based on the preference for a simple or complex method. This depends on the purpose of the CI. After aggregation, a method for determining weights should be assigned. Mazziotta and Pareto make a distinction between relative weighting methods and absolute weighting methods. Based on the type of comparison, relative or absolute, the framework determines the method for assigning weights based on the subjectivity or objectivity. In Appendix B the full framework can be found.

In this study, the appropriate methods for constructing a CI are determined based on the findings in Chapter 3 and the framework constructed by Mazziotta and Pareto [51]. In Figure 4.7 the construction of the environmental performance index for livestock feed with the selected methods is shown.

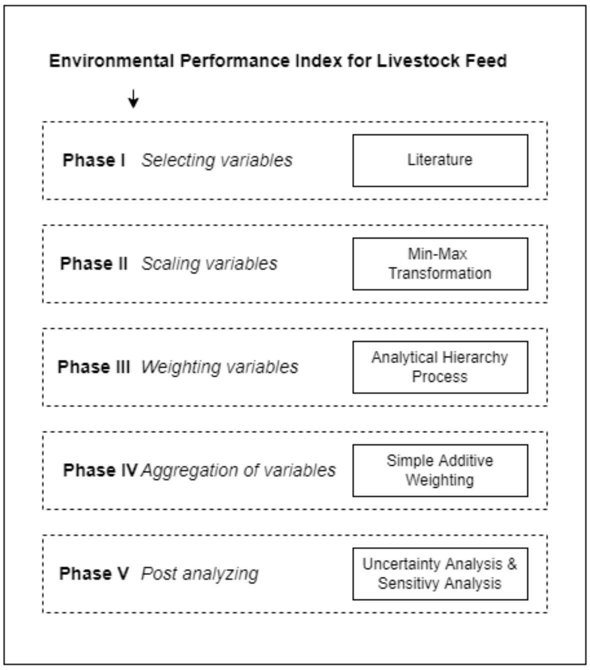

Figure 4.1: Construction environmental performance index for livestock feed

In this Figure there can be seen that for every phase of the construction of a CI a technique is selected. To create a composite indicator for the feed production of the livestock industry that assesses feed compositions, first the relevant variables are determined with knowledge from literature. This commonly used method is selected since relevant theory can be found and it provides the desired depth of information. The other methods are not relevant in this case since the variables will consist of one dimension.
Secondly, the selected variables are scaled using min-max transformation. This method is selected because in literature this is a commonly used method and the framework of Mazziotta and Pareto [51] identified this as the most appropriate method as well. This method is suitable because the spread of the data of livestock feed will not be extremely big. This technique will create a wider spread between the individual normalized values. A downside of this method could be that extreme values could become unreliable outliers, but the data set on livestock feed will not contain extreme values.
After the variables are normalized, weights are assigned to every variable using the analytical hierarchy process. This is the most appropriate method since the expert opinion can be well reflected while still computing the weights through a statistical model. It is important to have a participatory method where the experts opinion can be included because not every company has the same point of view on the distinction between the importance of economic and environmental sustainability performance.
Next, the aggregation of these weights and normalized variables is done with simple additive weighting. Simple additive weighting is widely used method that is simple to understand. This is necessary because the CI could be used by a wide range of people and companies. Following the framework designed by Mazziotta and Pareto [51], this means multivariate analysis such as PCA is not suitable and a mathematical function should be selected. Next to this, simple additive weighting requires the variables to be mutually preferentially independent. This means there is compensation amongst the

variables. This is preferred in the CI for livestock feed because a GHG balance requires compensation. Lastly, the CI is post analyzed with two different methods, namely sensitivity analysis and uncertainty analysis. These two methods should be combined to increase the transparency and robustness of the CI.
To be able to formulate the mathematical model of the CI, the chosen methods are elaborated on in more detail.

4.1.1. Phase I: Selecting variables

Relevant variables should be defined in the first phase of creating a CI for livestock feed. The variables are selected based on literature and verified with experts from the livestock feed industry. To determine the relevant variables, the purpose of the CI for livestock feed should be clear.
The goal of the CI is that the decision-making process of feed production companies, and possibly farmers, is optimized in terms of sustainability. As companies are the intended user, the economic perspective should also be included. Maximizing profits is (one of) the goal(s) of a company, and this cannot be left out of consideration when designing a decision-making model for companies. Thus, the goal is to create an environmental CI for the livestock feed industry from an economic perspective. The nutritional performance is left out of the CI, because it is assumed the feed compositions that are inserted in the CI have the correct nutritional values, otherwise it would not make sense to even dive deeper into the costs and the environmental sustainability.

Environmental sustainability performance variables

In Chapter 2.3 the GHG footprint of the livestock feed industry is elaborated on. Different sources of emissions are identified and the possibility to capture carbon is discussed. The GHG balance of livestock feed depends on the identified sources of emissions and carbon capture. These different sources determine the environmental sustainability performance.
The input variables to measure the environmental sustainability performance are based on the sources due to which GHG emissions are released and the sources of carbon capture, identified in Chapter 2.3. The identified sources are: LU, emissions from LUC, emissions from synthetic and organic fertilizers, emissions from transportation, emissions from storage, emissions from processing and carbon capture.

Economic performance variables

In the literature, livestock feed optimization models take the economic performance into consideration, but limited research is done on the inclusion of the environmental sustainability performance [4, 61]. This means a literature study had to be done to determine the relevant variables for the environmental sustainability performance, but for the economic performance this is already determined. Based on literature, the variables that determine the economic performance of livestock feed are identified. This selection is verified with experts. The economic performance can be determined based on three variables. The costs of commodities, the costs of transportation and the costs of storage are identified as important factors determining the economic performance.

All variables, the environmental sustainability and economic variables, are shown in Table 4.1.

Dimension		Variable	Unit	Impact
Environmental sustainability performance	V_1	Land use	$[\frac{m^2 a\ eq}{kg\ crop}]$	-
	V_2	Emissions LUC	$[\frac{kg\ CO_2 eq.}{kg\ crop}]$	-
	V_3	Production and use synthetic fertilizers	$[\frac{kg\ CO_2 eq.}{kg\ crop}]$	-
	V_4	Use organic fertilizers	$[\frac{kg\ o.\ fert.}{kg\ crop}]$	-
	V_5	Emissions transportation	$[\frac{kg\ CO_2 eq.}{kg\ crop}]$	-
	V_6	Emissions storage	$[\frac{kg\ CO_2 eq.}{kg\ crop}]$	-
	V_7	Emissions processing	$[\frac{kg\ CO_2 eq.}{kg\ crop}]$	-
	V_8	Carbon capture	$[\frac{kg\ CO_2 eq.}{kg\ crop}]$	+
Economic performance	V_9	Commodity costs	$[\frac{€}{kg\ crop}]$	-
	V_{10}	Transportation costs	$[\frac{€}{kg\ crop}]$	-
	V_{11}	Storage costs	$[\frac{€}{kg\ crop}]$	-

Table 4.1: Selection of variables

Variable one to eight determine the environmental sustainability performance. The last three variables, variable nine to eleven, determine the economic performance. The units and impacts associated with every variable are outlined as well. There are two impact categories. '+' means the larger the value of the variable, the better the result. '–' represents the smaller the value of variable is, the better result. There can be seen that only for carbon capture (V_8) the '+' impact applies, because the higher the carbon capture is, the better the GHG balance gets.

The notations employed in the model are as follows:

x_{ij}^t	Raw value of individual variable j for feed composition i at time t
$x_{ij}^{*,t}$	Normalized value of individual variable j for feed composition i at time t
CI_i^t	Value of the composite indicator for feed composition i at time t.
W_j	Weight associated to individual variable j
i	Feed composition i with $i = 1, 2, ..., n$
j	Individual variable j with $j = 1, 2, .., 11$
k	Element of feed composition i with $k = 1, 2, ..., m$

4.1.2. Phase II: Scaling

Min-max transformation is the selected method to normalize the variables. The variables are made dimensionless using this scaling method. In Equation 4.1 the formula to obtain the normalized values is shown [105].

$$x_{ij}^* = \frac{x_{ij} - min_i x_{ij}}{max_i x_{ij} - min_i x_{ij}} \tag{4.1}$$

In this formula $min_i x_{ij}$ is the lowest value present in the data set of variable j over all feed compositions i. $max_i x_{ij}$ is the maximum value present in the data of variable j over all feed compositions i.

In Table 4.1 the impact of every variable is shown. There can be seen that all variables satisfy the

'-' impact, which means 'the smaller the variable, the better'. Only for carbon capture (V_8) the higher the variable, the better this is for the environmental sustainability. The min-max transformation formula should be adjusted because the two impact categories are present in the CI [105]. The scale should be reverted. The formula is shown in Equation 4.2.

$$x_{ij}^{*} = \begin{cases} \frac{max_i\, x_{ij} - x_{ij}}{max_i\, x_{ij} - min_i\, x_{ij}}, & \text{for '+' impact} \\ \\ \frac{x_{ij} - min_i\, x_{ij}}{max_i\, x_{ij} - min_i\, x_{ij}}, & \text{for '-' impact} \end{cases} \tag{4.2}$$

4.1.3. Phase III: Weighting

The technique adopted to formulate weight factors is the Analytical Hierarchy Process. This multi-criteria decision making (MCDM) method is described by Saaty (1987). Decision variables can be compared to each other by prioritizing criteria over others and an overall ranking can be obtained. A pair-wise comparison matrix is created by assigning priorities to the variables by assessing the relative importance. The relative importance can be judged with a scale proposed by Saaty [68]. He introduced a fundamental linear scale that runs from 1 to 9 [68]. 1 represents equal importance between two variables. If there is a moderate importance of one variable over another this is represented with 3. 5 is considered when there is an essential or strong importance of one variable over another variable. When there is a very strong importance of one variable over another an intensity of importance of 7 should be assigned and 9 is considered when an extreme level of importance should be represented [68].

The weight factors can be determined with a pair-wise comparison matrix. This matrix is shown in Table 4.2. The levels of importance should be determined per application or sector, because the level of importance of the different variables can differ per sector, company or user of this CI. A non-implemented version of a pair-wise comparison matrix is shown in the Table. The matrix is a $(11 * 11)$ matrix since there are 11 independent variables determined for this application.

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	*Weight*
V_1	1	a	b	c	d	e	f	g	h	i	j	W_1
V_2	$\frac{1}{a}$	1	k	l	m	n	o	p	q	r	s	W_2
V_3	$\frac{1}{b}$	$\frac{1}{k}$	1	t	u	v	w	x	y	z	aa	W_3
V_4	$\frac{1}{c}$	$\frac{1}{l}$	$\frac{1}{t}$	1	ab	ac	ad	ae	af	ag	ah	W_4
V_5	$\frac{1}{d}$	$\frac{1}{m}$	$\frac{1}{u}$	$\frac{1}{ab}$	1	ai	aj	ak	al	am	an	W_5
V_6	$\frac{1}{e}$	$\frac{1}{n}$	$\frac{1}{v}$	$\frac{1}{ac}$	$\frac{1}{ai}$	1	ao	ap	aq	ar	as	W_6
V_7	$\frac{1}{f}$	$\frac{1}{o}$	$\frac{1}{w}$	$\frac{1}{ad}$	$\frac{1}{aj}$	$\frac{1}{ao}$	1	at	au	av	aw	W_7
V_8	$\frac{1}{g}$	$\frac{1}{p}$	$\frac{1}{x}$	$\frac{1}{ae}$	$\frac{1}{ak}$	$\frac{1}{ap}$	$\frac{1}{at}$	1	ax	ay	az	W_8
V_9	$\frac{1}{h}$	$\frac{1}{q}$	$\frac{1}{y}$	$\frac{1}{af}$	$\frac{1}{al}$	$\frac{1}{aq}$	$\frac{1}{au}$	$\frac{1}{ax}$	1	ba	bb	W_9
V_{10}	$\frac{1}{i}$	$\frac{1}{r}$	$\frac{1}{z}$	$\frac{1}{ag}$	$\frac{1}{am}$	$\frac{1}{ar}$	$\frac{1}{av}$	$\frac{1}{ay}$	$\frac{1}{ba}$	1	bc	W_{10}
V_{11}	$\frac{1}{j}$	$\frac{1}{s}$	$\frac{1}{aa}$	$\frac{1}{ah}$	$\frac{1}{an}$	$\frac{1}{as}$	$\frac{1}{aw}$	$\frac{1}{az}$	$\frac{1}{bb}$	$\frac{1}{bc}$	1	W_{11}

Table 4.2: Pair-wise comparison matrix livestock feed

After the parameters are formulated, the associated weights can be found by determining the principal eigenvector of the matrix. The weights of the different variables are obtained by normalizing the results of the principle eigenvector [68].
The consistency of the matrix should be checked to determine whether a coherent representation of the set of facts is formulated. This is important since an error in the measurement of consistency could appear because human judgement is involved with assigning the levels of importance to the various variables. Saaty [68] handles an inconsistency of 10%, this means the consistency ratio must not exceed 0.10. The Consistency Ratio (CR) can be determined by dividing the Consistency Index (CI)

with the Random consistency Index (RI). Equation 4.3 shows the equation for the consistency ratio [68].

$$CR = \frac{CI}{RI} \tag{4.3}$$

With Equation 4.4 the consistency index (CI) can be determined.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{4.4}$$

Where λ_{max} is the principle eigenvalue and n is the number of columns or rows of the pair-wise comparison matrix (n x n matrix).

The random consistency index (RI) is formulated by Saaty [68]. Using a fundamental linear scale, a reciprocal matrix is randomly generated. The random consistency index is obtained to determine if the CR exceeds 0.10. The average random consistency index with a sample size of 500 matrices is shown in Table 4.3. The RI can be found for $n = 1, 2, .., 10$ in the Table.

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Table 4.3: Random consistency index [68]

When the consistency ratio (CR) is below 0.10 the pair-wise comparison matrix is consistent. If it is 0.10 or above the problem should be looked at again and the judgement of the different variables should be revised [68].

4.1.4. Phase VI: Aggregating

The weight factors and the normalized variables are consolidated into the CI using Simple Additive Weighting. This relatively simple aggregation technique is a linear summation method. In Equation 4.5 the formula for SAW is shown [30, 73].

$$CI_i = \sum_{j=1}^{11} W_j x^*_{ij} \tag{4.5}$$

Where CI_i is the value for the composite indicator of feed composition i. W_j is the weight of variable j. The normalized value of feed composition i and variable j is represented with x^*_{ij}.

4.1.5. Phase V: Post analyzing

An uncertainty analysis and sensitivity analysis should be done to validate the constructed CI. It is done to ensure the robustness and transparency of the CI. The post analysis should be done to continuously optimize the CI [75].

Uncertainty analysis

Uncertainty analysis gives an insights on how the uncertainties of uncontrollable inputs are translated in the output of the CI [101]. Possible uncertainties appear in every phase of the construction of the CI. Ideally, all these uncertainties are assessed with the uncertainty analysis [23]. For the environmental CI for livestock feed the most relevant sources of possible uncertainty are selected. The sources of uncertainty that should be investigated are the scaling method and the selection of weights [23].

First, another scaling method could be implemented to investigate the uncertainty of the min-max transformation. With min-max transformation extreme values can become unreliable outliers. The conventional Linear Scaling Transformation (LST) method could take extreme values into account better. The intervals between the individual values could, however, become not wide enough. The LST method scales the variables with respect to an external reference or benchmark [75, 101]. A minimum and maximum value for the variables should be defined as a point of reference [75]. In Equation 4.6

the formula to scale the variables is shown. The external benchmark (y) can be determined based on the selected situation or case.

$$x^*_{ij} = \frac{x_{ij} - min\, y_j}{max\, y_j - min\, y_j} \tag{4.6}$$

Where $min\, y_j$ is the minimum value of the external reference for variable j and $max\, y_j$ is the maximum value of the external reference for variable j.

As for the min-max transformation, the formula needs to be adjusted because of the two impact categories. The variable for carbon capture (V_8) satisfies the 'the higher, the better' impact. The other variables have a '-' impact, which means 'the smaller the variable, the better' [105]. The scale is reverted. The formula is shown in Equation 4.7.

$$x^*_{ij} = \begin{cases} \frac{max\, y_j - x_{ij}}{max\, y_j - min\, y_j}, & \text{for '+' impact} \\ \\ \frac{x_{ij} - min\, y_j}{max\, y_j - min\, y_j}, & \text{for '-' impact} \end{cases} \tag{4.7}$$

Equation 4.6 and Equation 4.7 are similar to Equation 4.1, but in the case of LST external minimum and maximum values are used. For min-max transformation the minimum and maximum values are based on the data set.

Secondly, the weights are selected using the AHP. This method includes subjective judgement when determining the relative importance of the variables. Subjectivity brings uncertainty along [31], but is relevant in the case of the environmental CI for livestock feed. The uncertainty should therefore be assessed by formulating different plausible values for the relative importance of the different variables.

The results of the UA are compared to the results of the environmental performance index with Pearson's correlation test (2-tailed). With this test it is calculated whether there is a correlation between two sets of values [105]. The correlation coefficient measures the strength of the relationship between variables [40]. So, the results from the CI are compared to the values calculated with the alternative scaling method and the alternative selection of weights. The correlation between the results can vary between -1 and 1. -1 represents a perfect negative correlation and 1 indicates a perfect positive relationship. No correlation is indicated with 0. Correlation coefficients higher than $\pm\ 0.60$ show there is a strong correlation [40].

For both UA hypotheses are tested. For the UA of the scaling method the following hypotheses are set up:

- Null hypothesis (H_0): There is no correlation between the results of the CI computed with different scaling methods
- Alternative hypothesis (H_1): There is a positive correlation between the results of the CI computed with different scaling methods

For the UA of the alternative selection of weights, these hypotheses are defined:

- Null hypothesis (H_0): There is no correlation between the results of the CI computed with differently selected weights
- Alternative hypothesis (H_1): There is a positive correlation between the results of the CI computed with differently selected weights

Given the sets $(a_1, b_1), (a_2, b_2), (a_3, b_3), (a_4, b_4), (a_5, b_5), (a_n, b_n)$, the correlation coefficient (r) can be found with Equation 4.8 [40].

$$r = \frac{n \sum ab - \sum a \sum b}{\sqrt{(n \sum a^2 - (\sum a)^2)(n \sum b^2 - (\sum b)^2)}} \tag{4.8}$$

Where n is the sample size, this is the number of pairs of values.

It should be determined whether the correlation coefficient is statistically significant. A critical significance level of $\alpha = 0.05$ is handled for the 2-tailed test. The t-value can be calculated with the t-distribution formula, shown in Equation 4.9.

$$t = r\sqrt{\frac{n-2}{1-r^2}} \tag{4.9}$$

In this Equation, t is t-value, n represents the sample size and r is the correlation coefficient.
The 2-tailed p-value is determined from the t-value. If $p < \alpha$, the H_0 is rejected. If $p > \alpha$, H_1 is rejected.

Sensitivity analysis
The sensitivity analysis is a crucial part of the validation of the CI. This analysis measures the sensitivity of input variables by evaluating the correlation ratios or importance measures [101]. The variation in the output of the CI as a reaction to variation of different sources of input is evaluated. Importance measures are assessed by evaluating the uncertainty of the overall CI per feed composition if the uncertainty of one of the input variables is removed [23].
Variance-based sensitivity analysis is recommended to use to validate composite indicators [69, 100]. With the variance-based technique the range of variation of the input variables or the interaction among input variables or groups of input variables can be investigated [69].

For the environmental performance index, it is examined how the variation of the output is connected to the variation of the input variables. Per individual variable j, 20% it added to the value. The impact of this increase on the results of the CI is evaluated with the 2-tailed Pearson's correlation test. The level of correlation indicates the level of impact of the variation of a variable.

4.2. Data collection

The goal of the environmental CI for livestock feed in to systematically compare feed compositions in a quantitative way to each other. A feed composition is a mixture of different commodities with different origins. The proportions of every commodity in the mixture are known and add up to a 100%.

In Phase I of the CI a set of variables is formulated. In order to evaluate these variables, data for each variable should be obtained per feed composition. The data per variable for a feed composition are based on the data of the different commodity present in the feed mixture.
Ideally, primary data should be implemented in the CI. If primary data are not available secondary data sources can be used [95]. The outcome of the CI is based on environmental sustainability and economic performance.

In this Section, the data required to make optimal use of the environmental CI for livestock feed is outlined. With the prescribed data collection, data should be obtained for all the individual commodities present in a feed composition i. Per crop k, data should be determined for all eleven variables, so for variable j. The data of all the commodities in a feed composition are combined for every variable into one value with Equation 4.10.
For every feed composition i that is evaluated with the environmental CI for livestock feed, the data should be obtained in the format as shown in Table 4.4.

Commodity	*Origin*	*Proportion in composition [%]*	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}
Crop 1	A	p_1	$z_{1,1}$	$z_{1,2}$	$z_{1,3}$	$z_{1,4}$	$z_{1,5}$	$z_{1,6}$	$z_{1,7}$	$z_{1,8}$	$z_{1,9}$	$z_{1,10}$	$z_{1,11}$
Crop 2	B	p_2	$z_{2,1}$	$z_{2,2}$	$z_{2,3}$	$z_{2,4}$	$z_{2,5}$	$z_{2,6}$	$z_{2,7}$	$z_{2,8}$	$z_{2,9}$	$z_{2,10}$	$z_{2,11}$
Crop ...	C	$p_{..}$	$z_{..,1}$	$z_{..,2}$	$z_{..,3}$	$z_{..,4}$	$z_{..,5}$	$z_{..,6}$	$z_{..,7}$	$z_{..,8}$	$z_{..,9}$	$z_{..,10}$	$z_{..,11}$
Crop m	D	p_m	$z_{m,1}$	$z_{m,2}$	$z_{m,3}$	$z_{m,4}$	$z_{m,5}$	$z_{m,6}$	$z_{m,7}$	$z_{m,8}$	$z_{m,9}$	$z_{m,10}$	$z_{m,11}$

Table 4.4: Data collection per feed composition i

Where [A,B,C,D] are random origins and p is the proportion of crop k with k = [1,2,...,m] in feed composition i. The proportions in every feed composition should add up to a 100%. $z_{k,j}$ is the value for element k of variable j.
The value for all eleven variables should be determined per crop per origin. After this is done for feed composition i, a single value should be determined for every variable j with Equation 4.10.

$$x_{ij} = \sum_{k=1}^{m} z_{ijk} p_{ik} \tag{4.10}$$

Where x_{ij} is the value for variable j for feed composition i. These values should be combined in a data set, shown in Table 4.6.

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}
Feed composition 1	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,4}$	$x_{1,5}$	$x_{1,6}$	$x_{1,7}$	$x_{1,8}$	$x_{1,9}$	$x_{1,10}$	$x_{1,11}$
Feed composition 2	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,4}$	$x_{2,5}$	$x_{2,6}$	$x_{2,7}$	$x_{2,8}$	$x_{2,9}$	$x_{2,10}$	$x_{2,11}$
Feed composition ..	$x_{..,1}$	$x_{..,2}$	$x_{..,3}$	$x_{..,4}$	$x_{..,5}$	$x_{..,6}$	$x_{..,7}$	$x_{..,8}$	$x_{..,9}$	$x_{..,10}$	$x_{..,11}$
Feed composition n	$x_{n,1}$	$x_{n,2}$	$x_{n,3}$	$x_{n,4}$	$x_{n,5}$	$x_{n,6}$	$x_{n,7}$	$x_{n,8}$	$x_{n,9}$	$x_{n,10}$	$x_{n,11}$

Table 4.5: Data collection for the environmental CI for livestock feed

This format is compatible with the Python model created for the environmental CI for livestock feed.

For the data collection of the values for the individual variables (z_{ij}) that determine the environmental sustainability performance and the economic performance, a decision tree is introduced about the data needs. The decision tree clarifies what data are preferred with respect to the origin of the commodity. This is shown in Figure 4.2

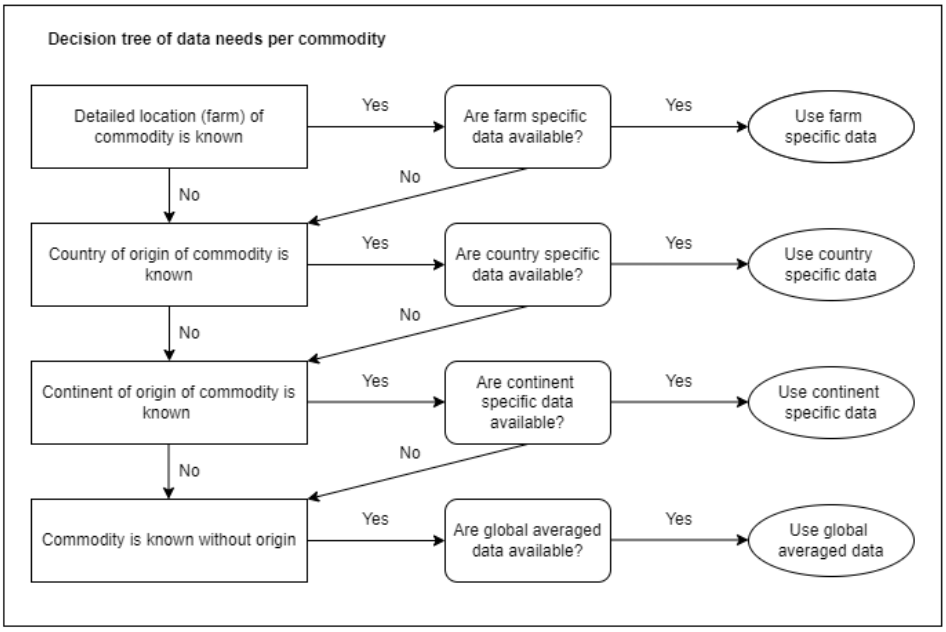

Figure 4.2: Decision tree of data need per commodity k

The decision tree should be used for every variable that is included in the environmental CI.

4.2.1. Environmental performance data

The total environmental performance is determined based on a set of eight variables, as described in Section 4.1.1. Six of the eight variables have the same unit, namely $\frac{kg\ CO_2eq.}{kg\ crop}$. As described in Section 1.5, CO_2-eq is the overarching unit to express the combined GWP of CO_2, NH_4 and N_2O.

The two variables that determine the environmental sustainability performance that are not expressed in $\frac{kg\ CO_2 eq.}{kg\ crop}$ are land use (V_1) and the use of organic fertilizers (V_4). Land use is measured in $\frac{m^2 a\ eq}{kg\ crop}$. This unit is land use area per unit of time per kilogram of crop. Criterion 4 has the unit $\frac{kg\ o.\ fertilizer}{kg\ crop}$. The amount of organic fertilizer applied per kilogram of crop is required.

For each individual variable, data should be obtained to be able to include the individual variables in the CI. Every feed composition i consists of different commodities k with an associated origin. The necessary data that should be determined per commodity per variable are discussed in this sub-section.

Land use
Land use is a variable that should be included to determine the environmental sustainability performance. Data should be available on land use per crop per origin. The unit of land use is the occupation of land over time per kilogram of crop, $\frac{m^2 a}{kg\ crop}$.

GHG emissions land use change
GHG emissions from LUC should be included in the CI to measure the environmental sustainability performance. Data should be available per type of crop per country of origin. The unit of measurement for the emissions from LUC is $\frac{kg\ CO_2 eq.}{kg\ crop}$.

Production and use of synthetic fertilizers
Data on the production and the use of synthetic fertilizers should be obtained to include this variable in the CI. Data on the production of synthetic fertilizers is expressed in $\frac{kg\ CO_2 eq.}{kg\ crop}$. Data on the GHG emissions of the production and use of fertilizers should be available.

Use of organic fertilizers
The amount of manure used as organic fertilizer is one of the variables that determines the environmental sustainability performance. Data on the use of organic fertilizers per kilogram of crop per origin should be available. This is expressed in $\frac{kg\ o.\ fert.}{kg\ crop}$.

GHG emissions transportation
The GHG emissions related to the transportation of commodities should be determined. Emissions associated with transportation should usually be derived from other values and data. There are several methods to calculate these GHG emissions. Three commonly used techniques are the fuel method, the distance method and the expenditure method. The fuel-based method determines the GHG emissions based on the amount of fuel used. The right emission factors is applied to convert this to GHG emissions. The distance-based method relies on the mass, the distance and the mode of transport. The appropriate emission factors for the transport mode should be applied. Lastly, the expenditure-based method determined the GHG emissions based on the amount of money spent on a mode of transport and the corresponding emission factors [95].
The fuel-based method gives the most accurate results when estimating GHG emissions and is the preferred method if the data availability allows this. However, often data on fuel is unavailable since independent companies handle the transport. Therefore, in most cases the distance-based method is the most appropriate. The expenditure-based method is the least preferred option since it is imprecise, this should only be used when no data on distance and fuel are available [12].

To determine the GHG emissions from transportation using the distance-based method the travelled distance, the mode of transport and the mass of the cargo should be available. When the CI for livestock feed is brought into practice, data on the travelled distance and the GHG emissions per mode of transport should be available. The GHG emissions of transportation are expressed in $\frac{kg\ CO_2 eq.}{kg\ crop}$. This means the mass of the cargo is in this case always 1 kg. The travelled distance should be expressed in kilometers (km) and the GHG emissions per transport mode in kilograms CO_2-eq per tonne-kilometers ($CO_2 eq/tkm$). This is visualized in Figure 4.3.

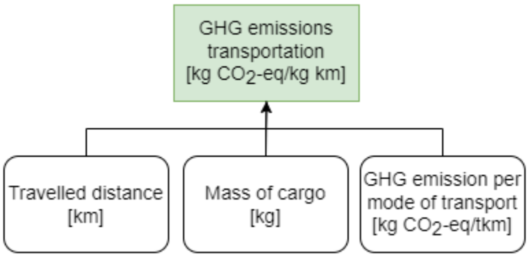

Figure 4.3: Data collection GHG emissions from transportation

An even more accurate picture on the GHG emissions of transportation can be obtained by including the Fill Rate (FR) of the mode of transport. This can be taken into account when the data are available. In Equation 4.11 the formula is shown to calculate the GHG emissions from transportation. The GHG emissions of transportation per element k for criterion 4 are calculated.

$$z_{i4k} = \frac{d_{ik} * m_{ik} * GHGM_{ik}}{FR_{ik}} \tag{4.11}$$

In this formula, d_{ik} is travelled distance of element k of feed composition i. The m_{ik} represents the mass of element k in feed composition i. The GHG emissions of transportation are calculated per kilogram, so m_{ik} is $1\ kg$. Lastly, $GHGM_{ik}$ is the GHG emission of the transport mode used at element k of feed composition i. FR_{ik} is the fill rate of the truck or ship of element k in feed composition i.

GHG emissions storage

In the CI the environmental sustainability performance is based on the GHG emissions from storage as well. The availability of data on storage should be available. In the ideal case, the period of storage and the emissions per type of storage should be known. The two information sources necessary to determine the GHG emissions from storage are visualized in Figure 4.4

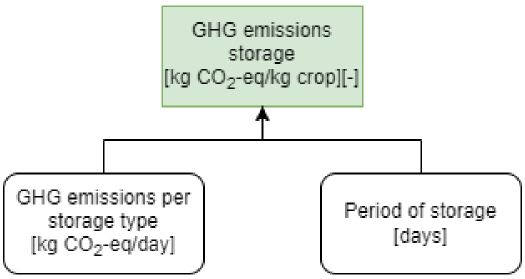

Figure 4.4: Data collection GHG emissions from storage

Equation 4.12 can be used to obtain the value for the GHG emissions from storage.

$$z_{i6k} = SP_{ik} * GHGS_{ik} \tag{4.12}$$

Where SP_{ik} is the storage period of element k in feed composition i. $GHGS_{ik}$ refers to the GHG emission of the storage type used at element k of feed composition i.

Emissions processing

Variable 8 in the CI is 'emissions processing'. Data should be available on the GHG emissions of processing. When determining the emissions from processing, two sources of processing should be taken into account. First of all, the processing of the commodity into different products. Next, the processing of creating compound feed in the feed mill. The GHG emissions from processing are measured in $\frac{kg\ CO_2}{kg\ crop}$.

Carbon capture

Carbon capture can be included in the environmental performance index. It is measured in $\frac{kg\ CO_2}{kg\ crop}$. Th increase of SOC per kilogram of crop should be taken into account. Carbon in the soil can be be converted to CO_2. The amount of carbon capture in the form of carbon dioxide is obtained by multiplying SOC by 3.67 [42].
Carbon capture should, ideally, be farm specific, since regenerative agricultural practices can help increase the SOC stocks. Farm specific data are currently unavailable, because the measurement of SOC in soil is expensive and time consuming.

4.2.2. Economic performance data

The economic performance is defined based on three variables. These variables are listed in Table 4.1, namely commodity costs, transportation costs and storage costs. All three variables are expressed in $\frac{€}{kg\ crop}$. For each variable data should be obtained to include the variable in the CI. In this sub-section, the data that should ideally be gathered per variable are discussed.

Commodity costs

The costs of the different commodities of the feed composition should be available. The price per kilogram of crop should be included. Ideally, the real cost price of the commodity is used. This is possible when the commodity is already acquired by the user of the CI. Otherwise, costs should be based on historical data of commodity prices.

Transportation costs

The costs related to transportation of commodities should be determined. The real costs of transportation per kilogram crop should be used in the CI if this is known by the user of the environmental CI for livestock feed. If the commodities are not transported yet and the real price is not known, the distance to be travelled by the commodity and the costs per mode of transport should be known. This is shown In Figure 4.5.

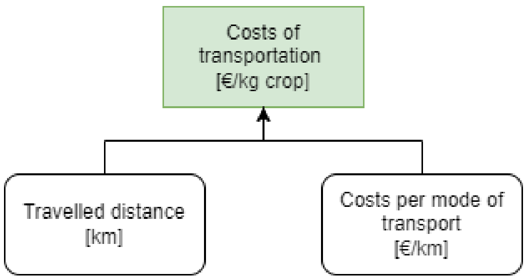

Figure 4.5: Data collection costs of transportation

Storage costs

The storage costs should be included in the CI. The availability of data on storage should be ensured. The costs of storage is either known by the user of the CI or it should be determined from other variables. To indirectly determine the costs associated with storage the period of storage should be know as well as the costs per storage type per day, see Figure 4.6.

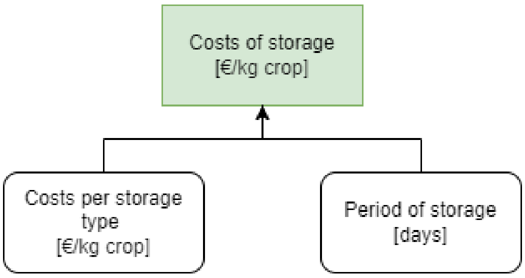

Figure 4.6: Data collection costs of storage

4.2.3. Allocation

The feed composition consists of different elements k. These elements can be final products, co-products, by-products or waste streams. This means an allocation method should be handled to determine what part of the total amount of for example the GHG emissions, total land use, total organic fertilizers used and costs should be assigned to which product.

The European Commission (EC) developed a Product Environmental Footprint (PEF) Guide on how to do a PEF study for livestock feed [20]. The allocation rules defined by the EC are used. For co-products and by-products from a crop at the farm and for the processing of feed processing, economic allocation should be handled. This means that the shares of a flow are divided based on the economic value of the products. For transport, mass allocation should be used. Mass allocation means the shares of the flow are divided based on the mass share of the products [20].

4.3. Summary

An environmental performance index for the livestock feed industry is constructed to assess the performance of feed compositions. Livestock feed companies can systematically compare systematically compare feed compositions to each with the mathematical model of a composite indicator. This answers sub-question 3: ”How can an environmental performance index for livestock feed be constructed?”.

The environmental performance index consists of five phases and the appropriate methods for each phase are selected. In Figure 4.7 the overview of the environmental performance index for livestock feed is shown.

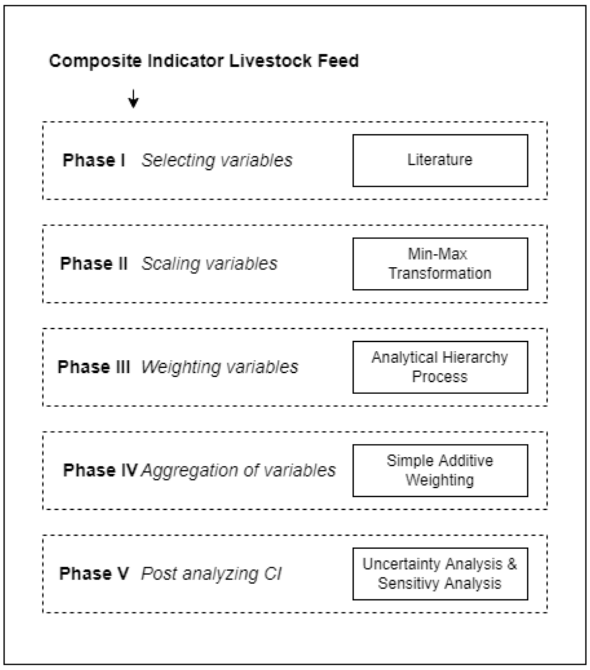

Figure 4.7: Construction CI for livestock feed

To make use of this index, data on feed compositions should be gathered. First, the feed compositions that need to be compared to each other should be formulated. For every feed composition the commodities, the associated origin and the proportions in the mixture should be known. For every feed composition, a value for every variable (j) should be determined. In this Chapter, the data collection is explained in detail per variable (j).

A summary of the data collection process per feed composition is made to get a clear understanding of the process. In Figure 4.8, a road map of the data collection for a feed composition is shown. This process should be repeated for every feed composition that is to be evaluated.

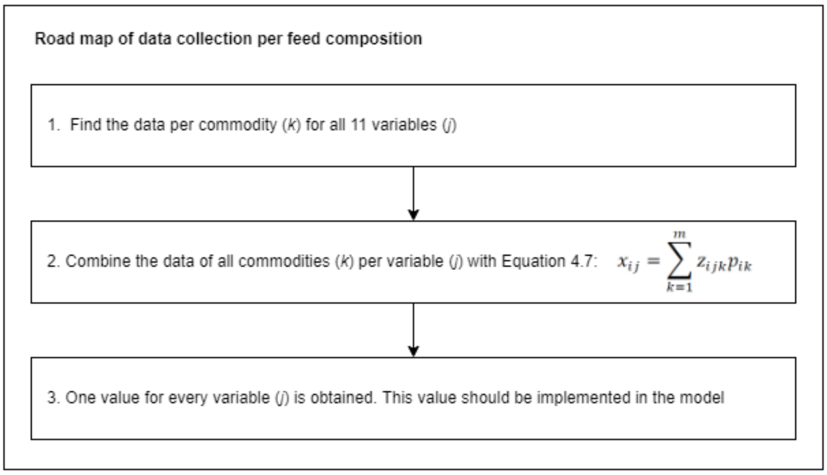

Figure 4.8: Road map on the data collection for a feed composition

The collection of data should be repeated for all feed compositions that should be evaluated with the environmental performance index for livestock feed. When this is completed for all feed compositions, a data set is obtained. This data set shows on the y-axis all feed compositions and on the x-axis the eleven variables are placed. The values obtained for every feed composition per variable should be included in the data set.

In Table 4.6, the final data set with all the feed compositions is shown. Finally, this set of data can be implemented in the environmental performance index. This layout is compatible with the Python calculation code.

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}
Feed composition 1	$x_{1,1}$	$x_{1,2}$	$x_{1,3}$	$x_{1,4}$	$x_{1,5}$	$x_{1,6}$	$x_{1,7}$	$x_{1,8}$	$x_{1,9}$	$x_{1,10}$	$x_{1,11}$
Feed composition 2	$x_{2,1}$	$x_{2,2}$	$x_{2,3}$	$x_{2,4}$	$x_{2,5}$	$x_{2,6}$	$x_{2,7}$	$x_{2,8}$	$x_{2,9}$	$x_{2,10}$	$x_{2,11}$
Feed composition ..	$x_{..,1}$	$x_{..,2}$	$x_{..,3}$	$x_{..,4}$	$x_{..,5}$	$x_{..,6}$	$x_{..,7}$	$x_{..,8}$	$x_{..,9}$	$x_{..,10}$	$x_{..,11}$
Feed composition n	$x_{n,1}$	$x_{n,2}$	$x_{n,3}$	$x_{n,4}$	$x_{n,5}$	$x_{n,6}$	$x_{n,7}$	$x_{n,8}$	$x_{n,9}$	$x_{n,10}$	$x_{n,11}$

Table 4.6: Data collection for the environmental CI for livestock feed

5

The environmental composite indicator in practice

In Chapter 4, an environmental performance index for livestock feed is developed and verified with experts. The constructed CI is brought in practice in this Chapter. A benchmark feed composition serves as a reference value and different scenarios are plotted against this reference. In this Chapter, first the benchmark feed composition is outlined. Besides this feed composition, the feed compositions of hypothetical scenarios that are analyzed with the CI are identified. This is followed by the presentation of the data input for the CI. The scenarios and data are then implemented in the constructed environmental CI for livestock feed.

5.1. Benchmark feed composition

To be able to draw a conclusion from a composite indicator, a reference value should be added to get a good quantitative comparison [75]. The benchmark feed composition, that acts as the reference case of the composite indicator, is provided by the Agrifirm. Agrifirm provided a standard feed composition based on feed for meat pigs and meat chickens. This standard composition consists of commodities with the associated origin and the proportions in the mixture. The origin is based on the country where the highest share of that commodity is coming from at Agrifirm. So, for example, the highest share of wheat comes from France. Than France is used as the origin of wheat. The data on emissions and costs per commodity are not available at Agrifirm. Therefore, these data are obtained from different data sources. This means these data are secondary data sources and represent rather the industry average than specific data from Agrifirm [95].

Agrifirm is a Dutch company active in the livestock farming and agricultural industry. They supply the livestock industry with high quality livestock feed, premixes, concentrates, mixtures of minerals, feed additives. For the agricultural sector they produce products to improve crop growth and cultivation. Furthermore, they provide crop and animal specific advice [1].

The benchmark feed composition consists of 21 different commodities, from which thirteen commodities originate from within Europe and eight from outside of Europe. From the total mixture, 83.2% of the commodities are from Europe and the other 16.6% is from outside of Europe. In Appendix D the full feed composition with the associated origins and proportions in the mixture can be found.

5.2. Scenario selection

When bringing the CI into practice, the goal is to built hypotheses and to validate the model. Different scenarios are evaluated with the environmental CI for livestock feed. There are three relevant cases identified in Chapter 2.3 that should be assessed. The three cases are additional processes that could be added to the current situation and approach of the livestock industry to improve the environmental sustainability. In Figure 2.8, a flow diagram of the current situation of the livestock industry is shown.

In Figure 2.9, the flow diagram with the three added cases to possibly improve the environmental sustainability of the the livestock feed industry is visualized. From these Figures, it becomes clear that the inclusion of carbon capture should be assessed when determining the environmental sustainability performance of livestock feed. The second and the third case are both examples of circular processes. The second possibility to improve the environmental sustainability of livestock feed is the replacement of raw materials with by-products and waste streams. Lastly, it should be evaluated whether the circular use of manure should be optimized and should get greater attention in terms of environmental sustainability.

There are several options to formulate hypothetical scenarios for feed compositions. First, the origins of commodities can be altered. Second, the commodities in the composition can be replaced. Lastly, both the origin and the commodities can be replaced. In this case, only origins are altered since there are no data available on alternative feed compositions that have similar nutritional values. Therefore, the second case, the replacement of raw materials with by-products and waste streams cannot be evaluated at this moment. This is replaced by the analysis of scenarios where either the sourcing of the commodities is more local or where the effects of LUC are investigated.

5.2.1. Carbon capture

The sequestration of carbon from the atmosphere into soil can be stimulated by introducing regenerative agricultural practices during the cultivation of crops. In December 2021, the EC presented a short- to medium-term action plan to stimulate carbon farming in Europe. The plan includes a reward strategy for land owner when adopting carbon capture measures [22].
The impact of regenerative agriculture should be assessed. Although the potential of carbon capture to mitigate GHG emissions is widely admitted [8, 22, 90, 109], the practical implementation of carbon capture to mitigate GHG emissions is not widely available and developed. The reason for this lack of research on the effects and practical implementation, is the unavailability of information on the size of the opportunity and how it could be realized [8]. Therefore, two scenarios are analyzed where hypothetical situations are used as the input. Zomer et al. [109] calculate the effects of two scenarios where regenerative agriculture is brought into practice. They illustrate how much carbon would be captured if SOC stocks would increase in agricultural land though regenerative practices. A medium optimistic scenario and a highly optimistic scenario are used. The two scenarios are described by Sommer and Bossio [77]. The medium scenario assumes an increase of 0.27% in SOC in the top 30 cm of soils after 20 years, this comes down to an annual increase of 0.012%. For the high scenario, an increase of 0.54% in SOC in the top 30 cm of soils after 20 years, this is an annual increase of 0.027% [109].

According to Sommer and Bossio [77], the SOC stocks will rise the most in the first 20 years and afterwards it will slowly stabilize. Their findings are shown in Figure 5.1. Findings from a meta-analysis done by Zomer et al. [109] show the SOC equilibrium point could in some instances be reached after 30 or even 40 years. Which would result in even more carbon capture and makes it more convenient to implement regenerative agricultural practices.
Zomer et al. [109] made use of the ISRIC SoilGrids250m global database of soil information and the FAO GLC-Share Land Cover database to provide an estimation on what the captured amount of carbon could be for the medium and high scenario. The results of the medium scenario are used for scenario 1 of the environmental CI for livestock feed and the results of the high scenario are the input for scenario 2 for the CI.

Scenario 1

Scenario 1 is a feed composition where carbon capture is included. This feed composition is the same feed composition as the benchmark feed composition, but the medium scenario formulated by Zomer et al. [109] for regenerative agriculture is included when calculating the performance of this feed composition. This feed composition is compared to the benchmark feed composition. The effect of the inclusion of medium adoption of regenerative practices worldwide is to sequester carbon is evaluated.

In Appendix D.2 the full feed composition can be found with the origin and proportions of every commodity that is present in the feed mix. This composition is equal to the benchmark feed composition.

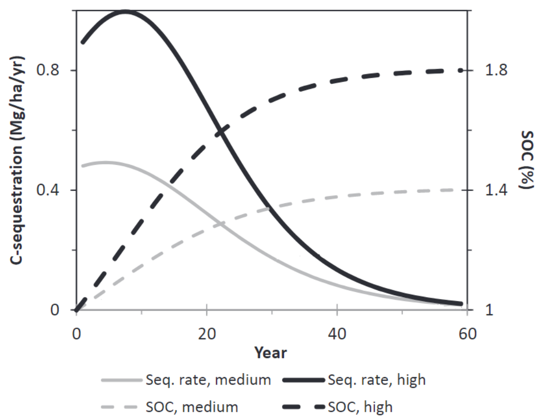

Figure 5.1: Assumed increase in %-SOC and SOC sequestration for the medium and high scenario [77]

Scenario 2

The effects of the worldwide implementation of regenerative agricultural practices is evaluated with scenario 2. This scenario is based on a highly optimistic scenario of the adoption of carbon sequestration measures. The high scenario of Zomer et al. [109] is used. The benchmark feed composition is used as the feed composition for this scenario, only a positive scenario of carbon capture is included. The effect of an increase in SOC stocks in agricultural soils is evaluated.

In Appendix D.2 the feed composition used for scenario 2 can be found. This is the same composition as the benchmark feed composition.

5.2.2. Circularity - Use of secondary streams

Introducing circular processes to the livestock feed industry could possibly help improve the environmental sustainability of this sector. Different forms of circularity are defined in Section 2.3.2. The use of more by-products and waste streams, known as secondary streams, is a circular process that could possibly improve the environmental sustainability performance of livestock feed. Pinotti et al. [56] raised the possibility to reduce GHG emissions by introducing by-products as feed. Mackenzie et al. [46], however, question this finding. They argue that the use of secondary streams in feed mixtures results in lower energy densities in the mixture. Due to different nutritional values, more feed is possibly necessary per kilogram of final product. Therefore, the emissions are not always reduced.
This scenario should be assessed with the environmental CI. It would be interesting to investigate whether the use of secondary streams could reduce the GHG footprint of livestock feed, and what waste streams are the most efficient to use in terms of environmental sustainability and costs.

A nutritional expert from Agrifirm confirmed that for example by-products from bread can be used in the feed mix for livestock. However, data on this scenario are not available at this moment. Therefore, the scenario of using more secondary streams cannot be assessed.
Secondary streams are usually associated with more locally sourced products [71]. Therefore, a scenario is defined to look into the effect of changing the sourcing location to more locally sourced products. Besides this, the different countries of origin of soy are assessed. Brazil is a big exporter of soy, but the cultivation of soy contributes to deforestation. Therefore, other origins are looked at to determine if this could improve the environmental sustainability of livestock feed.

Scenario 3

For scenario 3 a feed composition is created where commodities are cultivated in the Netherlands as much as possible. This is done by verifying which commodities from the benchmark feed composition could possibly be sources in the Netherlands. Every commodity that could be cultivated in the Netherlands, is coming from the Netherlands in this scenario. The assumption is made that enough can be produced from the different commodities in the Netherlands to make this possible.

In Appendix D.3 the feed composition used for scenario 3 can be found.

Scenario 4
Soy is an extremely efficient crop to grow and stimulates animal growth [5]. Soy products should be imported from outside of Europe. The climate conditions in Europe are not suitable to grow soy [24]. The biggest share of soy in the Netherlands comes from Brazil. Argentina and the US are two other major producers [17, 24, 80]. However, the soy industry in Brazil is accompanied by deforestation [5]. In this scenario, scenario 4, the impact on the performance of the overall feed composition is assessed by changing the origin of all soy products to Argentina.

In Appendix D.4 the feed composition for scenario 4 is shown completely.

Scenario 5
In the feed composition of scenario 5 soy products from Brazil are replaced due to the deforestation that is associated with soy from Brazil and the rest of South-America. Next to Argentina and Brazil, soy is produced in the US [17, 24, 80]. In this scenario, the soy products from Brazil are replaced with soy products from the US. It is evaluated how replacing soy from Brazil with soy from the US affects the overall performance of feed.

Ultimately, the effect of replacing soy with locally sourced products should be investigated. The European Parliament has declared that there is a need to reduce Europe's dependency on the import of protein-rich crops for livestock feed, which mainly originate from the US, Argentina and Brazil. This need is expressed because the European feed market becomes too vulnerable to volatile commodity prices and trade distortions [17]. The COVID pandemic and the conflict between Ukraine and Russia exposed the fragility of the feed, and also the food, system. However, at this moment there is a lack of information of the quantification of locally sourced commodities that could replace protein-rich crops, while maintaining the same nutritional values.

In Appendix D.5 the full feed composition for this scenario is shown. The same feed composition as the benchmark is maintained, only the origins of all soy products is changed.

5.2.3. Circularity - Use of organic fertilizers
The inclusion of circularity to mitigate the environmental pressure on global warming can be a circular process within livestock industry. Manure from livestock can be used as a (partial) replacement of synthetic fertilizer. Manure is referred to as organic fertilizer when it is used as a fertilizer. The replacement of synthetic fertilizers with organic fertilizers can help mitigate GHG emissions [24, 106, 107]. Zhang et al. [106] outline that the potential effect of the circular use of manure is not properly quantified. They explored the effect of the replacement of synthetic fertilizers with organic fertilizers. This is assessed with a combination of scenario analyses and a survey among 1500 Chinese farmers. There is assumed the crop yields do not reduce when not more than 50% of the synthetic fertilizers are replaced with organic fertilizer. This is based on a meta-analysis done by Zhang et al. [107]. This finding is used as an assumption in this scenario analysis as well. Besides this, the assumption is made that the mass of synthetic fertilizers is proportionally equal to the GHG emissions of synthetic fertlizers. So, if the mass of synthetic fertilizers decreases with 20%, the GHG emissions also decrease with 20%.

For scenario 6, 7, 8 and 9 the benchmark feed composition is used. This composition is shown in Appendix D.2. The ratios of synthetic and organic fertilizer are adjusted per scenario.

Scenario 6
The circular use of manure is evaluated with scenario 6. In this scenario, 20% of the synthetic fertilizer is substituted by organic fertilizer when a higher amount of synthetic fertilizer is used than organic fertilizer (based on the mass). This is evaluated for the benchmark feed composition and this composition is adjusted.

Scenario 7
Scenario 7 is a feed composition where, again, the replacement of synthetic fertilizer with organic fertilizer is evaluated. Now, 40% of the synthetic fertilizer is substituted by organic fertilizer when a

higher amount of synthetic fertilizer is used than organic fertilizer (based on the mass). The effect of the circular use of manure will be evaluated.

Scenario 8
In this scenario, 20% of the synthetic fertilizer is substituted by organic fertilizer. But in this case, for all commodities of the benchmark feed composition where the amount of synthetic fertilizer is higher than 50% the amount of organic fertilizer. So, if more than half the amount of organic fertilizer is equal to the amount of synthetic fertilizer.

Scenario 9
In scenario 9, 40% of the synthetic fertilizer is substituted by organic fertilizer for all commodities from the benchmark composition where the amount of synthetic fertilizer is more than 50% of the amount of organic fertilizer.

5.3. Data selection

The environmental performance index for livestock feed is brought into practice by doing scenario analyses. Nine scenarios are compared to each other systematically. The CI includes environmental sustainability performance variables and economic performance variables. Data on all variables should be available and obtained for every scenario. In this Section, the data sources for the practical implementation of the CI are elaborated on.

5.3.1. Environmental sustainability performance data

Data on the environmental sustainability of commodities is obtained from SimaPro. SimaPro is a Life Cycle Analysis (LCA) software that gives insight on the environmental performance of products and services. Initially SimaPro is developed to create full transparency and minimize blackbox processes on sustainability. It should be a source of science-based information. The software can be used for different proposes: sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators [59].
SimaPro contains many different LCA databases, and new databases can be made as well. Examples of well-known existing food industry related databases are the Ecoinvent v3 database, the Agri-footprint database, the Idemat database and the World Food LCA database [59].

In this study, the Agri-footprint 5.0 database is used. This is the newest version of the Agri-footprint database, it last updated in December 2019. It contains information on agricultural products. A wide variety of information on agriculture-specific impact categories is available. The database is developed by Blonk, an experienced sustainability consultancy firm [59].
The Agri-footprint 5.0 database has three different libraries for three different allocation methods. The economic allocation method is selected for study, as described in Section 4.2.3. The other two libraries of allocation that are available are mass allocation and energy allocation.

Land use
Data on land use is acquired from SimaPro. The data are ordered per commodity per country of origin. The data on land use is determined in m^2a per kg of crop. In the software, land use is shown in $10,000$ m^2a for a certain amount of a commodity. This is converted to $\frac{m^2a}{kg\ crop}$ with Equation 5.1 for every commodity (k) of every feed composition (i).

$$z_{m,1}\ [\frac{m^2a}{kg\ crop}] = \frac{10,000\ [m^2a]}{y_m\ [kg]} \tag{5.1}$$

The parameter for land use for a commodity (k) is $z_{m,1}$. y_m represents the amount of commodity (k) in kilograms that is produced per $10,000\ m^2a$.

GHG emissions land-use change
Accurate GHG emissions as a result of LUC can be found in the Agri-footprint 5.0 database in Simapro per commodity per country of origin. Carbon dioxide emissions due to LUC are shown. In SimaPro this is shown as: Carbon Dioxide, land transformation. This includes not only LUC in the form of

deforestation, but also the transformation of grass- and permanent cropland into annual crop land. There are no nitrous oxide or methane emissions due to LUC.

Production and use of synthetic fertilizers
The production and use of synthetic fertilizers is outlined in SimaPro. The Agri-footprint 5.0 database differentiates between synthetic fertilizers:

- Di ammonium phosphate ($(NH_4)_2HPO_4$)
- Ammonium sulfate ($(NH_4)_2SO_4$)
- Calcium ammonium nitrate (CAN)
- NPK compound
- Liquid urea-ammonium nitrate solution
- Urea ($CO(NH_2)_2$)
- PK compound
- Triple superphosphate ($Ca(H_2PO_4)_2$)
- Potassium chloride (KCl)
- Potassium sulfate (K_2SO_3)
- Lime fertilizer

The GHG emissions of all fertilizers are summed up. The GHG emissions from the production are based on European values. The application rate is based on the type of commodity and the county of origin. In SimaPro, the emissions are split into different categories:

- Carbon dioxide
- Carbon dioxide, biogenic
- Carbon dioxide, fossil
- Carbon dioxide, in air
- Methane
- Nitrous oxide

The GHG emissions of all categories are combined following the GWP value, which can be seen in Table 1.2 in Section 1.5.

Use of organic fertilizers
The use of organic fertilizers is outlined in the Agri-footprint 5.0 database. The data on manure use are country specific. In the software, the use of organic fertilizer is shown for a certain amount of a commodity. This is converted to $\frac{kg\ organic\ fertilizer}{kg\ crop}$ for every commodity (k) of every feed composition (i).

Transport mode	Data source travelled distance
Bulk carrier	www.ports.com
Inland vessel	www.blueroadmap.nl
Truck	www.maps.google.nl

Table 5.1: Data sources travelled distance

GHG emissions transportation
The data on transportation are not taken from SimaPro. The GHG emissions of transportation can be determined by obtaining data on the travelled distance (d), the mass of the cargo (m) and the GHG emissions per transport mode ($GHGM$), as defined in Figure 4.3 in Section 4.2.

The travelled distance should be obtained though several data sources since the transportation of livestock involves different modes of transport. The different transport modes require different data since this is more precise than determining the distances as the crow flies. The travelled distances should be retrieved manually from the data sources. In Table 5.1 the sources per transport mode are shown.
There are no existing data sets for distances between ports. Therefore, the distances should be searched for manually. For sea transport distances can be retrieved from Ports [57]. For distances between inland waterway ports data can be manually retrieved from Bureau Voorlichting Binnenvaart [9]. For trucks road distances can be found on Google [32].

The GHG emissions from transportation are determined per kilogram of crop. The mass of the cargo is 1 kilogram.

The GHG emissions per transport mode are determined from CE Delft [12], an independent research institute that focuses on research and innovation in the field of environmental sustainability. The calculation of CE Delft are based on the year 2018. It provides a comprehensive set of emission factors per mode of transport. In Table 5.2 the GHG emissions per tonne-kilometers and the GHG emissions per kilogram per kilometer handled for bulkcarriers, inland waterway transport and road transport is shown. Data on transport modes per origin was not available. There is assumed that crops from outside of Europe and from Denmark are transported with bulkcarriers and crops coming from Europe are transported with road transport.

Transport mode	Specifications	GHGM [kg CO_2eq/tonne-km]	GHGM [kg CO_2eq/kg-km]
Bulk carrier	DWT 10.000 - 34.999	0.007	$7 * 10^{-6}$
Inland vessel	CEMT-Class VA	0.0227	$2.27 * 10^{-5}$
Truck	Heavy load > 40 ton	0.08	$8 * 10^{-5}$

Table 5.2: Data sources travelled distance

During transport the vehicles rarely have a fill rate (FR) of 100%. There are no data available on fill rates of bulk carriers and inland vessels. A fill rate of 50% is handled. This is prescribed by the EC in the PEFCR, they assume a vessel has a FR of 100% and an empty return [20]. For trucks, research has shown that in the food supply chain of the UK a weight-based fill rate of 56% is achieved. This number is handled as the fill rate for all trucks transporting feed crops [37].

In Equation 5.2 the formula to calculate the GHG emissions from transportation per crop k is shown.

$$z_{i4k} = \frac{d_{ik} * m_{ik} * GHGM_{ik}}{FR_{ik}} \tag{5.2}$$

Where d_{ik} is travelled distance of element k of feed composition i. The m_{ik} represents the mass of element k in feed composition i and $GHGM_{ik}$ is the GHG emission of the transport mode used at element k of feed composition i. FR_{ik} is the fill rate of the truck or ship of element k in feed composition i.

GHG emissions storage
Commodities can be stored at two different occasions; before being processed and after being processed. According to Agrifirm, commodities are not stored at Agrifirm. So, only storage before processing is taken into account.
Data on storage are obtained from Simapro. In SimaPro, the emissions are split into different categories:

- Carbon dioxide
- Carbon dioxide, biogenic
- Carbon dioxide, fossil
- Carbon dioxide, in air
- Methane

The GHG emissions of all categories are combined following the GWP value, which can be seen in Table 1.2 in Section 1.5. There are no nitrous oxide emissions during the storage of commodities.

GHG emissions processing
In SimaPro the data on the GHG emissions of processing are shown. There are two forms of processing; processing of commodities into different products and the process of creating compound feed of different commodities. For the first form of processing, data from the Agri-footprint 5.0 are used. Processing contributes to global warming with emissions from carbon dioxide, methane and nitrous oxide. So, these different emission categories are taken into account from SimaPro:

- Carbon dioxide
- Carbon dioxide, biogenic
- Carbon dioxide, fossil
- Carbon dioxide, in air
- Methane
- Nitrous oxide

The GHG emissions of all categories are combined following the GWP value, which can be seen in Table 1.2 in Section 1.5.

For the second type, Agrifirm handles one value on the GHG emissions of processing the commodities in the feed mill. Therefore, there is assumed that the GHG emissions for creating compound feed from different commodities is the same for every commodity.

Carbon capture
Data on carbon capture are not available in SimaPro. In Section 5.2.1, a medium and a high implementation scenario for carbon capture are introduced. Data from these hypothetical scenarios are used. The results of the study give the average SOC stocks in carbon per hectare, this is assessed per region. In Table 5.3, the data on the annual increase of SOC stocks is shown.
To determine how much carbon dioxide is captured per kilogram of crop, there are two steps that should be taken. First, for every commodity it should be known how much kilogram of crop is harvested per hectare per year. And secondly, SOC stocks should be converted to carbon dioxide sequestration.

From the FAO [26] data are obtained on the crop yield per commodity per country based on 2020. The amount of carbon per kilogram of crop is calculated using Equation 5.3.

$$\frac{carbon}{kg\ crop} = \frac{average\ annual\ increase\ SOC\ stocks}{crop\ yield\ per\ commodity\ per\ country} \tag{5.3}$$

Region	Medium scenario [C/ha/year]	High scenario [C/ha/year]
North America	600.00	1220.00
Central America	530.00	1090.00
Central Asia	530.00	1080.00
East Asia	540.00	1120.00
Eastern and Southern Africa	550.00	1130.00
Europe	550.00	1140.00
North Africa	630.00	1280.00
Russia	500.00	1020.00
South America	530.00	1080.00
South Asia	620.00	1280.00
South-East Asia	530.00	1100.00
West and Central Africa	580.00	1190.00
Western Asia	600.00	1230.00
Australia/Pacific	570.00	1160.00

Table 5.3: Average annual increase of SOC [C/ha/year]

The data on crop yield per commodity per country can be found in Appendix F.

Next, this should be converted to the amount of carbon captured. The amount of carbon capture in the form of carbon dioxide is obtained by multiplying SOC by 3.67. This number is obtained by dividing the molecular mass of CO_2 with the atomic mass of C. This comes down to $\frac{44}{12} = 3.67$ [42].

5.3.2. Economic performance data

The economic performance data consists of three different variables; crop costs, transportation costs and storage costs. In this Section, a description of the data selection of the three variables is elaborated on.

Crop costs

Data on crop costs are determined based on global commodity market prices. Commodity prices from before the Ukraine-Russia conflict are used, to get a less distorted view on the prices. Prices from September 2021 are used [33, 38].

Transportation costs

The data on costs of transportation are determined by obtaining data on the travelled distance (d), the mass of the cargo (m) and the costs per transport mode.

The travelled distance should be obtained though several data sources since the transportation of livestock involves different modes of transport. This is explained in the Section 5.3.1.

The costs for transportation are determined per kilogram of crop. The mass of the cargo is 1 kilogram.

The costs per transport mode are derived from research done by Parkhurst and Paddeu [54]. This study determined the costs per tonne-mile per mode of transportation. The costs are determined in US Dollar. To convert this to Euro, an EUR-USD exchange rate of 1.04 is handled. In Table 5.4 the costs per tonne-mile and the costs per kilogram per kilometer handled for bulkcarriers, inland waterway transport and road transport is shown. Data on transport modes per origin was not available. There is assumed that crops from outside of Europe and from Denmark are transported with bulkcarriers and crops coming from Europe are transported with road transport.

Transport mode	Specifications	Costs transport [€/tonne-mile]	Costs transport [€/kg-km]
Bulk carrier	DWT 10.000 - 34.999	0.010417	$6.473 * 10^{-6}$
Truck	Heavy load > 40 ton	0.125	$7.767 * 10^{-5}$

Table 5.4: Data sources travelled distance

In Equation 5.4 the formula to calculate the costs from transportation per crop k is shown.

$$z_{i,11,k}[\frac{€}{kg\ crop}] = costs\ transport * d_{ik} \tag{5.4}$$

Where d_{ik} is travelled distance of element k of feed composition i. For costs of transport the costs of the corresponding mode of transportation should be selected.

Storage costs
There are no storage costs for the scenarios that are analyzed with the environmental CI for livestock feed. There are two occasions where commodities can be stored. Firstly, before the commodities are being processed and, secondly, after they are being processed. As mentioned before, according to Agrifirm, commodities are not stored at Agrifirm. So, only storage before processing is taken into account. This form of storage does not take place at the feed producer and these costs are therefore included in the price of the commodity. The price is not included separately.

5.4. Environmental CI for livestock feed in practice

The environmental CI for livestock feed is brought into practice. Hypothetical scenarios are assessed and compared to a benchmark scenario. The implementation is discussed per phase.

5.4.1. Phase I: Selecting variables

To bring the environmental CI for livestock feed into practice, the defined scenarios in Section 5.2 are the input for the model. Every scenario represents a feed composition. In Table 5.5 an overview of all scenarios is given.

Scenario	Description
1	Carbon capture from medium inclusion of regenerative agriculture practices
2	Carbon capture from high inclusion of regenerative agriculture practices
3	Commodities from the Netherlands, as much as possible
4	Soy from Brazil is replaced with soy from Argentina
5	Soy from Brazil is replaced with soy from the US
6	20% of the synthetic fertilizer is substituted for commodities where more synthetic than organic fertilizer is used
7	40% of the synthetic fertilizer is substituted for commodities where more synthetic than organic fertilizer is used
8	20% of the synthetic fertilizer is substituted for commodities where the amount of synthetic fertilizer is higher than 50% the amount of organic fertilizer
9	40% of the synthetic fertilizer is substituted for commodities where the amount of synthetic fertilizer is higher than 50% the amount of organic fertilizer

Table 5.5: Overview scenarios

For all scenarios, the data per variable are determined. The selection of data is described in Section 5.3. In Table 5.6, the data per variable are shown for the benchmark composition and the nine different scenarios.

	V1: Land use	V2: Emissions LUC	V3: Emissions synthetic fertilizer	V4: Emissions organic fertilizers	V5: Emissions transport	V6: Emissions storage	V7: Emissions processing	V8: GHG capture	V9: Commodity costs	V10: Storage costs	V11: Transportation costs
Feed composition	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg s. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Benchmark	1.6092	0.6630	0.0589	0.3787	0.1607	0.0007	0.0970	0.0000	0.3367	0.0000	0.0846
Scenario 1	1.6092	0.6630	0.0589	0.3787	0.1607	0.0007	0.0970	0.4020	0.3367	0.0000	0.0846
Scenario 2	1.6092	0.6630	0.0589	0.3787	0.1607	0.0007	0.0970	0.8302	0.3367	0.0000	0.0846
Scenario 3	1.3365	0.8172	0.0562	2.3687	0.1217	0.0003	0.0966	0.0000	0.3367	0.0000	0.0267
Scenario 4	1.6022	0.6599	0.0507	0.3487	0.1652	0.0007	0.1016	0.0000	0.3367	0.0000	0.0867
Scenario 5	1.6780	0.0716	0.0892	0.4585	0.1506	0.0007	0.1030	0.0000	0.3367	0.0000	0.0799
Scenario 6	1.6092	0.6630	0.0563	0.3860	0.1607	0.0007	0.0970	0.0000	0.3367	0.0000	0.0846
Scenario 7	1.6092	0.6630	0.0536	0.3930	0.1607	0.0007	0.0970	0.0000	0.3367	0.0000	0.0846
Scenario 8	1.6092	0.6630	0.0507	0.4003	0.1607	0.0007	0.0970	0.0000	0.3367	0.0000	0.0846
Scenario 9	1.6092	0.6630	0.0425	0.4144	0.1607	0.0007	0.0970	0.0000	0.3367	0.0000	0.0846

Table 5.6: Input data of CI for livestock feed per variable

In Appendix E the full data set of every feed composition is shown. These data sets are used to obtain the data for the benchmark composition and the different scenarios.

5.4.2. Phase II: Scaling

The data are normalized with the min-max transformation. This is done following Equation 4.2. In the data set, see Table 5.6, there can be seen that variable 9 (V_9), commodity costs, has the same value for every feed composition. Also, variable 10 (V_{10}), storage costs, is zero for every feed composition. This means that the min-max transformation cannot be applied to these two variable, because it ends up in $\frac{0}{0}$ = NaN. For these two variables, all data should be 0. This means the two variables are eliminated in this particular case. The calculation code in Python will convert all NaN values to 0.

5.4.3. Phase III: Weighting

The weight per variable should be determined after the data are normalized. The weights are determined based on expert knowledge from Agrifirm and information from literature.
The pair-wise comparison matrix for the AHP method is shown in Table 5.7.

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	*Weight*
V_1	1	$\frac{1}{3}$	$\frac{1}{3}$	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	3	3	3	W_1
V_2	3	1	1	3	1	1	1	1	5	5	5	W_2
V_3	3	1	1	3	1	1	1	1	5	5	5	W_3
V_4	1	$\frac{1}{3}$	$\frac{1}{3}$	1	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	3	3	3	W_4
V_5	3	1	1	3	1	1	1	1	5	5	5	W_5
V_6	3	1	1	3	1	1	1	1	5	5	5	W_6
V_7	3	1	1	3	1	1	1	1	5	5	5	W_7
V_8	3	1	1	3	1	1	1	1	5	5	5	W_8
V_9	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	W_9
V_{10}	$\frac{1}{5}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{5}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	1	1	1	W_{10}
V_{11}	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	W_{11}

Table 5.7: Pair-wise comparison matrix livestock feed

In the Table, the relative importance of the variables relative to each other is displayed. The environmental sustainability performance is determined based on variable 1 to 8. Land use (V_1) and the use of organic fertilizer (V_4) are classified as equally important in relation to each other, but moderately less important than the remaining environmental sustainability variables. These remaining variables (V_2, V_3, V_5, V_6, V_7 and V_8) are equally important in relation to each other.
Land use has no direct effect on global warming and is therefore slightly less important. The use of

organic fertilizers is also slightly less important because it stimulated a circular process. The remaining environmentally sustainability variables are all expressed in $\frac{kg\ CO_2}{kg\ crop}$ and form a GHG balance. This means they can compensate each other and are equally important.
The economic performance is determined based on variable 9, 10 and 11 (V_9, V_{10} and V_{11}). For this application it is determined that the environmental sustainability performance is more important than the economic performance. These three variables all express costs in $\frac{€}{kg\ crop}$ and can, thus, compensate each other. This means they are equally important relative to each other.

The consistency of the matrix is verified to determine whether the matrix gives a coherent representation. Equation 4.3 is used to define the Consistency Ratio (CR). The consistency index and the random consistency ratio should be determined. With Equation 4.4 the consistency index is determined. Where λ_{max} is 11.0905 and n is 11. The random consistency index can be found in Table 4.3. The random consistency index for n = 11 is 1.51.
The CR is 0.059903. This means this pair-wise comparison matrix gives a coherent set of facts and the matrix can be used to determine the weights for the implementation.

5.4.4. Phase VI: Aggregating

The variables are normalized and the weights for every variable are obtained. The aggregation of these normalized variables and the weights is done with Equation 4.5. A value is linked to every feed composition that is evaluated with the environmental performance index.

5.4.5. Phase V: Post analyzing

The CI is validated with an uncertainty analysis and a sensitivity analysis. The robustness and transparency of the environmental CI for livestock feed are ensured. The uncertainty analysis is done for two sources of uncertainty. The uncertainty of the scaling method and the selection of the weights is investigated. With the sensitivity analysis, the effect of variations in the input variables on the output of the index is evaluated. Both analyses are a crucial part of the validation of the model, it is determined whether the model is right.

Uncertainty analysis - the scaling method

An alternative scaling method, conventional linear scaling transformation, is used to evaluate the uncertainty of the selected min-max transformation. The values are normalized against an external point of reference. A minimum and maximum value are proposed as the external point of reference for every variable (j). These values are based on the data of this case and are shown in Table 5.8.

Reference	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}
Minimum ($min\, y_j$)	1.30000	0.07000	0.04000	0.30000	0.10000	0.00020	0.05000	0.00000	0.00000	0.00000	0.01000
Maximum ($max\, y_j$)	1.70000	0.85000	0.09000	2.40000	0.17000	0.00080	0.11000	0.90000	0.50000	0.00000	0.10000

Table 5.8: Values of external point of reference for LST

The data are normalized using these minimum and maximum reference values. This is done with Equation 4.7.

Uncertainty analysis - selection of weights

The subjective judgement of the relative importance of the variables in relation to each other bring uncertainty along. An alternative pair-wise comparison matrix is made to evaluate the effect of the possible uncertainty on the output of the CI. In Table 5.9, the alternative pair-wise comparison matrix to assess the uncertainty is shown.
For this alternative, all environmental sustainability performance variables are considered equally important, except for land use change. Deforestation is associated with land use change and it could be argued that therefore this variable is slightly more important. Next to the GHG emissions, the forests are cleared from the earth.
The economic performance is moderately less important that the environmental sustainability performance.

	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	*Weight*
V_1	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_1
V_2	3	1	3	3	3	3	3	3	5	5	5	W_2
V_3	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_3
V_4	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_4
V_5	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_5
V_6	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_6
V_7	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_7
V_8	1	$\frac{1}{3}$	1	1	1	1	1	1	3	3	3	W_8
V_9	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1	1	1	W_9
V_{10}	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1	1	1	W_{10}
V_{11}	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	1	1	1	W_{11}

Table 5.9: Pair-wise comparison matrix with alternative selection of relative importance

The consistency of the matrix is verified. The consistency index is determined with Equation 4.4. Where λ_{max} is 11.03746 and n is 11. The random consistency index can be found in Table 4.3. The random consistency index for n = 11 is 1.51.
The CR is 0.024810. This means this pair-wise comparison matrix gives a coherent set of facts.

Sensitivity analysis
The sensitivity is measured by changing the input variables and evaluating the effect per variable on the output of the environmental CI. Every variable is increased with 20%. This is done for every variable. This is done per variable, so one by one. The effect per variable becomes clearly visible if one is changed an the other are kept constant.

5.5. Verification and validation of the model

The constructed environmental performance index should compare the performance of different feed compositions. The model should be verified and validated. Verification should be done to ensure that 'this is the right model'. Validation indicates whether 'this model is right' [82].

5.5.1. Verification

Before a model is brought into practice, it is verified. The verification is done in the process of constructing the model. Verification is done to determine if the constructed model represents the intended purpose of the model [82, 99].
The relevance and appropriateness of the input variables and dimensions are examined. The input of the model is verified with expert knowledge. Interviews are conducted with several experts in the industry to verify the correctness of the environmental performance index.
The weighting method is verified in different ways. First of all, the judgement of relative importance in verified with experts. Secondly, the consistency of the matrix is verified by calculating the consistency ratio.

5.5.2. Validation

After the model is verified, the next step is to determine if the model accurately represents the real-life world. This is called validation of the model [82, 99]. With the validation of a composite indicator, the reliability of the selected methods and assumptions are inspected [2]. During the post-analysis phase of the CI, the model is validated with an uncertainty analysis and a sensitivity analysis. With the uncertainty analysis, the reliability of the selected methods for scaling and weighting is investigated. The sensitivity analysis validates if the model is resistant to differences in the input of the model and can still give relevant results that are accurate with the real world.

6
Experimental results

It should be determined whether a verified and validated conclusion can be drawn on the environmental performance of different feed compositions based on the outcome of the created environmental performance index. In this Chapter, the results of the practical implementation of the environmental performance index of livestock are outlined. Nine scenarios, that all represent a feed composition, are compared to the benchmark feed composition. The results are outlined per phase of the CI.

6.1. Phase II: Scaling

The data set is normalized with the min-max transformation. In Table 6.1, the results of scaling are shown. As can be seen in the Table, all values are scaled to values between 0 and 1.

	V_1: Land use	V_2: Emissions LUC	V_3: Emissions synthetic fertilizer	V_4: Emissions organic fertilizers	V_5: Emissions transportation	V_6: Emissions storage	V_7: Emissions processing	V_8: GHG capture	V_9: Commodity costs	V_{10}: Storage costs	V_{11}: Transportation costs
Feed composition	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Benchmark	0.7985	0.7932	0.3512	0.0149	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 1	0.7985	0.7932	0.3512	0.0149	0.8966	1.0000	0.0625	0.5158	0.0000	0.0000	0.9650
Scenario 2	0.7985	0.7932	0.3512	0.0149	0.8966	1.0000	0.0625	0.0000	0.0000	0.0000	0.9650
Scenario 3	0.0000	1.0000	0.2934	1.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
Scenario 4	0.7780	0.7890	0.1756	0.0000	1.0000	1.0000	0.7813	1.0000	0.0000	0.0000	1.0000
Scenario 5	1.0000	0.0000	1.0000	0.0544	0.6644	1.0000	1.0000	1.0000	0.0000	0.0000	0.8867
Scenario 6	0.7985	0.7932	0.2955	0.0185	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 7	0.7985	0.7932	0.2377	0.0219	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 8	0.7985	0.7932	0.1756	0.0255	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 9	0.7985	0.7932	0.0000	0.0325	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650

Table 6.1: Results phase II: Scaling with min-max transformation

6.2. Phase III: Weighting

From the pair-wise comparison matrix shown in Table 5.7, the weight for every variable is determined. The weights are shown in Table 6.2.

	Weight
W_1: Land use	0.05408
W_2: Emissions LUC	0.13632
W_3: Emissions synthetic fertilizer	0.13632
W_4: Emissions organic fertilizer	0.05408
W_5: Emissions transportation	0.13632
W_6: Emissions storage	0.13632
W_7: Emissions processing	0.13632
W_8: Carbon capture	0.13632
W_9: Commodity costs	0.02463
W_{10}: Storage costs	0.02463
W_{11}: Transport costs	0.02463

Table 6.2: Results phase III: Weights from Analytical Hierarchy Process

In the Table there can be seen that the weights represent what was intended when determining the relative importance of the various variables. The weights of the environmental sustainability variables are higher than the weights of the economic variables. Furthermore, the weights for 'land use' and 'emissions of organic fertilizers' are lower than the weights of the other environmental sustainability variables.

6.3. Phase IV: Aggregating

The results of phase VI, aggregating, are shown in Table 6.3. In the Table, the overall performance of every feed composition is shown. The lower the value, the better the performance of a feed composition.

Feed composition	**CI**
Benchmark	0.62715
Scenario 1	0.56114
Scenario 2	0.49083
Scenario 3	0.36672
Scenario 4	0.71368
Scenario 5	0.71473
Scenario 6	0.61976
Scenario 7	0.61206
Scenario 8	0.60379
Scenario 9	0.58023

Table 6.3: Results phase IV: Aggregation with Simple Additive Weighting

The feed compositions that include carbon capture, scenario 1 and 2, have a better performance than the benchmark. As expected, scenario 2 performs better than scenario 1. Scenario 1 represents a medium optimistic scenario of the inclusion of regenerative agricultural practices and scenario 2 a highly optimistic scenario.

Scenario 3, the feed composition where as many as possible commodities are sourced in the Netherlands, shows the best performance of all feed compositions. This means that sourcing commodities from the Netherlands has a big influence on the performance of livestock feed. The replacement of soy from Brazil with soy from Argentina of US has a bad influence on the performance. Both feed compositions, scenario 4 and scenario 5, have a worse performance than the benchmark feed composition.

The last four scenarios show the performance of the feed compositions where synthetic fertilizer is replaced with organic fertilizer. It becomes clear that the adoption of this circular measure impacts the overall performance. It shows, that the more synthetic fertilizer is replaced with organic fertilizer, the better the performance is.

In Figure G.1, the results from Table G.1 and Table 6.3 are visualized. In the Figure, the contribution of every variable to the total performance is shown.

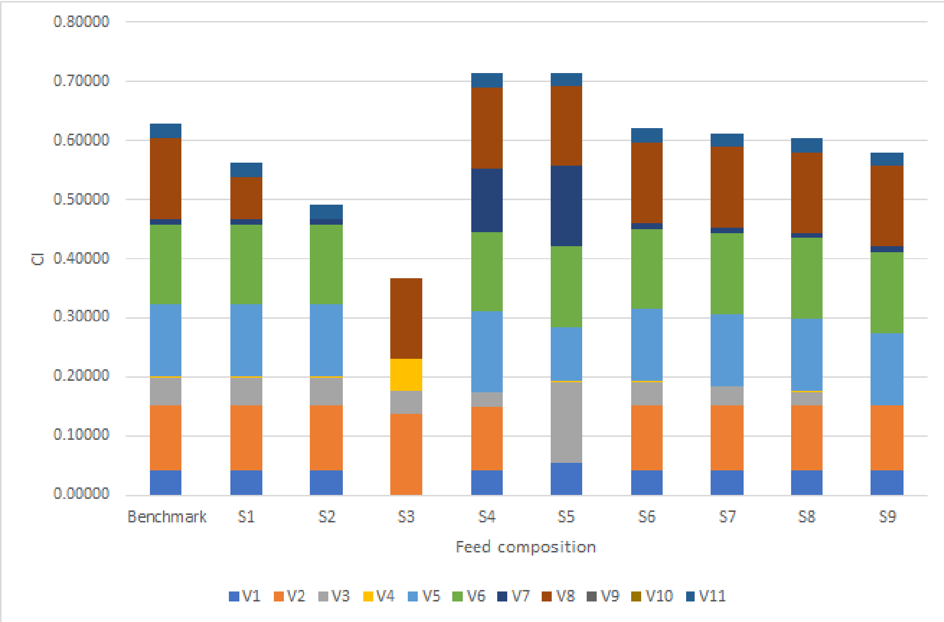

Figure 6.1: Results phase IV: Aggregation

From this Figure, the performance of individual variables can be compared per feed composition. It shows that the best performing feed composition, scenario 3, could be further improved by decreasing the amount of emissions from LUC (V_2) and by adopting regenerative agricultural practices to capture carbon (V_8).
The Figure shows that the increase in the performance of scenario 1 and 2 is due to carbon capture.
Scenario 4 and scenario 5 have a poorer performance than the benchmark. In scenario 4, this worse performance is mainly due to emissions from processing. The bad performance of scenario 5 is the result of emissions from the production and use of synthetic fertilizers and emissions from processing. In the field of emissions from transportation, the performance has increased in scenario 5.
For the last four scenarios, the Figure shows that the reduction of emissions from synthetic and organic fertilizers are the reason for the better performance.

6.4. Phase V: Post analyzing

To ensure the environmental performance index is robust and transparent, a uncertainty and sensitivity analysis are done. These analyses are done to validate the model.

Uncertainty analysis - the scaling method
A 2-tailed Pearson's correlation test is performed to find the relationship between the results of the constructed CI and the results of the CI with the LST method as the method for scaling. In Table 6.4, the results of the test are shown per feed composition.
The results show that there is a strong positive correlation between the results of the constructed CI with the min-max transformation as a scaling method and the results of the CI with the LST method. This means that the null hypothesis (H_0) is rejected.

In Appendix G.2.1 the results of all phases can be found for the UA of scaling method.

Feed composition	Correlation coefficient (r)	p-value	Significant ($\alpha = 0.05$)
Benchmark	0.83189	0.00149	Yes
Scenario 1	0.78927	0.00387	Yes
Scenario 2	0.80351	0.00289	Yes
Scenario 3	0.81127	0.00244	Yes
Scenario 4	0.98349	0.00000	Yes
Scenario 5	0.98566	0.00000	Yes
Scenario 6	0.83290	0.00146	Yes
Scenario 7	0.83378	0.00142	Yes
Scenario 8	0.83691	0.00131	Yes
Scenario 9	0.84654	0.00101	Yes
Average of all	0.90218	0.00036	Yes

Table 6.4: Results phase V: 2-tailed Pearson's correlation test for UA with LST

Uncertainty analysis - selection of weights

For the uncertainty analysis of the alternative selection of weights, a 2-tailed Pearson's correlation test is performed as well. The relationship between the results of the constructed CI and the results of the CI with the alternative selected weights is determined with this test. The results are shown in Table 6.5 per feed composition and for the overall results.

Feed composition	Correlation coefficient (r)	p-value	Significant ($\alpha = 0.05$)
Benchmark	0.79981	0.00312	Yes
Scenario 1	0.80116	0.00304	Yes
Scenario 2	0.82338	0.00184	Yes
Scenario 3	0.88648	0.00028	Yes
Scenario 4	0.78853	0.00393	Yes
Scenario 5	0.92422	0.00005	Yes
Scenario 6	0.80183	0.00299	Yes
Scenario 7	0.80420	0.00285	Yes
Scenario 8	0.80701	0.00268	Yes
Scenario 9	0.81627	0.00218	Yes
Average of all	0.86042	0.00140	Yes

Table 6.5: Results phase V: 2-tailed Pearson's correlation test for UA with differently selected weights

The results in the Table show there is a strong positive correlation between the results of the CI with the two different pair-wise comparison matrices. This means that the null hypothesis (H_0) is rejected at a significance level of $\alpha = 0.05$.

In Appendix G.2.2 the results of all phases can be found for the UA of the selection of weights.

Sensitivity analysis

The results of the Pearson's correlation test are shown in Table 6.6. In the first column the variable is shown and the percentage that is added to that variable. Next, the correlation coefficient is shown. This is the correlation between the results of the CI and the results of the CI with the increased values. In the last column, the deviation from a perfect positive correlation coefficient is shown in percentages. A perfect positive correlation coefficient is 1. All values are significant with a significance level of $\alpha = 0.05$

Variable and change [%]	**Correlation coefficient (r)**	**Deviation from perfect correlation [%]**
V_1 +20%	0.99924	0.076
V_2 +20%	0.99924	0.076
V_3 +20%	0.99875	0.125
V_4 +20%	0.99875	0.125
V_5 +20%	0.99875	0.125
V_6 +20%	0.99857	0.143
V_7 +20%	0.99875	0.125
V_8 +20%	0.99875	0.125
V_9 +20%	0.99924	0.076
V_{10} +20%	1.00000	0.000
V_{11} +20%	0.99924	0.076

Table 6.6: Results phase V: 2-tailed Pearson's correlation test for SA

The output is most sensible to the variation of variable 6, 'emissions storage'. For this variable, the deviation from perfect correlation is most significant. Variable 10 does not have an influence on the output of the CI. This shows that the model behaves as expected, because the values of variable 10 are 0 in this case, thus this variable does not influence the output. With this result, the functioning of the sensitivity analysis is validated.

In Appendix G.2.6 the extensive results of the SA can be found.

7

Conclusion and discussion

In this chapter the findings of this study are outlined. The findings are outlined by means of answering the five sub-questions. The main research question is answered based on these findings. Also, the scientific and societal relevance of this research are outlined. Next, the limitation of this research are discussed and a critical reflection on the implementation of this study is provided. Furthermore, recommendations for further research are made.

7.1. Conclusion

A transformation of the livestock industry is necessary to make it more environmentally sustainable and durable. The feed production for the livestock industry is a big contributor to climate change. The demand from both the EU and society to mitigate the GHG emissions associated with livestock feed has risen over the past decade. Therefore, research is done on mitigating the GHG emissions of livestock feed. Livestock feed consists of a mixture of different commodities. Optimization models based on costs and nutritional values are currently used to determine the appropriate proportions of every commodity in the mixture. To mitigate the emissions, feed compositions should not only be optimized against costs and nutritional values, but also against environmental sustainability. Livestock feed companies need to get insights into the environmental performance of different feed compositions to determine their strategy.
This study aimed to investigate how an environmental performance index could be created for the feed production of the livestock industry from an economic perspective. The main research question was formulated as follows:

”*How could an environmental performance index be created that balances GHG emissions with carbon capture for the feed production of the livestock industry from an economic perspective?*”

This question is answered by assessing the findings on every sub-question. The answers to the different sub-questions cover the following; the GHG balance of the feed production for the livestock industry is discussed. Techniques to construct an environmental performance index are outlined and the creation of a sector-specific environmental performance index for livestock feed industry is proposed. The technical feasibility of the environmental performance index is investigated by bringing the model into practice; different scenarios are quantitatively compared to a benchmark feed composition.

No prior research is done on a GHG balance, that includes GHG emissions and carbon capture, in combination with the optimization of feed compositions. A literature study on the GHG balance of livestock feed is presented in this research. Livestock feed production consists of three parts; crop cultivation, transportation and storage, and feed processing.
First, crops need to be cultivated. During this cultivation process, there are several sources of emissions; land use, land use change, the use and production of synthetic fertilizer and the use of organic fertilizer. Besides these sources of emissions, there is a possible opportunity to capture carbon. The in-

clusion of regenerative agricultural practices during crop cultivation offers the opportunity to sequester carbon from the atmosphere in the soil. This sequestration process has been ignored for a long time, but research has proven it can no longer be neglected. Even the European Commission announced the Farm to Fork Strategy, a program that aims to stimulate carbon farming within the EU to capture carbon in order to reach a carbon-neutral economy.
After the crops are produced, they need to be stored and transported. GHG emissions are released due to the use of energy and fossil fuels.
The third part is processing. Crops must be processed to obtain different products and to create compound feed. Both types of processing involve the use of energy and fossil fuels.

In order to create an environmental performance index for livestock feed, a literature survey is done on the construction of performance indices, also referred to as composite indicators. Literature on the construction of a composite indicator showed that a CI is a relevant tool to review the performance of a company or an industry. A CI makes it possible to systematically compare a set of indicators with different units of measurement.
The construction of a CI consists of five phases. In the first phase, the variables that should be included to measure the performance must be selected. Secondly, the variables should be scaled to get normalized values that can be combined in an index. In the third phase, the variables are weighted. Weights are assigned to the variables. In the fourth phase, the different variables with the accompanied weights are combined into a CI; called the aggregating phase. Finally, in the last phase, the CI is post analyzed. It is essential to conduct the post analysis to improve the quality of the index constantly.
For every phase, different methods can be used and the proper method should be selected based on the nature of the CI. A CI must be sector-specific, because the appropriate variables should be included with accurate data and the right choices to get a correct result.

The sector-specific CI for the livestock feed industry is composed of these five phases. In the first phase, variables are selected based on the literature. The literature on the GHG balance of the livestock industry is used as the input for the environmental performance index for livestock feed. Next, the variables are scaled using the min-max transformation. The min-max transformation is most appropriate because the spread within the data is not extremely big. The min-max transformation will create a wider spread between the values. In the third phase, weights are assigned to all variables with the analytical hierarchy process. Expert opinions can be well reflected with the AHP, but the weights are computed through statistical models. It is necessary to include the opinion of livestock feed companies, because the view on the importance of the variables varies. The scaled variables and the weights are aggregated with simple additive weighting. This is a widely used method that is easy to understand, which is important for a CI. Besides this, with SAW there is compensation amongst the variables, which is the case for this industry; the variables are mutually preferentially independent. The constructed CI is validated in the last phase with an uncertainty analysis and sensitivity analysis. The goal of the composite indicator for livestock feed is to be able to systematically compare feed compositions in terms of environmental sustainability performance and economic performance.

Next, the sector-specific environmental performance index is verified with experts from the livestock feed industry. The subjective elements, selecting the input variables and selecting the relative importance of the variables for weighting, of the environmental performance index are verified. There can be concluded that the created environmental CI accurately represents what the model was intended to do.
Now, the index is brought into practice to prove the technical feasibility. Different scenarios, that all reflect a feed composition, are compared to a benchmark feed composition. From the scenario analysis, it can be concluded that a feed composition with locally sourced commodities shows the best overall performance. The results show that the performance of the feed composition with locally sourced products can be further improved, compared to the other feed compositions, by reducing the emissions from LUC and by adopting regenerative agricultural practices to capture carbon.
Scenario 1 and scenario 2 both include, respectively, a medium and high scenario of the inclusion of regenerative practices to capture carbon. It can be deduced that carbon capture is effective to mitigate the GHG emissions.
The two scenarios where Brazil's soy products are replaced with soy products from Argentina and the

US perform significantly worse than the benchmark feed composition. This indicates that the concerns expressed in the literature about the high GHG emissions due to LUC from high-protein crops, such as soy, from Brazil cannot be resolved by replacing the soy from Brazil with soy from another origin.
Lastly, the last conclusion drawn from the scenario analysis is that the circular use of organic fertilizers will slightly improve the performance of livestock feed. However, the inclusion of carbon capture and using locally sourced products will have a more significant effect on the performance.
These results show that the environmental performance index for livestock feed is technically feasible.

The constructed environmental performance index is validated. The validation showed that the model generates logical outputs. The validation is done with an uncertainty analysis and sensitivity analysis. The uncertainty analysis showed that the selected method for scaling has a strong positive correlation with the conventional linear scaling transformation, which indicates that this method is reliable. Also, the selected weights show a strong positive correlation with alternatively selected weights with the AHP. There can be concluded that the results of the model are valid.
With the sensitivity analysis, the resistance of the model to variations in the input of the index is validated. The strong correlations between the CI results and the CI results with variations in the input data show that the model is resistant and still accurate when high variations are present.

After the environmental performance index was verified and validated, it has been proven that the index is a tool that can be used by decision-makers in the livestock feed industry. The model provides reliable and accurate results. It can help measure the performance of livestock feed compositions based on environmental sustainability performance and economic performance.

7.1.1. Scientific relevance

This study contributes to the academic literature. Several gaps in the literature are identified and addressed.
First of all, most scientific papers on the optimization of livestock feed solely take costs and nutritional values into account. Very limited research in done in the field of the optimization of livestock feed in terms of costs, nutritional values and environmental sustainability. The environmental sustainability of livestock feed is getting rising attention and the necessity to enhance the traditionally used optimization models with environmental sustainability is acknowledged in the literature. This research contributes to this knowledge gap by proposing an environmental performance index to assess and optimize the environmental performance of livestock feed from an economic perspective.

In the field of the environmental sustainability of livestock feed, usually only the GHG emissions are taken into consideration. A neglected topic in the area of environmental sustainability is the ability to capture carbon in soils. Research has shown that carbon capture can no longer be neglected. In this study, the impact of the inclusion of carbon capture when determining the environmental sustainability of livestock feed is addressed and evaluated. Knowledge is gained on the effect of possible carbon capture on the performance of livestock feed.

The two identified gaps are combined to create a tool to measure the performance of livestock feed. Existing knowledge on composite indicators is used to construct a sector-specific composite indicator for the livestock feed industry. This composite indicator determines the performance of livestock feed based on the environmental sustainability performance and economic performance. The environmental sustainability performance takes both GHG emissions and carbon capture into consideration. This contributes to the literature; until now, no performance measurement tool for the livestock feed industry was developed.

7.1.2. Societal relevance

This study contributes to the mitigation of GHG emissions in the livestock industry, a reduction that needs to occur. The index created in this study could help decision-makers within feed companies, and farmers, to assess the performance of different feed compositions. For example, with the index the effect of carbon capture can be made transparent. This could stimulate livestock feed companies to buy commodities from farmers that apply regenerative agricultural practices. Decision-makers can act on this knowledge and be aware that more environmentally sustainable compound feed can be composed. The emissions of the overall livestock industry can be reduced if feed companies would take GHG emissions into account in addition to costs and nutritional values. Many GHG emissions could be saved.

7.2. Discussion and recommendations

In this Section, different parts of this research are discussed and recommendations for future research are proposed. The discussion and recommendations are divided into five parts. First, the research approach is discussed. Secondly, there is reflected in the model assumptions. Thirdly, the findings of this study are critically looked at. Next, the limitations and implications of these limitations for future research are discussed. Furthermore, a future perspective is provided.

7.2.1. Research approach

Several limitations of the research approach can be identified. In this study, the scope is limited to feed production. To get a more accurate and detailed overview of the reduction of GHG emissions, the scope should be extended. The amount of GHG emissions from enteric fermentation is affected by the composition of feed. For future research, it would be interesting to assess the performance of livestock feed when considering the livestock industry as a whole. Also, the effect of feed additives can be taken into account. Feed additives can contribute to lowering emissions through enteric fermentation and manure [7, 93].

In this study, the GHG emissions that contribute to global warming are taken into account; carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In future research, this could be expanded. Besides contributing to global warming, there are other factors that have an impact on the environment and health of soils, such as the use of water, nitrogen (N) emissions and acidification.

7.2.2. Research assumptions

Assumptions were made when constructing the environmental index. Many assumptions concern the data collection to bring the environmental performance index into practice. These assumptions include the emission and cost figures used for the transportation modes. Also, the data on carbon capture per region are applied to countries; this is not very accurate. These assumptions should be taken into account when interpreting the results. These assumptions can be further investigated in future research.
Furthermore, the agricultural data are not all from the same year. For example, the data from SimaPro is based on data from 2012-2016 and the data on crop yield is based on 2020. It is assumed that the data are the same for every year. In real life, this is probably not the case.

7.2.3. Research findings

There are several points of discussion on the findings of this research. First of all, the data on crop costs are global commodity prices. Since only the origin of commodities is adjusted when bringing the index into practice, the total price of every feed composition was constant. In Figure 7.1, the results are clustered. In this clustered overview, it becomes even clearer that the environmental sustainability performance has a way higher influence on the overall result. This is due to the consistent economic data.
It would be more accurate to use the costs of real-life deals on commodities to get a more accurate view. Then the economic performance will be more reflected in the index.
Next to that, the data on emissions from LUC not only include LUC from deforestation. This could clarify why the emissions from LUC in scenario 3 are higher than the benchmark. It could be interesting to split the emissions from deforestation and other LUC in future research.
The data on carbon capture are calculated based on the how much of a commodity is obtained per hectare per year. It can be seen that a higher LU results in more carbon capture. In future research, the relationship between carbon capture and LU should be further investigated. High LU results in deforestation, but low LU results in intensive use of the soil which could decrease the soil health. The trade-off between carbon capture and LU is interesting to investigate more.
When the findings of the two different scaling techniques are compared, it becomes clear that the min-max transformation creates a wider spread between data. This was as expected. However, because

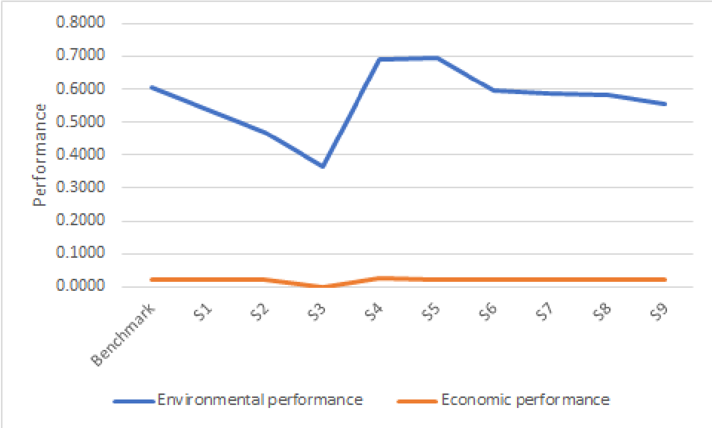

Figure 7.1: Clustered results

the data are normalized against each other, and not against an external benchmark, as with the LST method, some variables cannot be seen in the Figure G.1. The minimum value of a variable is normalized to 0.0000 and is therefore not present in the graph. This is no problem, but this should be correctly interpreted by the decision-maker. This does not mean that the data for that variable are non-existing.

7.2.4. Research limitations

There are several limitations in this research. Due to a lack of data, only scenarios are assessed where the origins are changed in relation to the benchmark feed composition. In future research, the model should be brought into practice with feed compositions with different commodities. This way, the effect of the use of secondary streams can be further explored. Another scenario that could be investigated is what the effect on the performance is when feed with lower nutritional values is produced. This could, for example, be interesting when there is a surplus of milk or meat.
Besides this, in future research, the model should be validated with real-life data to validate the model further. The accuracy of the representation of the real world can be even better validated.

7.2.5. Future perspectives

Over the past years, climate financing has become a topic with rising attention. The EC reviewed different reward strategies for carbon capture in soils and will further elaborate on this topic in 2022. A reward strategy for carbon capture is in the form of carbon credits [22]. A business can generate carbon credits when they undertake action to reduce GHG emissions [90]. By engaging in carbon capturing activities, such as regenerative agriculture, farmers could earn money with their cropland. The amount of carbon captured in the soil can be improved by adopting regenerative agricultural practices. Businesses that have a high GHG emissions profile can buy the carbon credits from farmers. In Figure 7.2, the concept of carbon credits is illustrated.
The Rabo Carbon Bank, from the Rabobank, started a pilot project study in the Netherlands and the US on carbon capture by farmers. In April 2022, the first carbon credits were sold to companies. The farmers that were part of the pilot study applied regenerative practices to increase their carbon capture. To deploy this concept of regenerative agricultural practices on a large scale, the Rabo Carbon bank and other experts in the carbon credit industry, identify the acquisition of data on the SOC stocks as one of the obstacles [60]. At this moment, a soil sample of every hectare of land should be taken and analyzed. This is accompanied by very high cost and a time-consuming process. The nonexistence of an efficient measurement system that can capture data on SOC stocks keeps farmers from taking part in the carbon credit reward system.

When the measurement of SOC stocks can be made less time-consuming and more cost-efficient, more farmers can adopt regenerative practices and sell carbon credits. This will stimulate farmers to become more sustainable and the income from carbon credits gives them more leeway to invest in the transition to an environmentally sustainable farming system [60].

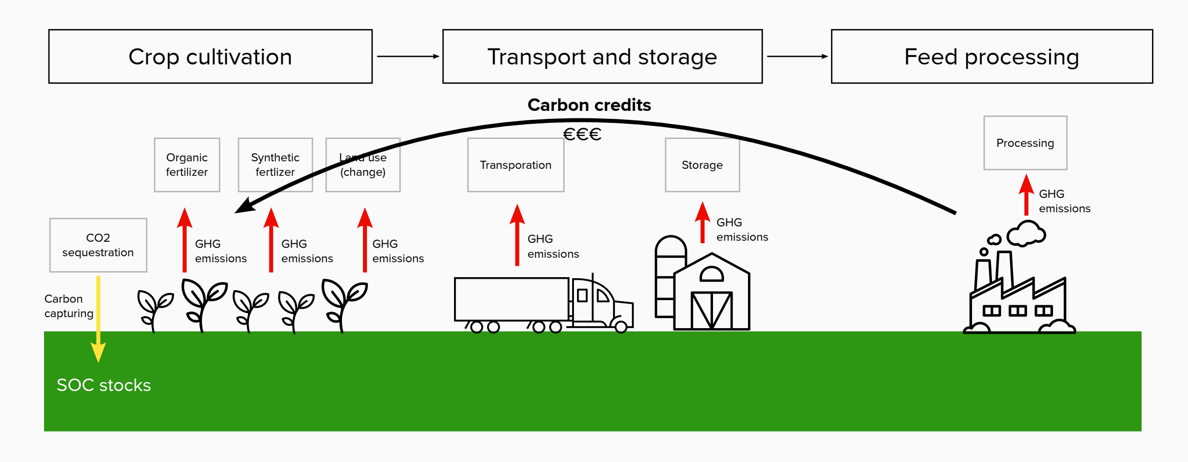

Figure 7.2: Carbon credit structure

As soon as farmers decide to measure the SOC stocks in their soils to earn carbon credits, this should be reflected in the environmental performance index for livestock feed. Carbon capture will become a source of income and is therefore an economic performance variable.

Carbon prices are expected to rise in the future because the pressure on the climate is getting bigger and the attention for climate change is rising. This means that the earning potential of carbon credits will get even bigger in the future.

Farmers are seen as the problem, but they can be part of the solution!

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A
Literature matrix

In Table A.1 a literature matrix is. This matrix was created in a previously done literature study on ”Carbon balancing in the feed production of the livestock industry” by Russell [67].

On the vertical axis the relevant literature is shown. The articles are separated into two parts. The upper part of the articles mainly elaborate on and assess emissions in the livestock industry. The lower part are the articles elaborate on optimal feed compositions for the livestock industry.
On the horizontal axis important objectives discussed in the literature are shown. This axis is divided into four parts.

There can be seen that all papers cover emissions from livestock feed and all articles agree on the link between emissions and feed composition. The upper part of the matrix shows that most studies include emissions from land-use change and use LCA to assess the emissions. The inclusion of capture carbon in the emissions overview to balance GHGs and circularity to mitigate GHG emissions are mostly excluded.
In the lower part of the matrix there can be seen that all articles include optimizing feed composition. Only two out of the five articles included all three defined objectives important for the feed composition. These two articles miss the link with carbon capture and circularity.

It is interesting to see in this matrix that all articles link GHG emissions of feed for the livestock industry to an optimized feed composition. However, non of the studies combined these two topics and include carbon capture.

A GHG balance that includes GHG emissions and carbon capture is never investigated in combination with the optimization of feed compositions in terms of environmental sustainability, cost and nutritional values. This provides opportunity for future research.
An index should be created to asses feed compositions in terms of cost, nutritional values and environmental sustainability. To assess the environmental sustainability GHG emissions and carbon capture should be included. Literature research on indices should be done and methods to measure carbon capture should be further investigated.
In this index emissions from pesticides can be left out of scope, because the emissions are negligible. Emissions from LULUC, fertilizers, fossil fuels and energy use should be taken into account. Circular processes should be implemented in the index. Waste streams from the livestock industry itself and other industries should be included as well as the use of manure as a replacement of fertilizers. Lastly, carbon capture with regenerative practices should be included in the index to create a GHG balance.
The output of the index should rate feed compositions for the livestock based on environmental sustainability, costs and nutritional values. The outcome of the index can contribute to improving the carbon balance and could, thus, help reduce GHG emissions from the feed production of the livestock industry.

Table A.1: Concept matrix literature study

	Elaborate on emissions of livestock feed	Emissions from land-use change (LUC)	Carbon capture	Circularity	Life Cycle Analysis (LCA)	Link emissions to feed composition	Investigate optimized feed composition	Optimize against cost	Optimize against nutritional values	Optimize against environmental sustainability
2021 FAO Global Livestock Environmental Assessment Model (GLEAM)	*	*			*	*				
2020 Post et al. Effects of Dutch livestock production on human health and the environment	*	*				*				
2019 van Grinsven et al. Benchmarking Eco-Efficiency and Footprints of Dutch Agriculture in European Context and Implications for Policies for Climate and Environment	*				*	*				
2017 Rojas-Downing et al. Climate change and livestock: Impacts, adaptation, and mitigation	*	*	*			*				
2016 FAO Environmental performance of animal feeds supply chains	*	*	*	*	*	*				
2013 Vellinga et al. Methodology used in FeedPrint: a tool quantifying greenhouse gas emissions of feed production and utilization	*	*	*	*	*	*				
2013 Gerber et al. Tackling climate change through livestock	*	*			*	*				
2012 Weis and Leip Greenhouse gas emissions from the EU livestock sector: A lifecycle assessment carried out with the CAPRI model	*	*	*		*	*				
2011 Lesschen et al. Greenhouse gas emission profiles of European livestock sectors	*					*				
2006 LEAD Livestock's long shadow	*	*	*	*		*				
2005 van der Werf et al. The environmental impacts of the production of concentrated feed: The case of pig feed in Bretagne	*			*	*	*	*			

2021 Pinotti et al. Recycling food leftovers in feed as opportunity to increase the sustainability of livestock production	*			*		*	*		*	*
2020 Rashid et al. Feeding blend optimization for livestock by using goal programming approach	*					*	*	*	*	
2016 Mackenzie et al. Towards a methodology to formulate sustainable diets for livestock: Accounting for environmental impact in diet formulation	*	*			*	*	*	*	*	*
2014 Sasu-Boakye et al. Localising livestock protein feed production and the impact on land use and greenhouse gas emissions	*			*	*	*	*			
2011 Babic et al. Optimization of livestock feed blend by use of goal programming	*					*	*	*	*	
2005 Castrodeza et al. Multicriteria fractional model for feed formulation: Economic, nutritional and environmental criteria	*					*	*	*	*	*

B

Framework for choosing methods to construct a CI

Mazziotta and Pareto [51] created a guide for choosing the ’best’ method for creating a CI. On the next page, in Figure B.1 the framework is shown.

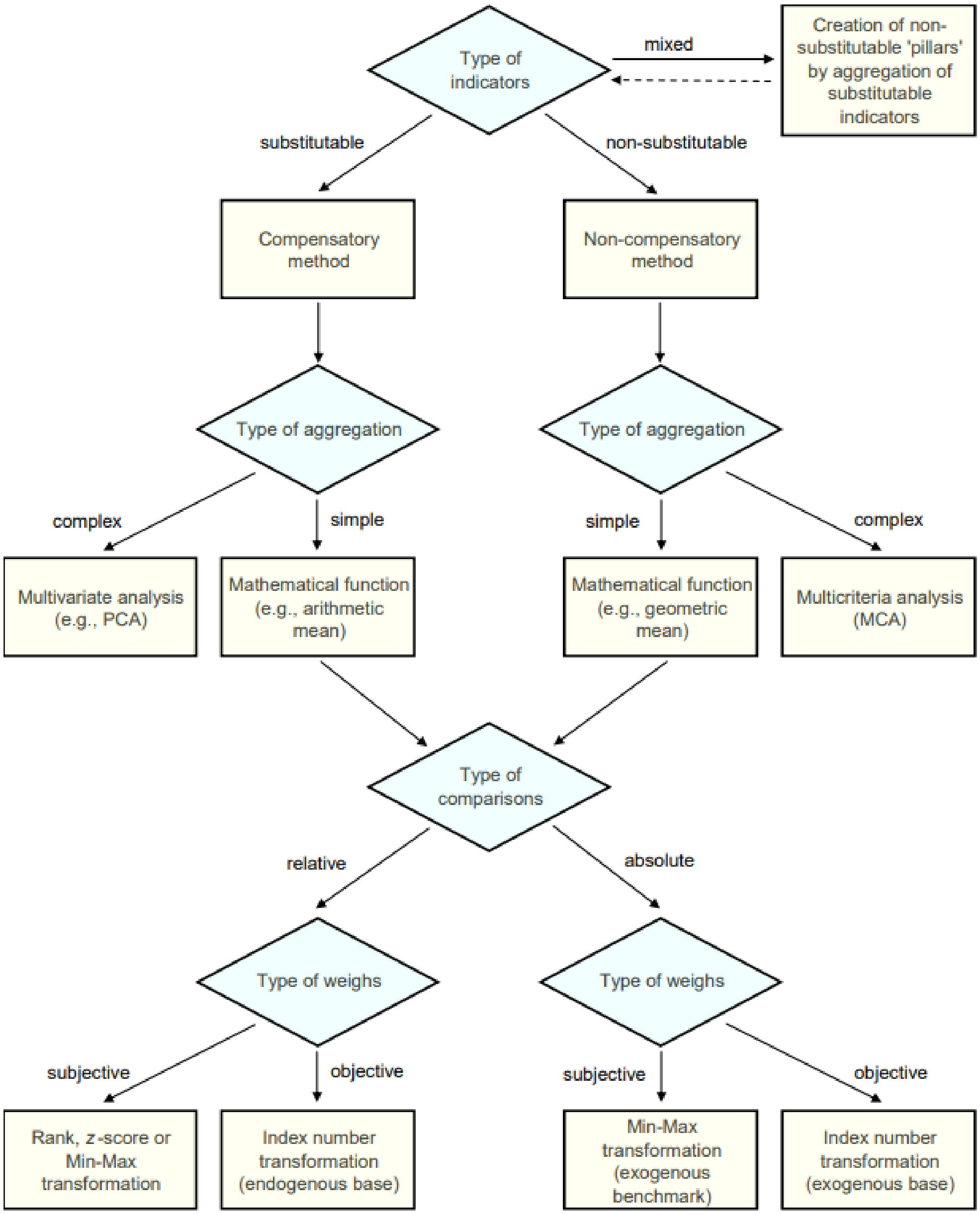

Figure B.1: Framewrok for choosing methods to construct a CI [51]

C
Literature study regenerative agriculture

The goal of regenerative agriculture is to restore degraded soils to improve the amount of soil organic carbon (SOC). SOC is defined by the FAO as ”organic carbon present in the fraction of soil that passes through the 2 mm sieve” [25]. SOC in soil works as a carbon sink for carbon from the atmosphere. Carbon sequestration by land currently used for agricultural purposes can be optimized by regenerative agriculture.

Regenerative agriculture is not solely based on increasing the carbon stocks in the soil. The benefits are listed here [43, 109]:

- Improvement of soil fertility
- Stimulation of biodiversity
- Availability of water
- Prevention of wind and water erosion
- Improvement soil organic carbon

The fertility of the soil is improved by increasing the soil organic matter, by N fixation and by recycling the nutrient by eliminating the input of chemical fertilizers. Biodiversity and the availability of water are optimized. It also involves preventative measures to prevent wind and water erosion from happening [43].

For a long time soil management to increase carbon capture has been ignored [90], but research has shown management of land can increase carbon capture in soil of crop and grassland [109]. Cropland is able to sequester less carbon than grassland [24, 25, 58, 79]. Grassland is of greater importance for carbon sequestration since they have higher SOC stocks than cropland [25]. Post et al. (2020) elaborates on the ratio of crop- and grassland in the Netherlands. 30% of the total agricultural land in the Netherlands for feed purposes is cropland, the other 70% is grassland.

Cropland
Currently, nearly 10% of the global soil organic carbon is stored in the top 30 cm of cropland, over 140 Pg (10^15) carbon. In Figure C.1 the current overview of the global SOC is shown.
The data for the image are retrieved from a geospatial analysis of datasets from the SoilsGrids250 database [109]. Temperature and precipitation have a strong effect on SOC stocks. In general in areas where it is hot and dry, tropic areas, SOC are lower. In the more cooler and wetter SOC stocks are higher. This is reflected in Figure C.1, around the equator a low density of SOC stocks is shown and in the more northern parts SOC stocks are higher [109]. The FAO [25] confirms the impact of precipitation on SOC stocks. A positive relationship between rainfall and SOC is shown, the higher the annual precipitation, the higher the SOC stocks [25]. The impact of temperature and precipitation is an important factor when discussing SOC stocks.

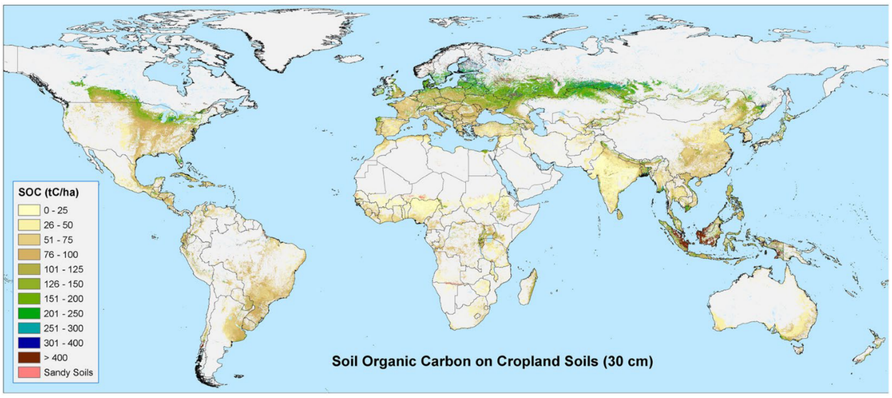

Figure C.1: Global SOC overview in top 30 cm of soil [109]

The management of soil, regenerative management, could improve the rate of carbon capture [90, 109]. Cultivation of crops results in a decrease in carbon stocks in the soil. The decrease of SOC stocks can be counteracted by executing different practices. Returning crop residues to the land, also known as mulching, and conservation tillage are know practices. Also, the use of organic manure increases SOC stocks [66, 88, 109]. Harder to implement, but effective, are cover cropping and agroforestry [109]. Rojas-Downing et al. [66] adds an optimal crop cultivation scheme should be determined with double-cropping and crop rotations.

Next to managerial practices, carbon capture depends on the type of crop grown on the land. A study done by Mathew et al. [50] argues that grass and maize have the greatest ability to sequester carbon from the atmosphere in the plant as well as the soil. The study found a possible direct link between plant C stocks and an increase of SOC stock in the soil. The study indicates that soil underneath maize and soybean have the highest SOC stocks. Unexpectedly high rates of SOC were found in soils where maize and soybean were rotated.
Different types of crops have varying SOC stocks dependent on temperature and precipitation conditions. In the tropics, equivalently high SOC stocks were found for maize and soybean. Under sub-tropical conditions the SOC stocks with soybean were higher than with maize. Even, SOC stocks with wheat were higher than maize in sub-tropical conditions, but in other climate conditions wheat is associated with the lowest SOC stocks. Again, it becomes clear that climate conditions have a high impact on soil carbon stocks. They emphasize that the comparison of crops is difficult due to the varying climate conditions and management practices ([50]).

Zomer et al. [109] created Figure C.2 which predicts the potential annual increase of SOC stocks, assuming regenerative measures are carried out. It is based on a scenario study developed by Sommer and Bossio [78], they formulated a pessimistic, a medium optimistic and highly optimistic scenario. Figure C.2 is based on the medium optimistic scenario. In this scenario, worldwide an annual increase of 0.012% SOC stocks is assumed.

Grassland
The FAO [25] elaborated on SOC stocks in grassland. As mentioned before, grassland occupies more land than cropland. Managing grassland is often done less intensively [76]. For this reason, Sommer and Bossio [78] assume it is more difficult to implement measures to increase SOC stocks in grassland. The FAO [25] and Smith et al. [76] both reflect on measures that could be taken to increase the amount of SOC stocks in the soil of grassland. Grazing intensity, fertilization, grass species selection, cutting frequency and reseeding are identified.

The effect of grazing intensity on SOC stocks are not unambiguous [25]. In response to this finding, Mcsherry and Ritchie [52] conducted a meta-analysis to investigate the effects of grazing of carbon stocks in grassland. They found that grazing has a significant influence on SOC stocks, but the effects of the grazing intensity vary dependent on the climate, soils and grass type. Smith et al. [76] has drawn the same conclusions. SOC stock are bigger in optimally grazed lands, however, the definition

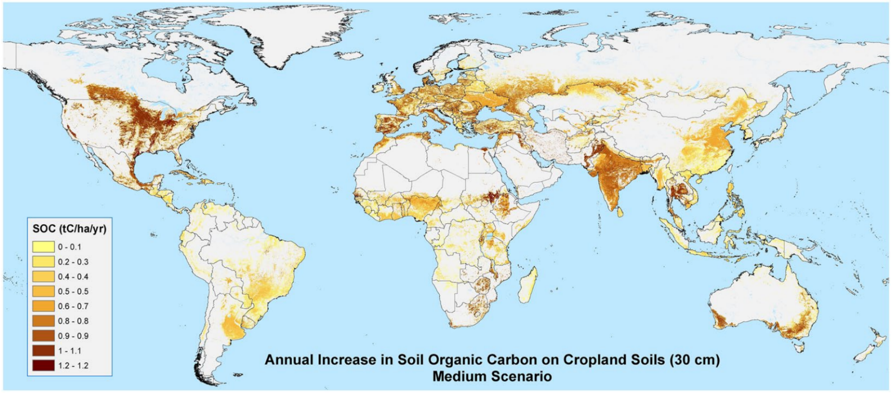

Figure C.2: Potential global SOC overview in top 30 cm of soil after executing regenerative measures [109]

of optimally grazed is not yet defined and because of inconsistent results [76]. It is difficult to draw a conclusion on the effects of grazing intensity.

Next to the grazing intensity, fertilization can affect SOC. Nutrients are essential to build up SOC stocks. Fertilizers are applied to stimulate growth and contain nutrients such as nitrogen (N), phosphorus (P) and potassium (K). Especially N contributes to the increase of SOC in the soil. Besides the nutrients, the increased biomass due to the use of fertilizers results in higher amounts of SOC stocks. The complexity of the effects of fertilizer is, however, higher [25]. The FAO [25]) makes this statement because several other studies found contradicting results when considering not just the aboveground biomass, but also the belowground biomass.
Manure is used as a fertilizer as well. The utilization of manure impacts the carbon and nitrogen stocks in the soil. Carbon present in manure can be partially be absorbed by the soil it is applied to ([25]). A meta-analysis done by Maillard and Angers [47] confirms this finding. This meta-analysis is based on 42 research articles, 49 websites and 130 observation worldwide. The study found that SOC stocks were positively impacted by the cumulative manure-C input. The input is responsible for a variability of 53% in SOC stocks compared to the reference cases, mineral fertilizers and unfertilized treatments [47].

In the Netherlands, animal products are produced at intensive livestock production sites. Livestock is mainly kept in the stables at intensive livestock production farms. This means hay is cut from grassland instead of shortened by grazing. The FAO [25] states that the effect of the cutting frequency on the SOC stock is not well understood, but the cutting frequency could have an effect on SOC due to changes in net primary production, the difference between carbon taken up through photosynthesis and the lost carbon through respiration, via changed canopy properties and plant species composition. A reason the effect of the cutting frequency is not well understood is the effects of cutting frequency and fertilizers are hard to keep apart, since grassland that is cut often receives more fertilizers [25].

The fourth and the last effect on SOC stocks identified are reseeding and grass species selection. Reseeding cultivars with desirable traits can increase yields of grassland and, thus, the profits from the land. Understandably, it is a frequently used practice. The seedbed is mechanically prepared for reseeding. The soil is disrupted due to the mechanical preparation and changes in the carbon and nutrients cycle in the soil go along with this disruption [25]. More long-term and holistic experiments on farm-scale are necessary but require a lot of money to maintain.
The selection of the grass species selection is identified as a factor that affects SOC stocks. Species rich grasslands have a higher aboveground net primary production and their roots are more diverse and complex. This root structure ensures a larger volume of soil is penetrated. The high net primary production and penetration of the soil potentially have a positive effect on the SOC stocks ([25, 76]).

The assessment of the influence factors on the SOC stocks on grassland shows that the sequestration of carbon by grassland is not yet well understood. This is also apparent from different studies, the rate of sequestration are not unambiguous per paper. Both Soussana et al. [79]) and Conant et al.

[16]) looked into carbon sequestration of grassland. Both state that SOC stocks in grassland increase over the years. However, Soussana et al. [79]) argues that the carbon sequestration is a continuing process. Conant et al. [16]) believes an equilibrium is reached over the years. Vellinga et al. [88]) and Mathew et al. [50]) share this view.

SOC stocks forests
Deforestation affects the carbon stocks of the land as well. Major carbon sinks are lost due to the loss of forests and the change of the designation of the land [6, 43]. Forests sequester significantly more carbon than crop- and grassland. The carbon sequestration potential of forests is of high importance for the global warming mitigation potential [36, 96]. By land-use change high amounts of CO_2 are released into the atmosphere [66]. After the land-use change, the high rate of carbon sequestration by forests is missed as well [15, 35].
Don et al. [18]) did a meta-analysis research based on 385 studies on changes in SOC stocks as a result of land-use change in tropic areas. The study indicated that an average decline of 25% in SOC stocks could be seen when converting primary forests into cropland and a decline of 12% when converting forests into grassland. The loss of carbon in the soil is partially reversible. If agricultural land is reforested the SOC stocks will increase with 29%. An increase in SOC stocks of 26% is seen when converting cropland to grassland [18]. The findings of a meta-analysis based on 74 papers done by Guo and Gifford [34]) and Soussana et al. [79]) are in line with the findings on the reversibility of land. Besides, Soussana et al. [79]) emphasizes the effect of climate conditions on SOC stocks as a result of land-use change. The findings of this study are that land-use change from grass- to cropland causes a decrease of 18% in dry climates and a decrease of 29% in moist climates in SOC stocks in the soil. When reverting this, so crop- to grassland, an increase of 18% in SOC stocks is seen in moist climates. In dry climates an increase of only 7% in reported. There can be concluded that the conversion of cropland to grassland or the conversion of crop- and grassland to forests could increase carbon capture.

The describes factors influencing the SOC stocks in the soil should be taken into account with regenerative agricultural practices. This way the carbon sequestration of farmers can be optimized to ultimately create a net zero balance in the feed production chain. Eventually, farmers can use regenerative practices to sell carbon credits.

D

Feed compositions

The feed compositions assessed with the composite indicator are listed below. For every scenario, the feed composition consists of certain commodities from different origin. The commodity, the origin of the commodity and the proportion in the feed mixture is displayed.

D.1. Benchmark feed composition

Commodity	Origin	Benchmark Composition [%]
Wheat	France	0.290
Maize	Ukraine	0.206
Soybean meal 49 P	Brazil	0.118
Barley	UK	0.111
Rape seed expeller	Denmark	0.052
Rape seed meal solvent extracted	Germany	0.037
Wheat middlings	Netherlands	0.035
Sunflower seed meal 29 P	Ukraine	0.032
Profit P4 (cookie/candy waste stream)	Netherlands	0.025
Palm kernel expeller	Indonesia	0.017
Soybean meal non GMO 49 P	Brazil	0.016
Sunflower seed meal 36 P	Ukraine	0.016
Oat grain	Poland	0.016
Soybean oil	Brazil	0.003
Poultry fat	Netherlands	0.006
Palm kernel fatty acid	Indonesia	0.005
Palm oil	Indonesia	0.003
Sunflower oil	Ukraine	0.002
Sugar beet pulp	Germany	0.002
Soybean hulls	Argentina	0.002
Potato protein	Netherlands	0.001

Table D.1: Benchmark feed composition

D.2. Scenario 1, 2, 6, 7, 8 and 9:

Commodity	Origin	Benchmark Composition [%]
Wheat	France	0.290
Maize	Ukraine	0.206
Soybean meal 49 P	Brazil	0.118
Barley	UK	0.111
Rape seed expeller	Denmark	0.052
Rape seed meal solvent extracted	Germany	0.037
Wheat middlings	Netherlands	0.035
Sunflower seed meal 29 P	Ukraine	0.032
Profit P4 (cookie/candy waste stream)	Netherlands	0.025
Palm kernel expeller	Indonesia	0.017
Soybean meal non GMO 49 P	Brazil	0.016
Sunflower seed meal 36 P	Ukraine	0.016
Oat grain	Poland	0.016
Soybean oil	Brazil	0.003
Poultry fat	Netherlands	0.006
Palm kernel fatty acid	Indonesia	0.005
Palm oil	Indonesia	0.003
Sunflower oil	Ukraine	0.002
Sugar beet pulp	Germany	0.002
Soybean hulls	Argentina	0.002
Potato protein	Netherlands	0.001

Table D.2: Feed composition scenario 1, 2, 6, 7, 8 and 9

D.3. Scenario 3:

Commodity	Origin	Benchmark Composition [%]
Wheat grain	Netherlands	0.290
Maize	Netherlands	0.206
Soybean meal 49 P	Brazil	0.118
Barley	Netherlands	0.111
Rapeseed expeller	Netherlands	0.052
Rapeseed meal solvent extracted	Netherlands	0.037
Wheat middlings	Netherlands	0.035
Sunflower seed meal 29 P	Ukraine	0.032
Profit P4 (cookie/candy waste stream)	Netherlands	0.025
Palm kernel expeller	Indonesia	0.017
Soybean meal non GMO 49 P	Brazil	0.016
Sunflower seed meal 36 P	Ukraine	0.016
Oat grain	Netherlands	0.016
Soybean oil	Brazil	0.003
Poultry fat	Netherlands	0.006
Palm kernel fatty acid	Indonesia	0.005
Palm oil	Indonesia	0.003
Sunflower oil	Ukraine	0.002
Sugar beet pulp	Netherlands	0.002
Soybean hulls	Argentina	0.002
Potato protein	Netherlands	0.001

Table D.3: Feed composition scenario 3

D.4. Scenario 4:

Commodity	Origin	Benchmark Composition [%]
Wheat	France	0.290
Maize	Ukraine	0.206
Soybean meal 49 P	Argentina	0.118
Barley	UK	0.111
Rape seed expeller	Denmark	0.052
Rape seed meal solvent extracted	Germany	0.037
Wheat middlings	Netherlands	0.035
Sunflower seed meal 29 P	Ukraine	0.032
Profit P4 (cookie/candy waste stream)	Netherlands	0.025
Palm kernel expeller	Indonesia	0.017
Soybean meal non GMO 49 P	Argentina	0.016
Sunflower seed meal 36 P	Ukraine	0.016
Oat grain	Poland	0.016
Soybean oil	Argentina	0.003
Poultry fat	Netherlands	0.006
Palm kernel fatty acid	Indonesia	0.005
Palm oil	Indonesia	0.003
Sunflower oil	Ukraine	0.002
Sugar beet pulp	Germany	0.002
Soybean hulls	Argentina	0.002
Potato protein	Netherlands	0.001

Table D.4: Feed composition scenario 4

D.5. Scenario 5:

Commodity	Origin	Benchmark Composition [%]
Wheat	France	0.290
Maize	Ukraine	0.206
Soybean meal 49 P	US	0.118
Barley	UK	0.111
Rape seed expeller	Denmark	0.052
Rape seed meal solvent extracted	Germany	0.037
Wheat middlings	Netherlands	0.035
Sunflower seed meal 29 P	Ukraine	0.032
Profit P4 (cookie/candy waste stream)	Netherlands	0.025
Palm kernel expeller	Indonesia	0.017
Soybean meal non GMO 49 P	US	0.016
Sunflower seed meal 36 P	Ukraine	0.016
Oat grain	Poland	0.016
Soybean oil	US	0.003
Poultry fat	Netherlands	0.006
Palm kernel fatty acid	Indonesia	0.005
Palm oil	Indonesia	0.003
Sunflower oil	Ukraine	0.002
Sugar beet pulp	Germany	0.002
Soybean hulls	Argentina	0.002
Potato protein	Netherlands	0.001

Table D.5: Feed composition scenario 5

E

Data per feed composition

E.1. Benchmark feed composition

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.04369	0.07435	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.02046	0.00000	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.08598	0.29928	0.17499	0.00000	0.32310	0.00000	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.02046	0.00000	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.02046	0.00000	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.07620	0.23163	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02634	0.07609	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.1: Benchmark feed composition

E.2. Scenario 1

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.30188	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.04369	0.07435	0.33814	0.00000	0.03460	0.35900	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.59335	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.34485	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.52534	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.54755	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.23570	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	0.99692	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.02046	0.00000	0.25054	0.00000	0.39721	0.11360	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.59335	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	0.99692	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.61985	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.08598	0.29928	0.17499	0.00000	0.32310	0.59335	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.02046	0.00000	0.25054	0.00000	1.26584	0.11360	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.02046	0.00000	0.25054	0.00000	1.21270	0.11360	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.07620	0.23163	0.33814	0.00000	0.18508	0.99692	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.02720	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02634	0.07609	0.20727	0.00000	0.10233	0.66594	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.04726	1.40000	0.00000	0.00388

Table E.2: Feed composition scenario 1

E.3. Scenario 2

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage cost	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.62571	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.04369	0.07435	0.33814	0.00000	0.03460	0.74409	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	1.20906	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.08757	0.07099	0.71476	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	1.08886	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	1.13489	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.48854	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	2.06630	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.02046	0.00000	0.25054	0.00000	0.39721	0.23577	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	1.20906	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	2.06630	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	1.28475	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.08598	0.29928	0.17499	0.00000	0.32310	1.20906	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.02046	0.00000	0.25054	0.00000	1.26584	0.23577	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.02046	0.00000	0.25054	0.00000	1.21270	0.23577	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.07620	0.23163	0.33814	0.00000	0.18508	2.06630	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.05638	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02634	0.07609	0.20727	0.0000	0.10233	1.35698	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.09795	1.40000	0.00000	0.00388

Table E.3: Feed composition scenario 2

E.4. Scenario 3

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	Netherlands	0.290	1.22770	0.06529	0.05593	2.51617	0.10200	0.00070	0.07416	0.00000	0.26500	0.00000	0.00388
Maize	Netherlands	0.206	0.80829	0.00336	0.01443	2.08738	0.10200	0.00000	0.03460	0.00000	0.27840	0.00000	0.00388
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Barley	Netherlands	0.111	1.29146	0.00000	0.04102	3.29359	0.10200	0.00070	0.07416	0.00000	0.26400	0.00000	0.00388
Rape seed expeller	Netherlands	0.052	0.49643	2.11184	0.15222	7.15983	0.10200	0.00000	0.09309	0.00000	0.37650	0.00000	0.00388
Rape seed meal solvent extracted	Netherlands	0.037	0.42610	1.81267	0.15222	7.15983	0.10200	0.00000	0.11480	0.00000	0.35000	0.00000	0.00388
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.02046	0.00000	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Netherlands	0.016	1.67942	0.00000	0.04780	4.18559	0.10200	0.00070	0.07416	0.00000	0.23000	0.00000	0.00388
Soybean oil	Brazil	0.003	7.35735	11.45801	0.08598	0.29928	0.17499	0.00000	0.32310	0.00000	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.02046	0.00000	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.02046	0.00000	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.07620	0.23163	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Netherlands	0.002	0.00012	0.00000	0.00516	0.31880	0.10200	0.00000	0.47952	0.00000	0.26000	0.00000	0.00388
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02634	0.07609	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.4: Feed composition scenario 3

E.5. Scenario 4

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.04369	0.07435	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	Argentina	0.118	2.6065	4.1150	0.0263	0.0761	0.2073	0.0000	0.1691	0.0000	0.4448	0.0000	0.09583
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.02046	0.00000	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Argentina	0.016	2.6065	4.1150	0.0263	0.0761	0.2073	0.0000	0.1691	0.0000	0.4448	0.0000	0.09583
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	Argentina	0.003	7.2208	11.3997	0.0263	0.2993	0.2073	0.0000	0.4073	0.0000	1.3450	0.0000	0.09583
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.02046	0.00000	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.02046	0.00000	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.07620	0.23163	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02634	0.07609	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.5: Feed composition scenario 4

E.6. Scenario 5

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.04369	0.07435	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	US	0.118	3.13533	0.01051	0.30566	0.87875	0.10159	0.00000	0.17830	0.00000	0.44475	0.00000	0.04697
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.02046	0.00000	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	US	0.016	3.13533	0.01051	0.30566	0.87875	0.10159	0.00000	0.17830	0.00000	0.44475	0.00000	0.04697
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.07620	0.23163	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	US	0.003	8.68581	0.02911	0.30566	0.87875	0.10159	0.00000	0.45212	0.00000	1.34500	0.00000	0.04697
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.02046	0.00000	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.02046	0.00000	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.07620	0.23163	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02634	0.07609	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.6: Feed composition scenario 5

E.7. Scenario 6

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.03495	0.09513	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.06096	0.28356	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.01637	0.00745	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.06096	0.28356	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.08598	0.29928	0.17499	0.00000	0.32310	0.00000	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.01637	0.00745	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.01637	0.00745	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.06096	0.28356	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02107	0.15218	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.7: Feed composition scenario 6

E.8. Scenario 7

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.05384	0.16995	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.02621	0.11590	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.04572	0.33549	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.01227	0.01491	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.08598	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.04572	0.33549	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.08598	0.29928	0.17499	0.00000	0.32310	0.00000	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.01227	0.01491	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.01227	0.01491	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.04572	0.33549	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.01580	0.13593	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.8: Feed composition scenario 7

E.9. Scenario 8

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertilizers	Emissions transport	Emissions storage	Emissions processing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.04307	0.19583	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.03495	0.09513	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.06878	0.35568	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.06096	0.28356	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.01637	0.00745	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.06878	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.05766	0.28356	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.06878	0.35568	0.17499	0.00000	0.32310	0.00000	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.01637	0.00745	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.01637	0.00745	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.05766	0.28356	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.02107	0.15218	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.9: Feed composition scenario 8

E.10. Scenario 9

Commodity	Origin	Proportions	Land use	Emissions LUC	Emissions synthetic fertilizer	Emissions organic fertiliz-ers	Emissions transport	Emissions storage	Emissions process-ing	GHG capture	Commodity costs	Storage costs	Transport costs
[-]	[-]	[%]	[m_2a crop-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg o. fert./kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[kg co_2-eq/kg]	[€/kg]	[€/kg]	[€/kg]
Wheat	France	0.290	1.22770	0.06529	0.03231	0.22171	0.08557	0.00073	0.07657	0.00000	0.26500	0.00000	0.04653
Maize	Ukraine	0.206	1.58131	0.07427	0.02621	0.07999	0.33814	0.00000	0.03460	0.00000	0.27840	0.00000	0.18385
Soybean meal 49 P	Brazil	0.118	2.65579	4.13601	0.05159	0.41208	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Barley	UK	0.111	1.48630	0.00000	0.05719	0.25365	0.08757	0.00385	0.07099	0.00000	0.26400	0.00000	0.04761
Rape seed expeller	Denmark	0.052	1.20797	0.03889	0.07902	1.96507	0.01939	0.00000	0.09530	0.00000	0.37650	0.00000	0.00897
Rape seed meal solvent extracted	Germany	0.037	1.20295	0.12111	0.12529	0.91470	0.10200	0.00000	0.12323	0.00000	0.35000	0.00000	0.05546
Wheat middlings	Netherlands	0.035	0.62749	0.01747	0.05608	2.51617	0.00714	0.00070	0.11775	0.00000	0.22867	0.00000	0.00388
Sunflower seed meal 29 P	Ukraine	0.032	2.90242	0.10745	0.05159	0.41208	0.33814	0.00000	0.06567	0.00000	0.27850	0.00000	0.18385
Profit P4 (cookie/candy waste stream)	Netherlands	0.025	0.00000	0.00000	0.00000	0.00000	0.02143	0.00000	0.03460	0.00000	0.24867	0.00000	0.00388
Palm kernel expeller	Indonesia	0.017	0.19623	0.24929	0.01227	0.01491	0.25054	0.00000	0.39721	0.00000	1.54500	0.00000	0.11583
Soybean meal non GMO 49 P	Brazil	0.016	2.65579	4.13601	0.05159	0.29928	0.17499	0.00000	0.13650	0.00000	0.44475	0.00000	0.08090
Sunflower seed meal 36 P	Ukraine	0.016	2.90242	0.10745	0.04324	0.33549	0.33814	0.00000	0.03107	0.06567	0.27850	0.00000	0.18385
Oat grain	Poland	0.016	3.31596	0.00000	0.06287	0.49283	0.15657	0.00070	0.08354	0.00000	0.23000	0.00000	0.08513
Soybean oil	Brazil	0.003	7.35735	11.45801	0.05159	0.41208	0.17499	0.00000	0.32310	0.00000	1.34500	0.00000	0.08090
Poultry fat	Netherlands	0.006	0.30833	0.20754	0.00000	0.00000	0.00714	0.00000	0.28760	0.00000	1.05500	0.00000	0.00388
Palm kernel fatty acid	Indonesia	0.005	1.35506	0.91184	0.01227	0.01491	0.25054	0.00000	1.26584	0.00000	0.23000	0.00000	0.11583
Palm oil	Indonesia	0.003	1.76828	2.24642	0.01227	0.01491	0.25054	0.00000	1.21270	0.00000	1.08500	0.00000	0.11583
Sunflower oil	Ukraine	0.002	16.48146	0.61016	0.04324	0.33549	0.33814	0.00000	0.18508	0.00000	1.65000	0.00000	0.18385
Sugar beet pulp	Germany	0.002	0.00020	0.00000	0.00720	0.05306	0.10200	0.00000	0.24117	0.00000	0.26000	0.00000	0.05546
Soybean hulls	Argentina	0.002	1.31023	2.06850	0.01580	0.13593	0.20727	0.00000	0.10233	0.00000	0.71500	0.00000	0.09583
Potato protein	Netherlands	0.001	1.75491	0.00093	0.01230	0.59959	0.00714	0.00000	0.77077	0.00000	1.40000	0.00000	0.00388

Table E.10: Feed composition scenario 9

F

Data on crop yield

Commodity	Origin	Crop yield [kg/ha/year]
Wheat	France	6680.3
Maize	Ukraine	5617.5
Soybean meal 49 P	Brazil	3275.2
Barley	UK	5848.0
Rape seed expeller	Denmark	3838.8
Rape seed meal solvent extracted	Germany	3683.1
Wheat middlings	Netherlands	8556.0
Sunflower seed meal 29 P	Ukraine	2022.9
Profit P4 (cookie/candy waste stream)	Netherlands	0.0
Palm kernel expeller	Indonesia	17106.5
Soybean meal non GMO 49 P	Brazil	3275.2
Sunflower seed meal 36 P	Ukraine	2022.9
Oat grain	Poland	3253.5
Soybean oil	Brazil	3275.2
Poultry fat	Netherlands	0.0
Palm kernel fatty acid	Indonesia	17106.5
Palm oil	Indonesia	17106.5
Sunflower oil	Ukraine	2022.9
Sugar beet pulp	Germany	74140.2
Soybean hulls	Argentina	2918.2
Potato protein	Netherlands	42675.1

Table F.1: Crop yield per commodity per country of origin, based on 2020

G

Results environmental performance index of livestock feed

In this Appendix more extensive results of phase IV and phase V of the environmental performance index are shown.

G.1. Results aggregating

In Table G.1, the aggregated values per variable (j) and feed composition (i) are shown.

Feed composition	V_1: Land use	V_2: Emissions LUC	V_3: Emissions synthetic fertilizer	V_4: Emissions organic fertilizers	V_5: Emissions transportation	V_6: Emissions storage	V_7: Emissions processing	V_8: GHG capture	V_9: Commodity costs	V_{10}: Storage costs	V_{11}: Transportation costs
Benchmark	0.04318	0.10813	0.04787	0.00080	0.12222	0.13632	0.00852	0.13632	0.00000	0.00000	0.02377
Scenario 1	0.04318	0.10813	0.04787	0.00080	0.12222	0.13632	0.00852	0.07031	0.00000	0.00000	0.02377
Scenario 2	0.04318	0.10813	0.04787	0.00080	0.12222	0.13632	0.00852	0.00000	0.00000	0.00000	0.02377
Scenario 3	0.00000	0.13632	0.03999	0.05408	0.00000	0.00000	0.00000	0.13632	0.00000	0.00000	0.00000
Scenario 4	0.04208	0.10756	0.02394	0.00000	0.13632	0.13632	0.10650	0.13632	0.00000	0.00000	0.02463
Scenario 5	0.05408	0.00000	0.13632	0.00294	0.09057	0.13632	0.13632	0.13632	0.00000	0.00000	0.02184
Scenario 6	0.04318	0.10813	0.04028	0.00100	0.12222	0.13632	0.00852	0.13632	0.00000	0.00000	0.02377
Scenario 7	0.04318	0.10813	0.03240	0.00119	0.12222	0.13632	0.00852	0.13632	0.00000	0.00000	0.02377
Scenario 8	0.04318	0.10813	0.02394	0.00138	0.12222	0.13632	0.00852	0.13632	0.00000	0.00000	0.02377
Scenario 9	0.04318	0.10813	0.00000	0.00176	0.12222	0.13632	0.00852	0.13632	0.00000	0.00000	0.02377

Table G.1: Results phase IV: Aggregation with Simple Additive Weighting

G.2. Results post analysis

The results of the post analysis are outlined in this Section. First, the results of the uncertainty analysis are shown. The results for scaling with the conventional linear scaling transformation method are outlined as well as the results for the alternative selection of weights. Furthermore, the results for the sensitivity analysis are shown.

G.2.1. Results UA - the scaling method

Results phase II

	V1: Land use	V2: Emissions LUC	V3: Emissions synthetic fertilizer	V4: Emissions organic fertiliz-ers	V5: Emissions trans-portation	V6: Emissions storage	V7: Emissions process-ing	V8: GHG capture	V9: Commodity costs	V10: Storage costs	V11: Transportation costs
Feed compo-sition	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Benchmark	0.77305	0.76020	0.37892	0.03748	0.86784	0.79146	0.78298	1.00000	0.67344	0.00000	0.82893
Scenario 1	0.77305	0.76020	0.37892	0.03748	0.86784	0.79146	0.78298	0.55337	0.67344	0.00000	0.82893
Scenario 2	0.77305	0.76020	0.37892	0.03748	0.86784	0.79146	0.78298	0.07750	0.67344	0.00000	0.82893
Scenario 3	0.09132	0.95789	0.32473	0.98509	0.31068	0.19276	0.77619	1.00000	0.67344	0.00000	0.18508
Scenario 4	0.75539	0.75634	0.21474	0.02319	0.93131	0.79146	0.86062	1.00000	0.67344	0.00000	0.85175
Scenario 5	0.94489	0.00203	0.98363	0.07545	0.72352	0.79146	0.88355	1.00000	0.67344	0.00000	0.77703
Scenario 6	0.77305	0.76020	0.32510	0.04094	0.86784	0.79146	0.78298	1.00000	0.67344	0.00000	0.82893
Scenario 7	0.77305	0.76020	0.22365	0.03748	0.86784	0.79146	0.78298	1.00000	0.67344	0.00000	0.82893
Scenario 8	0.77305	0.76020	0.21403	0.04778	0.86784	0.79146	0.78298	1.00000	0.67344	0.00000	0.82893
Scenario 9	0.77305	0.76020	0.05065	0.05446	0.86784	0.79146	0.78298	1.00000	0.67344	0.00000	0.82893

Table G.2: Results phase II: scaling with LST

Results phase III

	Weight
W_1: Land use	0.05408
W_2: Emissions LUC	0.13632
W_3: Emissions synthetic fertilizer	0.13632
W_4: Emissions organic fertilizer	0.05408
W_5: Emissions transportation	0.13632
W_6: Emissions storage	0.13632
W_7: Emissions processing	0.13632
W_8: GHG capture	0.13632
W_9: Commodity costs	0.02463
W_{10}: Storage costs	0.02463
W_{11}: Transport costs	0.02463

Table G.3: Results phase IV: scaling with LST

Results phase IV

Feed compo-sition	V1: Land use	V2: Emissions LUC	V3: Emissions synthetic fertilizer	V4: Emissions organic fertiliz-ers	V5: Emissions trans-portation	V6: Emissions storage	V7: Emissions process-ing	V8: GHG capture	V9: Commodity costs	V10: Storage costs	V11: Transport costs
Benchmark	0.04181	0.10363	0.05166	0.00203	0.11831	0.10790	0.10674	0.13632	0.01659	0.00000	0.02042
Scenario 1	0.04181	0.10363	0.05166	0.00203	0.11831	0.10790	0.10674	0.07544	0.01659	0.00000	0.02042
Scenario 2	0.04181	0.10363	0.05166	0.00203	0.11831	0.10790	0.10674	0.01057	0.01659	0.00000	0.02042
Scenario 3	0.00494	0.13058	0.04427	0.05327	0.04235	0.02628	0.10581	0.13632	0.01659	0.00000	0.00456
Scenario 4	0.04085	0.10311	0.02927	0.00125	0.12696	0.10790	0.11732	0.13632	0.01659	0.00000	0.02098
Scenario 5	0.05110	0.00028	0.13409	0.00408	0.09863	0.10790	0.12045	0.13632	0.01659	0.00000	0.01914
Scenario 6	0.04181	0.10363	0.04432	0.00221	0.11831	0.10790	0.10674	0.13632	0.01659	0.00000	0.02042
Scenario 7	0.04181	0.10363	0.03049	0.00203	0.11831	0.10790	0.10674	0.13632	0.01659	0.00000	0.02042
Scenario 8	0.04181	0.10363	0.02918	0.00258	0.11831	0.10790	0.10674	0.13632	0.01659	0.00000	0.02042
Scenario 9	0.04181	0.10363	0.00690	0.00295	0.11831	0.10790	0.10674	0.13632	0.01659	0.00000	0.02042

Table G.4: Results phase IV: scaling with LST

The results of Table G.4 and Table G.5 are visualized in Figure G.1.

Feed composition	CI
Benchmark	0.61266
Scenario 1	0.56731
Scenario 2	0.51900
Scenario 3	0.46010
Scenario 4	0.67005
Scenario 5	0.56490
Scenario 6	0.60779
Scenario 7	0.60269
Scenario 8	0.59722
Scenario 9	0.58142

Table G.5: Results phase IV: scaling with LST

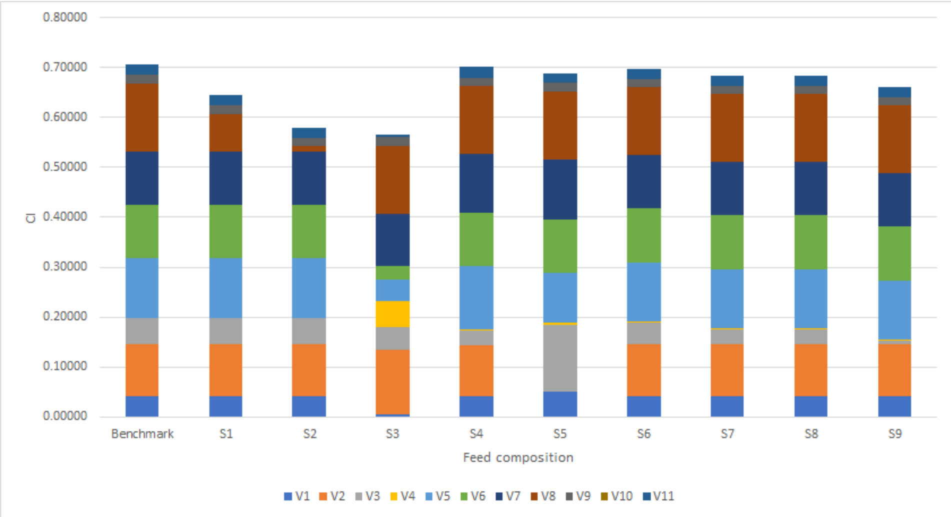

Figure G.1: Results phase IV: scaling with LST

G.2.2. Results UA - selection of weights

G.2.3. Results phase II

	V1: Land use	V2: Emissions LUC	V3: Emissions synthetic fertilizer	V4: Emissions organic fertiliz-ers	V5: Emissions trans-portation	V6: Emissions storage	V7: Emissions process-ing	V8: GHG capture	V9: Commodity costs	V10: Storage cost	V11: Transportation costs
Feed compo-sition	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Benchmark	0.7985	0.7932	0.3512	0.0149	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 1	0.7985	0.7932	0.3512	0.0149	0.8966	1.0000	0.0625	0.5158	0.0000	0.0000	0.9650
Scenario 2	0.7985	0.7932	0.3512	0.0149	0.8966	1.0000	0.0625	0.0000	0.0000	0.0000	0.9650
Scenario 3	0.0000	1.0000	0.2934	1.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000
Scenario 4	0.7780	0.7890	0.1756	0.0000	1.0000	1.0000	0.7813	1.0000	0.0000	0.0000	1.0000
Scenario 5	1.0000	0.0000	1.0000	0.0544	0.6644	1.0000	1.0000	1.0000	0.0000	0.0000	0.8867
Scenario 6	0.7985	0.7932	0.2955	0.0185	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 7	0.7985	0.7932	0.2377	0.0219	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 8	0.7985	0.7932	0.1756	0.0255	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650
Scenario 9	0.7985	0.7932	0.0000	0.0325	0.8966	1.0000	0.0625	1.0000	0.0000	0.0000	0.9650

Table G.6: Results phase II: Alternative selection of weights

G.2.4. Results phase III

	Weight
W_1: Land use	0.09366
W_2: Emissions LUC	0.24530
W_3: Emissions synthetic fertilizer	0.09366
W_4: Emissions organic fertilizer	0.09366
W_5: Emissions transportation	0.09366
W_6: Emissions storage	0.09366
W_7: Emissions processing	0.09366
W_8: GHG capture	0.09366
W_9: Commodity costs	0.03302
W_{10}: Storage costs	0.03302
W_{11}: Transport costs	0.03302

Table G.7: Results phase III: Alternative selection of weights

G.2.5. Results phase IV

Feed composition	V1: Land use	V2: Emissions LUC	V3: Emissions synthetic fertilizer	V4: Emissions organic fertilizers	V5: Emissions transportation	V6: Emissions storage	V7: Emissions processing	V8: GHG capture	V9: Commodity costs	V10: Storage costs	V11: Transportation costs
Benchmark	0.07479	0.19457	0.03289	0.00139	0.08397	0.09366	0.00585	0.09366	0.00000	0.00000	0.03187
Scenario 1	0.07479	0.19457	0.03289	0.00139	0.08397	0.09366	0.00585	0.04831	0.00000	0.00000	0.03187
Scenario 2	0.07479	0.19457	0.03289	0.00139	0.08397	0.09366	0.00585	0.00000	0.00000	0.00000	0.03187
Scenario 3	0.00000	0.24530	0.02748	0.09366	0.00000	0.00000	0.00000	0.09366	0.00000	0.00000	0.00000
Scenario 4	0.07287	0.19355	0.01645	0.00000	0.09366	0.09366	0.07317	0.09366	0.00000	0.00000	0.03302
Scenario 5	0.09366	0.00000	0.09366	0.00509	0.06223	0.09366	0.09366	0.09366	0.00000	0.00000	0.02928
Scenario 6	0.07479	0.19457	0.02768	0.00173	0.08397	0.09366	0.00585	0.09366	0.00000	0.00000	0.03187
Scenario 7	0.07479	0.19457	0.02226	0.00205	0.08397	0.09366	0.00585	0.09366	0.00000	0.00000	0.03187
Scenario 8	0.07479	0.19457	0.01645	0.00239	0.08397	0.09366	0.00585	0.09366	0.00000	0.00000	0.03187
Scenario 9	0.07479	0.19457	0.00000	0.00305	0.08397	0.09366	0.00585	0.09366	0.00000	0.00000	0.03187

Table G.8: Results phase IV: alternative selection of weights

Feed composition	**CI**
Benchmark	0.61266
Scenario 1	0.56731
Scenario 2	0.51900
Scenario 3	0.46010
Scenario 4	0.67005
Scenario 5	0.56490
Scenario 6	0.60779
Scenario 7	0.60269
Scenario 8	0.59722
Scenario 9	0.58142

Table G.9: Results phase IV: alternative selection of weights

In Figure G.2, the results of Table G.8 and Table G.9 are visualized.

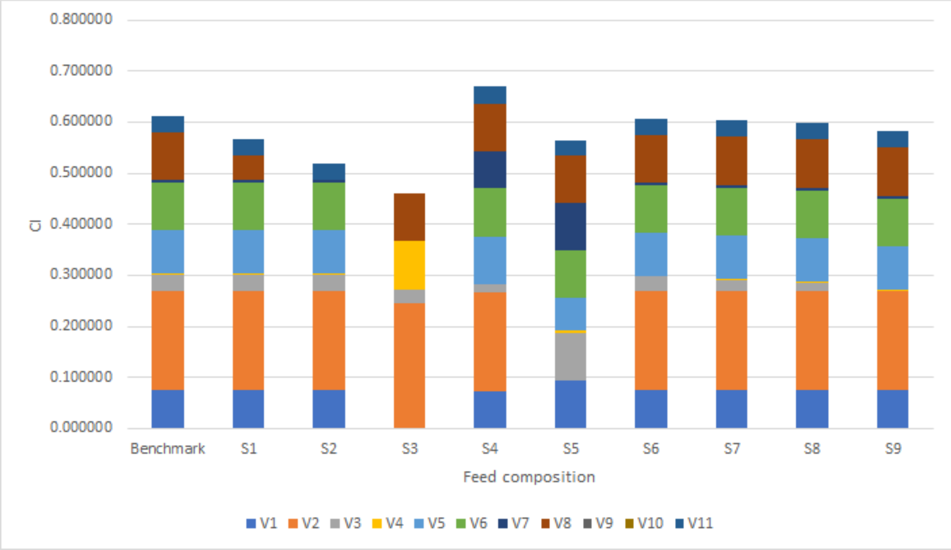

Figure G.2: Results phase IV: alternative selection of weights

G.2.6. Results SA

G.2.7. SA variable 1 +20%

Feed composition	CI V_1	CI V_1 +20%
Benchmark	0.62715	0.61685
Scenario 1	0.56114	0.55085
Scenario 2	0.49083	0.48053
Scenario 3	0.36672	0.36679
Scenario 4	0.71369	0.70381
Scenario 5	0.71473	0.70412
Scenario 6	0.61976	0.60918
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.59332
Scenario 9	0.58023	0.56982

Table G.10: Results phase V: SA variable 1

G.2.8. SA variable 2 +20%

Feed composition	CI	CI V_2 +20%
Benchmark	0.62715	0.61685
Scenario 1	0.56114	0.55085
Scenario 2	0.49083	0.48053
Scenario 3	0.36672	0.36679
Scenario 4	0.71369	0.70381
Scenario 5	0.71473	0.70412
Scenario 6	0.61976	0.60919
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.59332
Scenario 9	0.58023	0.56982

Table G.11: Results phase V: SA variable 2

G.2.9. SA variable 3 +20%

Feed composition	CI	CI V_3 +20%
Benchmark	0.627153	0.64147
Scenario 1	0.561142	0.57547
Scenario 2	0.49083	0.50515
Scenario 3	0.36672	0.39140
Scenario 4	0.71369	0.72841
Scenario 5	0.71473	0.72875
Scenario 6	0.61976	0.63380
Scenario 7	0.61206	0.61262
Scenario 8	0.60379	0.61794
Scenario 9	0.58023	0.59445

Table G.12: Results phase V: SA variable 3

G.2.10. SA variable 4 +20%

Feed composition	CI	CI V_4 +20%
Benchmark	0.62715	0.64148
Scenario 1	0.56114	0.57548
Scenario 2	0.49083	0.50516
Scenario 3	0.36672	0.39142
Scenario 4	0.71369	0.72844
Scenario 5	0.71473	0.72875
Scenario 6	0.61976	0.63382
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.61795
Scenario 9	0.58023	0.59445

Table G.13: Results phase V: SA variable 4

G.2.11. SA variable 5 +20%

Feed composition	CI	CI V_5 +20%
Benchmark	0.62715	0.64148
Scenario 1	0.56114	0.57548
Scenario 2	0.49083	0.50515
Scenario 3	0.36672	0.39142
Scenario 4	0.71369	0.72844
Scenario 5	0.71473	0.72874
Scenario 6	0.61976	0.63381
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.61795
Scenario 9	0.58023	0.59445

Table G.14: Results phase V: SA variable 5

G.2.12. SA variable 6 +20%

Feed composition	**CI**	**CI V_6 +20%**
Benchmark	0.62715	0.64335
Scenario 1	0.56114	0.57735
Scenario 2	0.49083	0.50703
Scenario 3	0.36672	0.39142
Scenario 4	0.71369	0.73031
Scenario 5	0.71473	0.73062
Scenario 6	0.61976	0.63569
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.61983
Scenario 9	0.58023	0.59633

Table G.15: Results phase V: SA variable 6

G.2.13. SA variable 7 +20%

Feed composition	**CI**	**CI V_7 +20%**
Benchmark	0.62715	0.64127
Scenario 1	0.56114	0.57527
Scenario 2	0.49083	0.50494
Scenario 3	0.36672	0.39142
Scenario 4	0.71369	0.72817
Scenario 5	0.71473	0.72875
Scenario 6	0.61976	0.63360
Scenario 7	0.61206	0.61252
Scenario 8	0.60379	0.61774
Scenario 9	0.58023	0.59424

Table G.16: Results phase V: SA variable 7

G.2.14. SA variable 8 +20%

Feed composition	**CI**	**CI V_8 +20%**
Benchmark	0.62715	0.64148
Scenario 1	0.56114	0.57548
Scenario 2	0.49083	0.50516
Scenario 3	0.36672	0.39142
Scenario 4	0.71369	0.72844
Scenario 5	0.71473	0.72875
Scenario 6	0.61976	0.63382
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.61795
Scenario 9	0.58023	0.59445

Table G.17: Results phase V: SA variable 8

G.2.15. SA variable 9 +20%

Feed composition	CI	CI V_9 +20%
Benchmark	0.62715	0.61685
Scenario 1	0.56114	0.55085
Scenario 2	0.49083	0.48053
Scenario 3	0.36672	0.36679
Scenario 4	0.71369	0.70381
Scenario 5	0.71473	0.70412
Scenario 6	0.61976	0.60919
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.59332
Scenario 9	0.58023	0.56982

Table G.18: Results phase V: SA variable 9

G.2.16. SA variable 10 +20%

Feed composition	CI	CI V_{10} +20%
Benchmark	0.62715	0.62715
Scenario 1	0.56114	0.56114
Scenario 2	0.49083	0.49083
Scenario 3	0.36672	0.36672
Scenario 4	0.71369	0.71368
Scenario 5	0.71473	0.71473
Scenario 6	0.61976	0.61976
Scenario 7	0.61206	0.61206
Scenario 8	0.60379	0.60379
Scenario 9	0.58023	0.58023

Table G.19: Results phase V: SA variable 10

G.2.17. SA variable 11 +20%

Feed composition	CI	CI V_{11} +20%
Benchmark	0.62715	0.61685
Scenario 1	0.56114	0.55085
Scenario 2	0.49083	0.48053
Scenario 3	0.36672	0.36679
Scenario 4	0.71369	0.70381
Scenario 5	0.71473	0.70412
Scenario 6	0.61976	0.60919
Scenario 7	0.61206	0.61263
Scenario 8	0.60379	0.59332
Scenario 9	0.58023	0.56982

Table G.20: Results phase V: SA variable 11