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Methods and means

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DECARBONIZATION OF THE BEEF PRODUCT CHAIN

METHODS AND MEANS

BY
EMIL PEDERSEN

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

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AALBORG UNIVERSITY
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Dissertation submitted

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I do research on life cycle assessment methods and the way companies use them to manage their production and product chains. This research includes the development of LCA models and tools for companies and supporting companies in their LCA projects.

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References

Available upon request.

ENGLISH SUMMARY

This PhD study aims to broaden academic research on companies that apply life cycle management (LCM) and claim to use life cycle assessment (LCA) as part of their strategy for decarbonizing their product chain. The focus is both on issues with modelling an LCA on beef production and understanding the link between the work performed by company employees in relation to the LCA model and the company's reductions in greenhouse gas (GHG) in the product chain. The goal of this dissertation is to provide insights that can help with the implementation and development of life cycle management and life cycle assessments in beef production. In line with the aim of this study, the following main research question was formulated:

To what extent can life cycle assessment be used to manage the transition towards decarbonizing beef production?

This project was conducted at the large Danish meat manufacturer Danish Crown and Aalborg University. The backbone of the research in this PhD thesis is the involvement and collaboration with Danish Crown, where observations and interviews with employees were conducted over the course of the PhD. The collaboration with Danish Crown was focused on the development of an LCA of the company's beef production in relation to their strategy of decarbonizing their product chain. The main research question is answered through three papers each of which have their own sub-research questions. These papers each have a specific aim whereby the first paper focuses on the way LCA is used by a company in their work with reducing GHG emissions from their product chain. The two other papers focus on the European Commission's Product Environmental Footprint (PEF) method, which is a guide to conducting LCAs.

The first paper analyzes the connection between Danish Crown's work with LCA and its work to reduce GHG emissions in the product chain. The paper did not find a clear link between the work with LCA and the efforts to reduce GHG emissions. Instead, the work with LCA mainly had the role of monitoring the development in GHG emissions from the product chain, sharing the results with farmers, and developing partnerships of potential commercial value. The focus of the activities related to the LCA model was on ensuring the model calculated in the "right" way and on calculating footprints for all products so they could be communicated.

Through a structured review of the European Commission's product environmental footprint (PEF) method, the second paper concluded that there are some open issues with the method. These include the extent to which the defined functional units in the

PEF Category Rules (PEFCR) are inadequate to ensure a fair comparison between products; impact categories for biodiversity and indirect land use change are not included; the existing and new PEFCR need to adopt a benchmarking method that enables the development of communication schemes; uncertainty exists about how the costs of conducting an LCA study are affected by PEF; and it is unclear how the results of a PEF study should be communicated.

If the intention is to use PEF for background studies in existing policies or for business-to-consumer communication, the fact that PEF only assesses environmental impacts and does not include social aspects represents a challenge. Another challenge is that the quality and nutritional value of products is not considered in some of the PEFCR. A third challenge for PEF in business-to-consumer communication is that a framework for how to communicate environmental impacts does not exist yet. If PEF were to become mandatory for substantiating green claims, the fact that the costs of conducting a PEF study are too high for SMEs would be problematic.

By testing four ways of modelling multifunctionality (multiple different outputs of products and by-products) in the abattoir, the third paper shows that the substitution model is the only model that adequately reflects the environmental consequences of changing production processes. Therefore, the modelling of multifunctionality should apply a substitution approach when the purpose of the LCA is to assess the environmental impact of 1) changing the demand for a product, or 2) changing the production process. Three other recommendations are given regarding the modeling of multifunctionality in beef production: 1) The mass fractions, indicating how many of the cattle are used for human consumption versus other purposes, should be based on company-specific data; 2) The relative prices for cuts of meat used in the model should reflect market-based average prices over a longer period, rather than company-specific prices and 3) The results should be presented for different cuts of meat, instead of only one product category, as described in the PEF guidelines.

In conclusion, in Danish Crown’s work with decarbonizing their beef production, LCA is used as a tool for monitoring the development in GHG emissions from the product chain and collaborating with farmers and customers. The PEF method has some issues and is not suitable in its current form for assessing the environmental impact of initiatives in a cattle abattoir. However, with some updates, it could become an important instrument for future environmental policies.

DANSK RESUME

Denne Ph.d.-afhandling har til formål at udvide den akademiske forskning på virksomheder, der anvender livscyklusledelse (LCM) og hævder at anvende livscyklusvurdering (LCA) som en del af deres strategi for at reducere klimapåvirkningen i deres produktkæde. Fokus er både på modelleringsproblemer i forhold til LCA af oksekødsproduktion og forståelse af forbindelsen mellem det arbejde, som virksomhedens medarbejdere udfører i forhold til LCA-modellen og virksomhedens reduktioner i drivhusgasemissioner i produktkæden. Målet med denne afhandling er at give indsigt, der kan hjælpe med implementeringen og udviklingen af livscyklusledelse og livscyklusvurderinger i oksekødsproduktion. I overensstemmelse med målet for denne undersøgelse blev følgende hovedforsknings spørgsmål formuleret:

I hvilket omfang kan livscyklusvurdering anvendes til at styre overgangen til at reducere klimapåvirkningen i oksekødsproduktionen?

Dette projekt blev gennemført i samarbejde med den danske kødproducent Danish Crown og Aalborg Universitet. Fundamentet for forskningen i denne Ph.d.-afhandling er involveringen og samarbejdet med Danish Crown, hvor observationer og interviews med medarbejdere blev gennemført i løbet af PhD-perioden. Samarbejdet med Danish Crown fokuserede på udviklingen af en LCA af virksomhedens oksekødsproduktion i relation til deres strategi om at reducere klimapåvirkningen i produktkæden. Det overordnede forskningsspørgsmål besvares gennem tre artikler, hver med deres egne underforsknings spørgsmål. Disse artikler har hver deres specifikke mål, hvor den første artikel fokuserer på, hvordan LCA bruges af en virksomhed i deres arbejde med at reducere drivhusgasemissioner fra deres produktkæde. De to andre artikler fokuserer på den europæiske kommissions metode for *Product Environmental Footprint* (PEF), som er en vejledning til gennemførelse af LCA'er.

Den første artikel analyserer forbindelsen mellem Danish Crowns arbejde med LCA og deres arbejde med at reducere drivhusgasemissioner i produktkæden. Artiklen fandt ikke en klar sammenhæng mellem arbejdet med LCA og indsatsen for at reducere drivhusgasemissioner. I stedet havde arbejdet med LCA primært til rolle at overvåge udviklingen i drivhusgasemissioner fra produktkæden, dele resultaterne med landmænd og udvikle partnerskaber med potentiel kommerciel værdi. Fokus for aktiviteterne relateret til LCA-modellen var at sikre, at modellen regnede på den "rigtige" måde og at beregne fodaftryk for alle produkter, så de kunne kommunikeres.

Gennem en struktureret gennemgang af Den Europæiske Kommissions PEF metode blev det konkluderet i den anden artikel, at der er nogle åbne udfordringer med metoden. Disse omfatter i hvilket omfang de definerede funktionelle enheder i PEF *Category Rules* (PEFCR) er utilstrækkelige til at sikre en fair sammenligning mellem produkter; manglende påvirkningskategorier for biodiversitet og indirekte landanvendelsesændringer; de eksisterende og nye PEFCR skal vedtage en benchmarking-metode, der muliggør udviklingen af kommunikationsinstrumenter; der er usikkerhed om, hvordan omkostningerne ved at gennemføre en LCA-studie påvirkes af PEF; og det er uklart, hvordan resultaterne af et PEF-studie skal kommunikeres.

Hvis intentionen er at anvende PEF til baggrundsstudier i eksisterende politikker eller til kommunikation med forbrugere, så udgør det en udfordring, at PEF kun vurderer miljømæssige påvirkninger og ikke inkluderer sociale aspekter. En anden udfordring er, at kvaliteten og ernæringsværdien af produkter ikke overvejes i nogle af PEFCR'erne. En tredje udfordring for PEF i kommunikation mellem virksomhed og forbruger er, at der endnu ikke findes en ramme for, hvordan miljøpåvirkninger skal kommunikeres. Hvis PEF skulle blive obligatorisk for at underbygge grønne påstande, ville det være problematisk, at omkostningerne ved at gennemføre et PEF-studie er for høje for SMV'er.

Ved at teste fire måder at modellere multifunktionalitet (produktionen af flere forskellige produkter og biprodukter) i slagteriet, viser den tredje artikel, at substitutionsmodellen er den eneste model, der tilstrækkeligt afspejler miljøkonsekvenserne af ændringer i produktionsprocesser. Derfor bør modellering af multifunktionalitet anvende en substitutionsmetode, når formålet med LCA er at vurdere den miljømæssige påvirkning af 1) ændring af efterspørgslen efter et produkt eller 2) ændring af produktionsprocessen. Tre andre anbefalinger gives vedrørende modellering af multifunktionalitet i oksekødproduktion: 1) Data for vægt der angiver, hvor meget af kvægene der anvendes til menneskelig forbrug versus andre formål, bør baseres på virksomhedsspecifikke data; 2) De relative priser for kødstykker, der anvendes i modellen, bør afspejle markedsbaserede gennemsnitspriser over en længere periode, i stedet for virksomhedsspecifikke priser og 3) Resultaterne bør præsenteres for forskellige kødstykker i stedet for kun en produktkategori, som beskrevet i PEF-retningslinjerne.

Konklusionen er, at i Danish Crowns arbejde med at nedbringe CO2-udledningen i deres oksekødproduktion anvendes LCA som et redskab til at overvåge udviklingen i GHG-udledninger fra produktkæden og samarbejde med landmænd og kunder. PEF-metoden har visse udfordringer og er ikke egnet i sin nuværende form til at vurdere den miljømæssige påvirkning af initiativer i en kvægbesætning. Men med nogle opdateringer kan den blive et vigtigt instrument for fremtidige miljøpolitikker.

ACKNOWLEDGEMENTS

This thesis is the culmination of a three-year PhD research project at Danish Crown and the research group of Sustainability, Innovation and Policy (SIP) at the Department of Planning at Aalborg University, funded through Manufacturing Academy Denmark. I would not have succeeded without the support of several people, and I would therefore like to begin with a word of thanks.

Doing a PhD is not an easy endeavor as several objectives, opinions and factors influence the work. I want to thank my supervisors Arne Remmen and Jannick Schmidt who kept me focused and guided me through the process.

I want to thank Danish Crown for being so open to my research and give a special thanks to my close colleagues Morten Pedersen, Liselotte Gjerdrum Carlsen, Gustaf Bock, Mette Schulin-Zeuthen, Jens Krogh Mikkelsen and Selma Al-Zohairi without whom this project would never have existed.

I want to thank my SIP colleagues from Aalborg University for inspiring discussions and for providing a good environment for me to take my first steps as a researcher.

A special thank is going to Henrikke Baumann for a very inspiring stay in the Environmental Systems Analysis group at Chalmers Technical University. It will always stand as one of the most exiting times during my PhD. I also want to thank your family for being very kind hosts during my stay-

My last thank go to the people around me. I could not have done this without the support of my friends, family, and fiancée Laura who made sure that I remembered to enjoy all the good things that happened and kept encouraging me when things did not go as planned.

- Emil

LIST OF PUBLICATIONS

The following list present the papers included in this PhD project and the corresponding chapter in this thesis.

Paper I: Pedersen, E., & Baumann, H., (202x). *Transforming the meat sector towards net zero greenhouse gas emissions: The role of life cycle work*. Submitted to The International Journal of Life Cycle Assessment. **Chapter 5**.

Paper II: Pedersen, E., & Remmen, A. (2022). *Challenges with product environmental footprint: a systematic review.* The International Journal of Life Cycle Assessment, 27(2), 342-352. **Chapter 6**.

Paper III: Pedersen, E., & Schmidt, J. (202x). *Testing different modelling of by-products in the Product Environmental Footprint in cattle abattoirs.* Submitted to The International Journal of Life Cycle Assessment. **Chapter 7**.

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CHAPTER 1. INTRODUCTION

The world has made significant progress in raising food consumption per person. In the last three and a half decades, consumption has increased from an average of 2370 kcal/person/day to 2770 kcal/person/day (Alexandratos and Bruinsma, 2012). Despite this seemingly positive development in consumption and food production, the world is still facing problems with ending hunger, food insecurity, and malnutrition (FAO, 2022). In 2015, nearly 10 % of the world's population suffered from obesity (Friedrich, 2017) while 16% of the world's population suffered from chronic hunger (Mc Carthy et al., 2018). Food production is also facing the challenge of water scarcity (FAO, 2020), food loss (FAO, 2019), and climate change (FAO, 2016). Therefore, there is a need for sustainable farming practices that can ensure food security for more people and resilience to climate change and other environmental risks (FAO, 2016).

1.1 LIVESTOCK FARMING

Diets are shifting towards the inclusion of more livestock products, and approximately 70% of the world's 1.4 billion "extremely poor" depend on livestock to support their livelihoods (Alexandratos and Bruinsma, 2012). Between 1961 and 2020, the global area for crop production increased by 30 percent while cattle stock has increased by 62 percent ((FAOSTAT1; FAOSTAT2). In the same period, the production of meat from cattle increased by 167 percent (FAOSTAT2).

In the EU, beef production peaked in 1991 at 9.6 million tonnes per year (Eurostat1; Nielsen and Jeppesen, 2001). Since then, the production of beef has decreased and in 2021 the EU produced 6.8 million tonnes annually (Eurostat1). France, Germany, Ireland, Spain, and Poland are the 5 countries in the EU that have the largest populations of cattle (63 percent combined) (Eurostat1). The European beef production is derived from both specialized beef production and excess cattle from dairy production. There are approximately 73 million farms in the EU 46 percent of which produce either beef or dairy. 27 percent of farms in EU specialize in dairy production, 15 percent in cattle rearing and fattening, and 4 percent are combined dairy, rearing productions (Eurostat2). This is also reflected in the age of slaughtered cattle with 86 percent of the beef coming from adult cattle and remainder from young cattle (5 percent) and calves (9 percent) (Eurostat1).

1.2 ENVIRONMENTAL IMPACT OF BEEF PRODUCTION

Historically, agriculture has had impacts on habitats, biodiversity, carbon storage and soil conditions (Foleay et al., 2011). Worldwide, 70% of grasslands, 50% of savannas, 45% of temperate deciduous forests, and 27% of tropical forest biomes have been cleared or converted for agriculture (Foleay et al., 2011). Agricultural environmental impacts include those from both the expansion of agricultural lands and intensification of production (Foleay et al., 2011). Expansion of agricultural lands is mainly occurring in the tropics, where approximately 80% of new croplands are replacing forests (Foleay et al., 2011). This expansion leads to biodiversity loss and disruption to ecosystem services and is also a major source of GHG emissions (Foleay et al., 2011). Intensification of agricultural production leads to the withdrawal of freshwater and disrupted global nitrogen and phosphorus cycles, which has a negative impact on water quality, aquatic ecosystems and marine fisheries. Both agricultural expansion and intensification are contributors to climate change (Foleay et al., 2011). In 2019, agriculture, forestry, and other land use sectors accounted for 22% of total GHG emissions (IPCC, 2023).

Livestock is the world's largest user of land resources with grazing land and cropland for the production of feed representing almost 80 % of all agricultural land (FAO, 2009). The livestock sector also accounts for 41 % of global agriculture water consumption (Heinke et al., 2020). The livestock sector releases nitrogen, phosphorus and other nutrients, pathogens and other substances into waterways and ground water (FAO, 2009). Poor manure management contributes to the pollution and eutrophication of surface waters, groundwater and coastal marine ecosystems, and the accumulation of heavy metals in soils, which may harm human health, result in a loss of biodiversity, contribute to climate change, soil and water acidification and degrade ecosystems (FAO, 2009). Separation of industrialized livestock from the land that supports it interrupts the nutrient flow between the land and livestock, which creates a problem in the form of the depletion of nutrients on the land used for feed production and pollution problems where animal wastes are disposed (FAO, 2009). Livestock production impacts biodiversity by modifying ecosystems through land use and land use changes, through overexploitation, e.g., overgrazing of pasture plants, and through water pollution and ammonia emissions, which impacts aquatic ecosystems (FAO, 2009).

In their study of European beef production, Nguyen et al. (2010) found that the environmental impact of 1 kg beef (slaughter weight) was larger for meat from suckler cows than meat from dairy cows, Table 1-1.

Table 1-1 the environmental impact of 1 kg beef meat (slaughter weight) (Nguyen et al., 2010).

Impact category	Dairy calves	Suckler cows
Climate change (kg CO2e)	16,0-19,9	27,3
Acidification (g SO2e)	101-173	210
Eutrophication (g NO3e)	622-1140	1651
Land use (m2year)	16,5-22,7	42,9
Non-renewable energy (Mj)	41,3-48,2	59,2

1.2.1 GREENHOUSE GAS EMISSIONS

Beef has one of the highest GHG emissions per kg product (Mogensen et al., 2009, Garnett, 2011). Within Europe, it has been estimated that meat and milk consumption is responsible for 24% of the total environmental impact (Weidema et al., 2008). The contribution to global warming from beef production depends on the production system applied (Nguyen et al., 2010, Mogensen et al., 2015a).

For a young bull born to a Danish dairy cow, GHG emissions are 10.1 kg CO2e / kg edible product while for a young Danish bull from the beef breed limousine, GHG emissions are 30.7 kg CO2e / kg edible product (Mogensen et al., 2015a). The contribution from the slaughtering stage accounts for 0.2 kg CO2e / kg edible product for both systems (Mogensen et al., 2015a). The contribution to GHG emissions from the slaughtering stage ranges between 0.5 and 2 % depending on the production system in place.

1.3 FUTURE DEVELOPMENTS AND CHALLENGES OF BEEF PRODUCTION

In the latest 2010 revision of the UN’s population projections, the world’s population will continue to grow past 2075 to reach 10.12 billion by 2100 (Alexandratos and Bruinsma, 2012). Since at the world level (but not for individual countries or regions) consumption equals production, this means global production in 2050 would need to be 60 percent higher than it was in 2005/2007 (Alexandratos and Bruinsma, 2012). Another study predicts a growth in food demand of 30 – 62 % when climate change is taken into consideration (van Dijk et al., 2021). A slowdown in the consumption of meat has been projected due to relatively modest increases in consumption and near stationary population development in developed countries, growth rates per capita that are lower than they have been in the past in China and Brazil, relatively low levels of consumption in India, and low incomes and poverty in many developing countries (Alexandratos and Bruinsma, 2012). The production of meat is projected to increase from 258 million tons per year in 2005/2007 to 455 million tons per year in 2050. In 2021, the global annual production of meat was 353 million tonnes (FAOSTAT).

Between 2007 and 2050, it is projected that the consumption and production of beef will increase by 1.2% annually worldwide (Alexandratos and Bruinsma, 2012). In the developed countries, the growth in consumption is projected to be 0.4% annually while production is projected to increase by 0.5% annually (Alexandratos and Bruinsma, 2012).

1.3.1 EXPECTED GHG EMISSIONS AND OTHER ENVIRONMENTAL IMPACTS OF FUTURE PRODUCTION.

In the period from 1920 – 2010, the net energy used for milk and meat in percent and land use has steadily decreased. In the same period, GHG emissions were reduced from 25.4 to 16.3 kg CO2 per kg meat (Kristensen et al., 2015).

GHG emissions have been reduced per kilo of meat during the last century, but with growing populations worldwide and increasing consumption of meat, the production of meat must become less GHG intensive in the future. Improved feed and animal management as well as improved grazing are seen as cost-effective climate mitigation initiatives needed between now and 2030 to stabilize global warming to be below 2 °C (Griscom et al., 2017). Others argue that the production of meat from cattle will need to be halved to meet the 1.5-degree goal (Henderson et al., 2020).

1.4 A LIFE CYCLE PERSPECTIVE

The farming stage including feed production accounts for approximately 99% of GHG emissions in the production of beef. However, in the beef product chain, there are several other stages and actors involved in the process of delivering meat to the consumers, see Figure 1-1. Looking backwards in the product chain from the farmer, there are feed suppliers, fertilizer suppliers, energy suppliers, and machinery dealers. In the other direction in the product chain, there are abattoirs, processing facilities, retailers, and consumers.

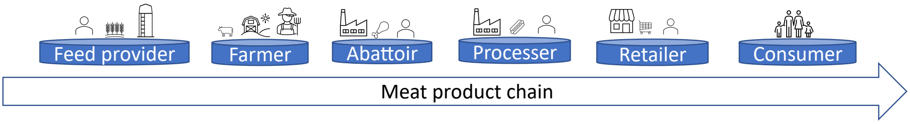

Figure 1-1 A generic product chain for meat (Adapted from Pedersen and Baumann, 2022)

The actors in the product chain have different options for reducing the environmental impacts of their food consumption and production. Farmers can introduce sustainable farming practices, e.g., improved manure handling, manure for biogas production and/or increased productivity. The other actors can also take action to reduce their environmental impacts such as reducing their consumption and food waste, choosing products with a smaller environmental footprint, or encouraging other actors to make greener choices. What most initiatives that actors can implement to reduce the environmental impact of their consumption or production have in common is that they require a life cycle perspective, which can include quality and nutrition perspectives. The actors need a life cycle perspective to manage the environmental impacts of their products or consumption. An environmental management strategy with a life cycle perspective is called life cycle management (LCM).

1.4.1 LIFE CYCLE MANAGEMENT

Life cycle management is an environmental management strategy that is based on a life cycle perspective. Actors that apply LCM are interested in all product stages from extraction of raw materials, design and production, packaging, distribution, use, maintenance, and end of life. Actors' interest is not limited by organizational boundaries, which means that LCM engages both internal and external stakeholders for environmental improvements in the value chain. Life cycle management is also a toolbox full of methods for assessing and reducing environmental impacts, e.g., life cycle assessment (LCA), ecolabels and certifications, sustainable procurement, and stakeholder engagement (Remmen et al., 2007). These methods are used to collect, structure, and disseminate product-related information. (Remmen et al., 2007). Life cycle management can also be viewed as a business management strategy for businesses and organizations that wish to improve their sustainability performance (Klos et al, 2022) or as the link between science and application (Hunkeler et al, 2001). It can also be used to support the circular economy (Zink et al., 2018).

1.4.2 USE OF LIFE CYCLE ASSESSMENT IN AGRI-FOOD SECTOR

Life cycle assessment is a method for assessing the potential environmental impacts of a product or service through its life cycle (ISO 14040:2008). It can be applied to improve the environmental performance of products, inform decision makers, select relevant indicators of environmental performance, and in marketing (ISO 14040:2008).

Life cycle assessment is an important topic in environmental management research. After the idea of LCA was conceived in the 1960s, the methodology was further developed and there was an increase in collaboration in the scientific community in the 1980s and 1990s (Bjørn et al., 2018). Efforts were also made to standardize LCA, which led to the creation of the ISO 14040 standard on LCA principles and frameworks, which was released in 1997 (Bjørn et al., 2018). During the following years, the private sector started to use LCA and, in 2015, more than 500 companies mentioned LCA in their CSR report (Bjørn et al., 2018).

Previous studies on the use of LCA by industry have shown that companies use the method for research, developing and designing products, comparing alternatives, tracking changes between product generations, preparing Environmental Product Declarations, communicating with customers, authorities and other stakeholders, and developing procurement specifications (Frankl & Rubik, 1999; Cooper & Fava, 2006; Nygren & Antikainen, 2010; Testa et al, 2016). The application of LCA can be classified into the following five categories: 1) decision support in product and process development; 2) marketing purposes; 3) development and selection of indicators for monitoring of environmental impacts; 4) selection of suppliers and subcontractors, and 5) strategic planning (Owsianiak et al., 2018). However, the use of LCA depends on how well implemented LCA is in the company as in the early stages of implementation it is primarily used for learning (Frankl & Rubik, 1999). An LCA can also serve more than one purpose in a company and one application of LCA in a company can trigger another application, e.g., an LCA on product performance can lead to changes in supplier (Owsianiak et al., 2018).

In the agri-food sector, companies are also using LCA as part of their sustainability strategies. Some of the largest agri-food companies in Europe such as Nestle, Heineken, Danone, Unilever, Diageo, Ferrero, FrieslandCampina, Arla, Danish Crown, Carlsberg, and others have made public statements about their use of LCA as part of their work with sustainability. All the above-mentioned companies have also set goals for reducing environmental impacts at their facilities and in their product chain.

1.5 AIM OF THE PHD STUDY AND STRUCTURE OF THESIS

The aim of this PhD study is to broaden academic research on meat companies that apply LCM and claim to use LCA as part of their sustainability strategy. The focus is both on issues with modelling a LCA on beef production and understanding the link between the work performed by company employees in relation to the LCA model and the company’s reductions in greenhouse gas (GHG) emissions in the product chain. The goal of this dissertation is to provide insights and recommendations that can facilitate the implementation and development of life cycle management and life cycle assessments in beef production. In line with the aim of this study, the following main research question was formulated:

To what extent can life cycle assessment be used to manage the transition towards decarbonizing beef production?

This thesis consists of four main parts, as illustrated in Table 1-2. The core part consists of three academic papers, which address different aspects of life cycle management and provide answers to four sub-questions. The knowledge gaps that each of the sub-questions aims to address are presented in Chapter 2.

Table 1-2 Structure of the thesis

Introduction
Chapter 1 introduction *Outlining the problem field of this dissertation, Chapter 1 discusses the current state of beef production and consumption at the global scale. The life cycle perspective is presented as a way companies are working with environmental impacts outside their own facilities.*
Framing the research
Chapter 2 Conceptual framework *The conceptual framework of this dissertation builds on company strategies to handle environmental impacts, life cycle management, and life cycle assessment. This provides the foundation to conceptualize key issues in companies work with environmental issues in a life cycle perspective.*
Chapter 3 Context of the project *The context of this project is the Danish production of beef, and more specifically, Danish Crown's beef production chain. Danish Crown and its work with sustainability and LCA are presented to illustrate how Danish Crown works with the life cycle perspective.*
Chapter 4 Research design and methods *The research design and data collection methods are presented to demonstrate how the research questions were answered. A more thorough explanation of the methods can be found in each of the three papers.*
Research findings

CHAPTER 5. Transforming the meat sector towards net zero greenhouse gas emissions: The role of life cycle work

The link between working with LCA in a company and reducing greenhouse gas emissions in the product chain is investigated through interviews and observation in a product chain. Socio-material interaction points are identified and analyzed for potential reductions.

Research sub-question 1: How is the life cycle assessment in a company linked to reductions of GHG emissions in the product chain?

Chapter 6. Challenges with Product Environmental Footprint: a systematic review

A systematic literature review of the Product Environmental Footprint (PEF) method highlights the current issues with the method. The review highlights which issues are still relevant and which have been resolved in the updated version of the PEF method. The possibility of using the PEF method in policies is discussed.

Research sub-question 2: What have the methodological issues been in the discussion on PEF, and how do the suggested updates address them?

Research sub-question 3: What are the challenges of using PEF in public policies and how can these be resolved?

Chapter 7. Testing different modelling of by-products in the Product Environmental Footprint in cattle abattoirs

This paper investigates how the modelling of multifunctionality affects the result of an LCA on beef from cattle. The study is based on an LCA of a cattle abattoir in Denmark, and the paper identifies the drawbacks and advantages of four different approaches to modelling multifunctionality.

Research sub-question 4: How does the modelling of multifunctionality affect the result of an LCA on beef?

Chapter 8. Discussion

This chapter discusses the findings of the three papers to synthesize the overall findings of the dissertation.

Conclusion and recommendations

Chapter 9. Conclusion

The findings are summarized and overall conclusions are drawn.

Chapter 10. Recommendations

Recommendations for continuing the work with the life cycle perspective in Danish Crown are provided as well as recommendations for further research.

CHAPTER 2. CONCEPTUAL FRAMEWORK

This chapter outlines the conceptual foundation for this thesis, which positions itself in the field of life cycle management and seeks to contribute to the academic and practical knowledge on LCA as a tool for companies seeking to reduce their GHG emissions.

2.1 FROM END-OF-PIPE TO SYSTEMS THINKING

The understanding of environmental impacts has developed over time. In the period leading up to the 1970s, the approach to environmental impacts was characterized by an out-of-sight, out-of-mind mindset. What were characterized as environmental problems were emissions of smoke, noise, and waste from point sources. The solution to these problems was to dilute the environmental impacts by building higher chimneys or extending the wastewater pipeline further into the water. In the 1970s and 1980s, emissions from industry and households started to be perceived as environmental problems and the government started to become involved. The solutions introduced were end-of-pipe approaches and the period was characterized by a desire to protect the local environment. In the 1990s, resource use and emissions started to be perceived as environmental problems caused mainly by production processes. Industries, NGOs, and governments were involved in finding solutions that focused on cleaner production approaches. The initiatives in this period can be characterized as pollution prevention. In the 2000s, impacts from products were added to the list of what was considered an environmental problem. Environmental problems were seen as being caused mainly by consumption volumes and patterns. Consumers were becoming more involved, and the solutions were focused on cleaner products. This period was characterized by life cycle thinking. The 2010s was characterized by systems thinking and the Circular Economy concept was applied to identify solutions. The linearity of production was considered to be the cause of environmental problems. Networks for facilitating collaboration and partnerships for reducing, reusing, recycling, and regenerating were formed.

MEAT INDUSTRY

DEVELOPMENT OF ENVIRONMENTAL UNDERSTANDING

The same development is evident in the environmental work at abattoirs. Up until the 1970s, many abattoirs were located next to waterways into which they sent waste products and wastewater. With the formation of the Ministry for Pollution in 1971 and the implementation of an environmental protection law in 1973, the Danish government set standards and requirements for protecting the environment. This meant that industry such as abattoirs needed to take measures to reduce their environmental impact on the local environment. In 1992, a new broader environmental protection law was introduced which, among other things, introduced an approach whereby the authorities assessed what would be possible to do by using the *best available technology* (BAT) (Baaner & Anker, 2009). This approach meant that abattoirs had to use BAT to reduce the environmental impact of their production. The environmental protection law was updated in the following years to comply with the EU Directive on *Integrated Pollution Prevention Control* (IPPC) from 1996. In the 2000s, the focus on environmental impacts for the abattoirs was still on the production facilities, but during the 2010s, the abattoirs started to see their environmental impact through a life cycle perspective.

2.1.1 MANAGING ENVIRONMENTAL IMPACTS

Companies have a unique role to play in managing and reducing environmental impacts as they have a central role in the economy. The strategies or approaches that the companies use to manage their environmental impacts reflects different perceptions of environmental work and willingness to change their business case. Companies adopt different strategies for managing their environmental impacts. In general, there are three different strategies for managing environmental impacts (Adams et al., 2016):

1. Operational optimization.
2. Organizational transformation.
3. Systems building.

The difference in strategy is also related to the process of working with environmental impacts. In the application of an operational optimization, the company will mainly focus on technical aspects and incremental changes in their innovation while the people aspect will be included more in innovation when using an organizational transformation strategy or system building strategy. The same can be seen with the firm’s view of itself in relation to society. If the company applies a system building strategy, it will see itself as part of an organizational ecosystem in which the strategy depends on other actors besides the company. If the company strategy is to optimize its operations, it will likely have a sole focus on itself. The extent to which innovation is implemented in the company is also related to its strategy. With incremental changes, the strategy will only involve a single department in the company. If the strategy is system building, the strategy will extend to all the departments of the company.

Operational optimization is an environmental strategy whereby the company continues producing the same products and has the same business case. The strategy is to reduce the environmental impacts from production while continuing to produce the same product (Adams et al., 2016). The ambition is to comply with regulations and reduce harm by maximizing material and energy efficiency. The strategy can also be to create value from waste or substituting virgin materials with renewable and natural sources (Bocken et al., 2014; Bocken & Short, 2021). The strategy can be characterized as a defensive strategy where the objective is to adjust the business model (Schalteger et al,). The strategy is focused on technological innovations (Boons and ludeke, 2013).

Organizational transformation is a strategy whereby the company develops novel products or changes the product to a service as part of a new business model. The focus of the company is on delivering functionality instead of ownership (Bocken et al., 2014) and it requires experimentation and organizational innovation (Boons and Ludeke, 2013; Schaelteger et al, 2012. The company can also take on a stewardship role or encourage sufficiency (Bocken et al., 2014).

Systems building involves creating novel products, services, or business models that would be impossible to create without other companies. The strategic goal is to create a net positive impact, which can be described as net positive for nature and society and even flourishing where societal and environmental well-being are prioritized above economic optimization (Bocken & Short, 2021). The strategy extends beyond the company and aims to drive institutional change (Adams et al., 2016), and the business model is repurposed for society and the environment (Bocken et al., 2014).

One thing is how companies perceive environmental challenges and the strategic goals they set to mitigate their environmental impacts, another is the means they apply to manage these impacts. Strategic goals and means are, of course, linked. A means to achieving operational optimization is an *Environmental Management System* whereby a company uses a set of processes and practices that allows them to reduce their environmental impacts and increase their operating efficiency. Another means to managing environmental impacts is *Life Cycle Management* (LCM), which takes a life cycle perspective on environmental impacts connected to a product. LCM demands a more integrated approach from the companies that apply it, and that the companies interact with other actors in their ecosystem.

2.2 LIFE CYCLE MANAGEMENT

Life cycle management is based on life cycle thinking and the understanding that the environmental impact of a product is not only related to the smoke, dust, and noise from their production, but also to the use and recycling of the products (Remmen & Thrane, 2007). Many different definitions of LCM have been put forward in the last 20 years, see Table 2-1. All the definitions include a life cycle perspective, but they also differ in some ways. Some of the earliest definitions of LCM had a purely environmental perspective (Finkbeiner et al., 1998; Baumann and Tillman, 2004), but more recent definitions include a more holistic view of sustainability. Coordination and connectedness of actors in the product chain is included in some of the definitions (Nilsson-Linden et al., 2021; Bianchi et al., 2021; Baumann and Tillman, 2004) while other definitions focus on the decision-making support of LCM (Bey, 2018; Finkbeiner, 2011; Hunkeler et al., 2003). LCM is also considered a management system or concept by some (Bianchi et al., 2021; Sonnemann and Margni, 2015; Gemechu et al., 2015; Remmen et al., 2007; Hunkeler et al. 2003; Finkbeiner et al., 1998). LCM is also seen as the application of tools or a collection of tools, concepts, and techniques (Finkbeiner, 2011; Hunkeler et al., 2001; Finkbeiner et al; 1998).

Table 2-1 Definitions of life cycle management from the last 20 years.

Source	**Definition**
Nilsson-Linden et al., 2021	LCM provides a holistic and interconnected perspective on environmental impact throughout the product life cycle extending from raw material extraction to product end of use.
Bianchi et al., 2021	Life cycle management is a holistic approach to environmental management, as it strategically takes into consideration all phases and actors involved along a product life cycle.
Bey, 2018	LCM is the making of managerial decisions with a sustainability-oriented, holistic view on the life cycles of the products, service activities and systems that the managerial decisions are dealing with.
Sonnemann & Margni, 2015	Life Cycle Management is a management concept applied in industrial and service sectors to improve products and services while enhancing the overall sustainability performance of business and its value chains.
Finkbeiner, 2011	Life cycle sustainability management is the implementation of life cycle-based sustainability assessment into real world decision making, be it in the product, process, or organization level. In a nutshell, LCSM aims at maximizing the triple bottom line

	and is based on Life Cycle Sustainability Assessment as one key element of a broader toolbox.
Remmen et al., 2007	LCM is a product management system aiming to minimize environmental and socioeconomic burdens associated with an organization's product or product portfolio during its entire life cycle and value chain.
Baumann & Tillman, 2004	LCM is the managerial practices and organizational arrangements that apply life cycle thinking. This mean that environmental concerns and work are coordinated in the whole life cycle instead of being independent concerns in each company.
Hunkeler et al., 2003	The life cycle management concept is an integrated system for improving operations, products and services that ensures information and decisions from a life cycle perspective and, quite often, is seen to improve decision making by placing better information in front of decision makers.
Hunkeler et al., 2001	Life Cycle Management is a flexible, integrated, framework of concepts, techniques, and procedures to address environmental, economic, technological, and social aspects of products and organizations to achieve continuous environmental improvement from a life cycle perspective.
Finkbeiner et al., 1998	LCM is a comprehensive approach towards product and organization related environmental management tools that follow a life cycle perspective.

It is evident from the definitions that LCM can be applied to improve sustainability. This expectation is reflected in the LCM literature, where it is stated that LCM can be used for operationalizing sustainability in organizations (Sonnemann & Margni, 2015), and that LCM can be used to link sustainability management and performance to business value and value creation (Rebitzer, 2015; Harbi et al., 2015). LCM is also seen as something that can be used to support decisions and actions to improve sustainability performance (Sonnemann et al., 2015; Bey, 2018). It has been suggested that LCM represents an opportunity for companies to differentiate on the marketplace (Sonnemann and Margni, 2015) while it is also thought to have the potential to transform the market by making sustainability a differentiator in the same way as quality and ensure that companies deliver real world improvements (Rebitzer 2015). The hopes and expectations seem to indicate that LCM may be the key to a sustainable transformation of products, companies, and markets.

Successful implementation of LCM should achieve long term results without leading to sub-optimization in the organization or product chains, and it requires a holistic view and understanding of the interdependence of business (UNEP, 2007; Bey, 2018). Support from top management is important as it costs time and resources to introduce

LCM in a company and involves a learning curve within all the relevant departments, which in the end means a new way of thinking for all involved (Bey, 2018). To succeed, top management should provide the required time and educational resources and participate actively in establishing the strategic goals of the organization (Sonnemann et al., 2015). LCM also means the entire organization must be involved through communication and by encouraging employees to contribute ideas and suggestions regarding how to use life cycle approaches (Sonnemann et al., 2015). The goal for this process is that all departments are aligned, and that the LCM function becomes a self-running part of all other functions (Bey, 2018). All departments of a company such as research and development, procurement, marketing, production, and management should be involved in the LCM, Table 2-1.

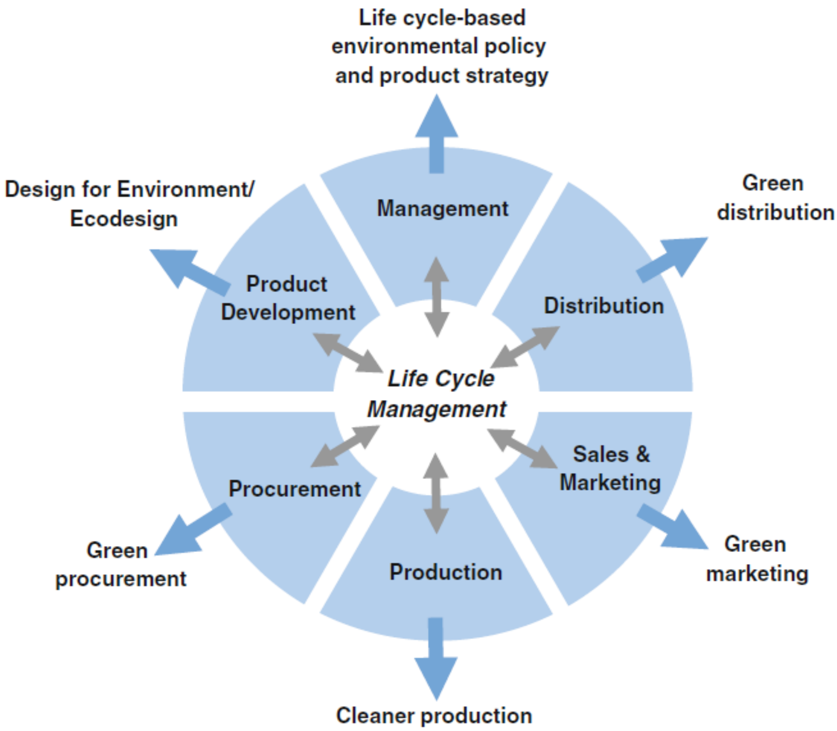

Figure 2-1 (Remmen and Münster, 2002)

Life cycle management involves many actors inside the organization, but it also requires the involvement of actors outside the organization. Companies need to go beyond their organizational boundaries and expand their scope of collaboration to all actors in their product chain (Sonnemann et al., 2015). All actors have individual areas of influence and can either be catalysts for or obstacles to sustainability efforts leading to either the success or failure of such efforts (Bey, 2018). The power and thereby the possibility for initiating change also varies between the actors in the product chain (Sonnemann et al., 2015). The involvement of outside actors can take different forms depending on the logic behind, e.g., risk minimization, product differentiation, or resource security (for more examples, see Nilsson-Lindén, 2018b).

A range of tools for supporting LCM in organizations exists. These tools can be applied separately or in combination and can be used by different departments in a company or by various stakeholders in a product chain (Bey, 2018). It is up to the organization or stakeholder to choose which tool should be used. A key tool in LCM is LCA, but there are also other tools such as Life Cycle Costing, Material Flow Analysis, and Environmental Risk Assessment.

Research on LCM has been ongoing since the 1990s and has focused on different aspects. A recent focus in the literature is the role played by life cycle promoters or entrepreneurs, and how they try to exert their influence to introduce LCM in their organizations. This was investigated by Nilsson-Lindén et al. (2019), who investigated the way in which life cycle promoters use their knowledge and skills to transfer life cycle insights into decision making processes in an organization. In relation to this, Bianchi et al. (2022a) focused on the learning process in organizations that implement LCM. Integrating LC professionals in the organization and bringing their capabilities into play was also the focus of Goedkoop et al. (2015). The work of these LC professionals has received attention in the LCM literature in recent years, which has led to the development of the concept *Life Cycle Work* (Nilsson-Linden et al., 2021), which is used to describe the work undertaken in an organization to translate life cycle ideas into the organization and the following emergence and performance of life cycle practices in the organization. Another branch of research investigates the use of data for LCM and seeks to shed light on the challenges to using data to govern product chains (Freidberg, 2017) and determine how data flow integration and exploitation can be improved (Bey, 2018).

In continuation of this research, a case study of the LC work in Danish Crown is undertaken to answer the following research question:

Research sub-question 1: How is the life cycle work in a company linked to reductions of GHG emissions in the product chain?

2.3 LIFE CYCLE ASSESSMENT

Life cycle assessment is a method for assessing the environmental impact of a product during its life cycle. The assessment follows a cradle-to-grave approach, meaning it considers the entire life cycle of a product from raw material extraction through production and manufacturing to use and end of life treatment and final disposal (ISO 14040:2008). The systematic overview and perspective of an LCA can identify and possibly avoid the shifting of a potential environmental burden between life cycle stages and individual processes. The LCA is structured around a functional unit (FU), which defines what is being studied. All inputs and outputs in the life cycle inventory and life cycle impact assessment are related to the FU. LCA was initially developed by chemists, but it can be used to assess many different environmental impacts, e.g., climate change, land use, ozone depletion, water use, etc.

The way in which LCA is applied depends on the organization that is performing the study. There are numerous applications of LCA, and it was initially developed as a method for comparing alternative products or materials. This makes it suitable for product development as alternative production processes or materials can be compared to identify which alternative has the best environmental performance. For long term strategic planning in the organization, LCA can be used to identify areas where the organization should allocate resources to address environmental impacts. LCA can also be used for public policy making as a background study for identifying relevant environmental impacts or processes that should be regulated. LCA is also used for marketing purposes where organizations communicate based on the results of an LCA study. An LCA consists of the following four steps (ISO 14040:2008):

1. Goal and scope
2. Life cycle inventory
3. Life cycle impact assessment
4. Interpretation

Goal and scope describe the intended application of the LCA and the reasons for carrying out the study. This description should include the target audience and whether the results are intended for comparative assertions. The scope defines the product system that is being studied, its functions, and thereby the FU, the allocation procedures, and which impact categories are to be used. Data requirements, assumptions and limitations are also defined in this step. Life cycle inventory is where data collection and calculations are performed to quantify the relevant inputs and outputs of a product system. Data collection includes energy inputs, raw material inputs, products, co-products, waste, emissions to air, discharges to water and soil and any other environmental aspects. The life cycle impact assessment step is aimed at evaluating the significance of potential environmental impacts using the LCI results (ISO 14040:2008). This process involves associating inventory data with environmental impact categories to better understand the impacts. The interpretation step is where the findings from the LCI and LCIA are considered and where conclusions that are consistent with the goal and scope of the study are presented.

The LCA method has been criticized for a number of shortfalls. Some environmental impacts are vaguely modelled in LCA, e.g., the impact on rare species or effect on landscape. This is due to the method originally being used to model chemical reactions, which means it is much better at showing the global effect of chemical reactions in the atmosphere rather than local effects (Arler et al., 2015). LCA is also technology focused, which means that efficiency is often highlighted as a solution instead of self-limiting behavior (Arler et al., 2015; Hauschild et al, 2018).

The ISO 14040:2008 and 14044:2008 standards are the international standards for conducting LCAs. However, other standards and guidelines on how to conduct LCAs exist with the two most widely used being the Product Environmental Footprint (PEF) method (European Commission, 2021) and the Environmental Product Declaration (EPD) (EN 15804). In this thesis, the focus is on the PEF method.

2.3.1 PRODUCT ENVIRONMENTAL FOOTPRINT

The Product Environmental Footprint method is an LCA method applied to assess the environmental impacts of products. The method is one of two Environmental Footprint (EF) methods developed by the European Commission (EC). The development of the two methods was initiated by the EC in the *Roadmap to a Resource Efficient Europe,* which aimed to promote sustainable consumption and production (European Commission, 2011). The goal was to establish a common methodological approach that would enable the member states and the private sector to assess, display, and benchmark the environmental performance of products, companies, and services based on an assessment of the environmental impacts during its life cycle (European Commission, 2011). At the time, many standards and methods for assessing the environmental impacts of products and services throughout the product life cycle existed, but in an assessment of these standards and methods, it was concluded that they did not provide an adequate basis for comparative assertions (Chomkhamsri and Pelletier 2011). Therefore, the EC decided to provide a solution that would build on existing methods, which resulted in the development of the PEF method (Galatola and Pant 2014).

The development and testing of the PEF method began in 2013 and reached a milestone in 2018, when the pilot phase ended. During the pilot phase, 280 organizations and 3000 stakeholders participated in developing the PEF method and 19 Product Environmental Footprint Category Rules (PEFCRs) (Partl et al. 2019). The objective of PEFCR is to enable comparative assertions within a product category by determining a consistent set of rules to calculate the environmental impacts (European commission, 2021). Eight of these PEFCRs were developed for food and agricultural products and two more are currently under development. A PEFCR for red meat was under development during the pilot phase, but it was discontinued as there was a disagreement about the method description. The development of PEF has received mixed reactions from academia, LCA experts, companies, and NGOs. From some parts of academia, there has been criticism of the PEF method as some disagree with the way of conducting an LCA prescribed by the PEF method and point to methodological issues with the PEF method, which are also relevant for an LCA on beef. These are, therefore, investigated:

Research sub-question 2: What have the methodological issues been in the discussion on PEF, and how do the suggested updates address them?

The EC has recommended that Member States use the PEF method in voluntary policies that aim to measure and communicate the life cycle environmental performance of products (European Commission, 2021). Therefore, the PEF method should be considered as valid in national schemes that involve measurement or communication of the environmental performance of products (European Commission, 2021). Companies and private organizations are also recommended to use the PEF method if they decide to measure or communicate the life cycle environmental impact of their products. Companies are also recommended to provide support for SMEs in their product chain (European Commission, 2021). The promotion of PEF from the EC leads to the following research question:

Research sub-question 3: What are the challenges of using PEF in public policies and how can these be resolved?

2.3.2 MODELLING OF MULTIFUNCTIONALITY

There are two main methods to LCA: Consequential LCA (CLCA) and attributional LCA (ALCA). The two methods have a life cycle perspective in their modelling, but they aim to answer two different questions.

Consequential LCA takes a system approach to modelling. The question that a CLCA aims to answer is *what is the consequence of consuming a product or service?* In Baumann & Tillman (2004), a CLCA is described as a change-oriented type of LCA that aims to assess what would happen if more or less of the product was produced. The consequential LCA attempts to provide information on the environmental burdens that occur, directly or indirectly, because of a decision (Sonnemann & Vigon, 2011). It means that the consequence of the decision is of interest and CLCA thereby involves modelling the broader economic system that the decision affects (Hauschild et al, 2018). The overall aim is to describe the changes to the economy caused by the introduction of the studied product system, i.e., the consequences of the product system (Hauschild et al, 2018).

In contrast, attributional LCA conducts environmental accounting for each stage of the life cycle. The question that an ALCA aims to answer is *what environmental impacts can this product or service be held responsible for?* This has also been called an accounting LCA (Baumann & Tillman, 2004). The attributional approach attempts to provide information on what proportion of global burdens can be associated with a product (Sonnemann & Vigon, 2011). The question addressed by attributional LCA can be said to be "what environmental impact can be attributed to product X?" or "what environmental impact is product X responsible for?" (Hauschild et al, 2018).

Life cycle assessments on beef production have provided very varied results, see Table 2-2, which stems from differences in modelling methods and in the studied cases. The papers included in this table have been randomly selected, but they show that there is great variation in the results from LCAs on beef production.

Table 2-2 GHG emissions from 1 kg beef and the modelling method.

Source	**Method**	**Result kg CO2e / kg beef**
Nguyen et al., 2011	ALCA (Mass, protein, and economic allocation)	17.8 – 34.9
Mogensen et al., 2016	ALCA (biophysical allocation between milk and meat. System expansion at abattoir)	10-13 (Dairy) 30-45 (beef breed)
Huerta et al., 2016	ALCA (economic allocation between milk and meat. No allocation at abattoir)	20.6 intensive production 21.7 extensive production
Ferronato et al., 2021	Both ALCA and CLCA	32.6 – 56.6
Saget et al., 2021	ALCA (biophysical and economic allocation)	52.9 - 59.1

There can be many reasons for the variation in the results, but here the focus is on the modelling of multifunctionality at the abattoir. In an LCA on beef production, multifunctionality is modelled in connection with the farm processes (only dairy) and the processes at the abattoir. At the farm, multifunctionality is present in the dairy production when there are outputs of both milk and meat. The milk is the primary product, and the meat is an important co-product. The meat that leaves this production system is in the form of retired dairy cows and calves that are sent to fattening or slaughtering. At the abattoir, multifunctionality is present in the form of dividing the slaughtered cattle into carcasses, hides, and other by-products.

The different methods to modelling multifunctionality in an LCA lead to different results. Therefore, it is relevant to investigate how the modelling affects the results and to attempt to determine which method is most suitable:

Research sub-question 4: How does the modelling of multifunctionality affect the result of an LCA on beef?

2.4 OVERVIEW OF RESEARCH QUESTIONS

This section presents an overview of the research questions and sub-research questions and illustrates how they are connected. The focus of this PhD dissertation is the life cycle assessment method and the use of the method in a food company producing beef. The investigation of this dissertation is based on the following research question:

To what extent can life cycle assessment be used to manage the transition towards decarbonizing beef production?

This research question includes a focus on the life cycle assessment method and the management related to the method. A research gap has been identified in the literature on the management method related to life cycle assessment. The research gap is concerns the work performed by the employees in companies that apply a life cycle perspective in their work with environmental impacts, which is referred to as *life cycle work*. The first sub-research question is proposed to understand the connection between conducting *life cycle work* and reducing emissions in a product chain:

Research sub-question 1: How is the life cycle work in a company linked to reductions of GHG emissions in the product chain?

The second sub-research question aims to summarize the literature on the Product Environmental Footprint (PEF) LCA method. PEF has been discussed intensely since its emergence in 2013, and there have been a few updates to the method since. The second question is proposed to summarize the discussions on the PEF method and provide an overview of which issues have been resolved and which still need to be addressed:

Research sub-question 2: What have the methodological issues been in the discussion on PEF, and how do the suggested updates address them?

The third sub-research question builds on the findings of the second sub-research question and continues with a discussion of the challenges to using the PEF method in policies. This discussion is limited to the policy proposals and strategies that the European Commission has published. The third sub-research question is proposed to highlight the challenges to using PEF in policies and how these challenges can be resolved:

Research sub-question 3: What are the challenges of using PEF in public policies and how can these be resolved?

The fourth sub-research question focuses on a specific issue in the modelling of an LCA in an abattoir. The issue is the multifunctionality of the products, co-products and by-products that leave the abattoir. There are different approaches to modelling multifunctionality in abattoirs, and the fourth sub-research question is proposed to better understand how it affects the result of an LCA on beef products when one approach is taken instead of another:

Research sub-question 4: How does the modelling of multifunctionality affect the result of an LCA on beef?

CHAPTER 3. CONTEXT OF THE PROJECT

The project was initiated in May 2020 during the first Covid-19 lockdown and ended in April 2023. In the first two years of this project, the Covid-19 pandemic led to several lockdowns in Denmark and the rest of the world, which created uncertainty about the future for both people and companies. In February 2022, just as the world was once again opening after another winter lockdown, the war in Ukraine started. Because of reduced grain supplies from Ukraine and uncertain natural gas deliveries from Russia to Europe, there was a sharp increase in inflation, especially for energy and food products. Meanwhile, the agenda for sustainable development continued to receive attention.

In Denmark, the agri-food sector faced increasing pressure from the government and the population to act on climate change. Approximately 30 percent of greenhouse gas emissions in Denmark come from agriculture. 45 percent of those emissions are methane from animals, 40 percent are nitrous oxide from nitrogenous manure and 15 percent are CO_2 from energy consumption and liming of agricultural land (Statistics Denmark). Therefore, the animal-based production also received the most attention for its large environmental impacts.

3.1 BEEF INDUSTRY IN DENMARK

In Denmark, 58.8 percent of land area is used for agricultural production. Approximately 80 percent of that area is used to produce feed for the country's large animal production (own calculations based on data from Statistics Denmark and Holmstrup et al., 2018). The agricultural production builds on strong cooperative traditions with the first co-operatives founded back in the late 19th century, which began with farmers cooperating to build dairies with modern equipment and hiring skilled dairy men who were able to produce good quality butter and cheese. Soon after, abattoirs and farm supply companies followed. Over the past 50 years, consolidation has taken place with smaller companies merging to form large operators (Danish Agriculture & Food Council). The three largest co-operatives in the Danish agricultural sector are Arla, Danish Crown, and DLG. Today these companies are all multinationals.

Danish agriculture is best known for its large pork production, but there is also a sizeable stock of cattle. However, the stock of cattle has declined since the 1960s.

Nevertheless, since 2005, the stock has stabilized at around 1.5 million head of cattle, Figure 3-1.

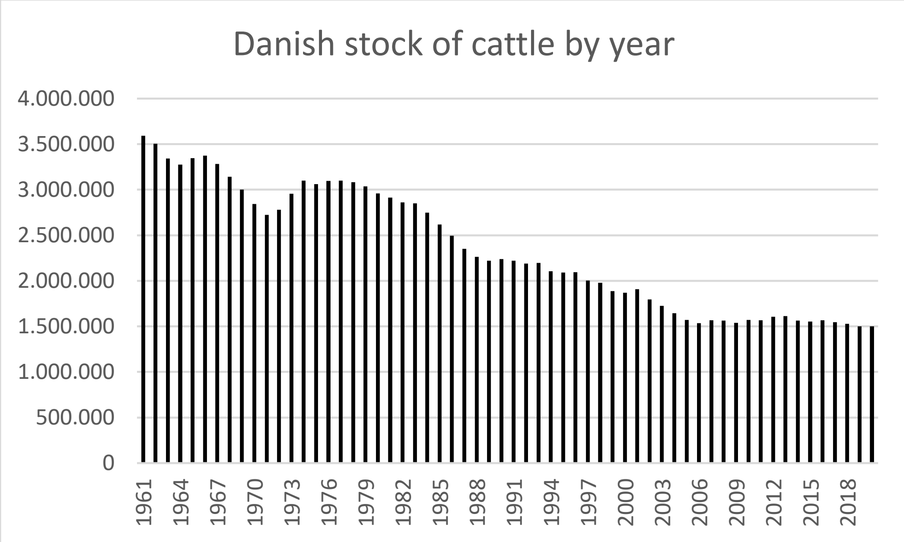

Figure 3-1 Cattle stock in Denmark from 1961 to 2020 (FAOSTAT).

The cattle farms in Denmark specialize in either dairy production or rearing and fattening of cattle for meat production. In 2021, there were 3,486 farms specialized in rearing and fattening of cattle and 2,369 farms specialized in dairy cattle (Statistics Denmark). The average size of the dairy farms (196 ha) is larger than that of the rearing and fattening farms (32 ha) (Statistics Denmark). The rearing and fattening farms are generally smaller farms, see Figure 3-2, with 68 percent of the farms smaller than 20 hectares (Statistics Denmark). This is only the case for four percent of the dairy farms (Statistics Denmark).

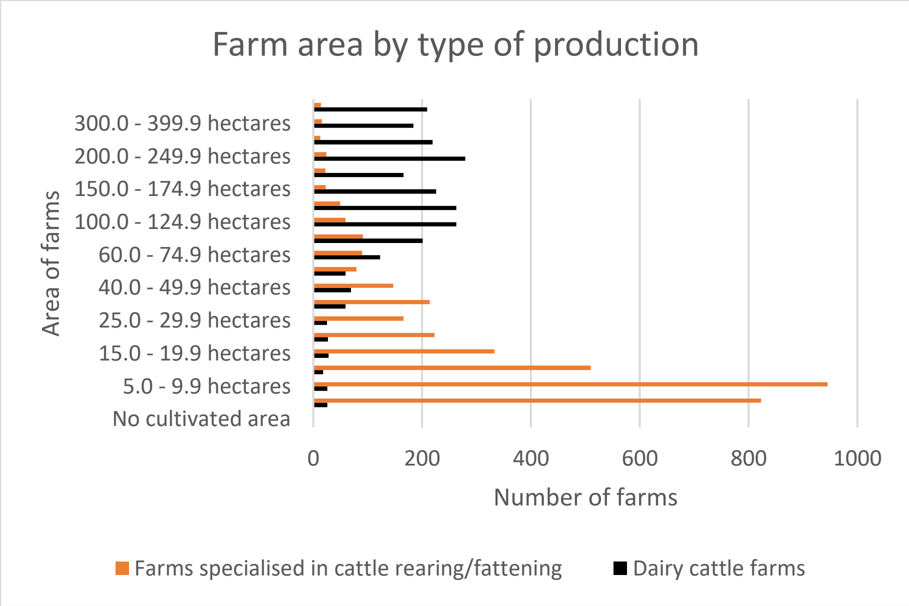

Figure 3-2 Number of farms specialized in cattle rearing and fattening or dairy production and their area (Statistics Denmark).

Food safety and quality have been driving factors of the success of Danish agricultural production (Danish Agriculture & Food Council). Full traceability from farmer to retailer has made it simple to control each part of the value chain (Danish Agriculture & Food Council). In the EU, the production of food and agricultural products is highly regulated and the Danish authorities interpret and implement these regulations strictly leading to even higher standards on hygiene, animal welfare, and the use of medicine, pesticides, and fertilizers (Danish Agriculture & Food Council).

Danish consumers purchase more organic food items than any other Europeans, and 12 percent of Danish farmland is cultivated organically, which means it is prohibited to use inorganic fertilizers, chemical pesticides, and GMOs (Danish Agriculture & Food Council). From 2012 to 2022, the organic area increased by 70 percent. The area increases every year, and the Danish government has set a goal of doubling the area of organic farmland by 2030 (Regeringen, 2022). This development reflects an increased awareness of healthy and sustainable food products among consumers for whom climate change, biodiversity, and animal welfare are topics of concern (Organic Denmark, 2022). The food companies have also understood the importance of producing sustainable food products. In particular, the need to produce food items with a low carbon footprint has gained the attention of these companies. One of the companies that has made public claims about its aim to reduce its climate impact is Danish Crown.

3.4 DANISH CROWN

Danish Crown is a global food company with headquarters in Denmark and a presence in 26 countries with 57 abattoirs and processing facilities in six countries and sales in Europe, Asia, and North America. The history of the company begins in 1887, when the first co-operative abattoir was founded in the city of Horsens. This initiated a period in Danish agriculture when Danish bacon, in particular, was an important export good. In 1962, there were 62 co-operative abattoirs in Denmark, but throughout the 1960s, 70s, and 80s, the Danish abattoirs merged into larger operators, which culminated in 1990 with the creation of the company called Danish Crown. Since then, Danish Crown has grown to become Europe’s largest exporter of pork with a yearly production of 18.7 million pigs and 0.8 million cattle in 2022. The animals come from farmers in Denmark, Sweden, Poland, and Germany. The company is organized as a group with several subsidiaries, which are Danish Crown Beef, which has four beef production plants in Denmark and Germany, KLS in Sweden, which is Sweden’s second largest meat company, Sokolow in Poland, which is the strongest business brand in the Polish meat sector. Besides the main production of meat cuts, the company also has subsidiaries in related sectors. These are ScanHide, which handles and refines cattle hides, DAT-Schaub, which produces and sells natural and artificial casings, ESS-FOOD, which sells and exports meat products to most of the world, and SPF-Danmark, which is Europe’s largest trader of weaners and the world’s largest transporter of live pigs. In total, there are 25,000 employees in the Danish Crown Group and a global revenue of 64 billion DKK in 2022.

Danish Crown has developed a sustainability strategy and for them sustainability is key business driver (Danish Crown, 2022). Under the headline of sustainable farming, sustainable food production, good jobs for everyone, and together with customers and consumers, they have set goals for GHG, soy, palm oil, water, waste, packaging, noise pollution, work-related accidents, and a diverse workforce. Most of these goals are related to Danish Crown’s own production facilities, e.g., eliminating animal waste, improving energy and water efficiency, fossil fuel free production, low emission transport, and animal welfare certification at all abattoirs. The company has also set climate targets under the Science Based Target initiative, which were validated and approved in November 2022. The overall goal for these initiatives is to become the world’s most successful and sustainable meat producer by 2030. To reach this goal, the company launched a strategy called Feeding the Future, where the main focus is that the company will stop increasing the number of animals slaughtered and instead focus on increasing the value of the animals they already slaughter.

The target for GHG emissions is a reduction of 50 percent by 2030 compared to the level in 2019 and to deliver climate neutral food production by 2050. The company expects to reach this goal by involving the farmers in a program called “The Climate Track”, which was launched in 2019 and is a development program for Danish Crown and the farmers that involves a sustainability certification that the farmers must get to become part of the program. The requirement is that the farmers must set voluntary sustainability targets and implement sustainability initiatives. To ensure that the right technology and knowledge is in place, Danish Crown invests in and develops new solutions that the farms can implement. Some examples of this are the company's investment in the development of feed additives to cattle and a technology to burn excess methane gas from slurry tanks.

Each year, a carbon footprint is calculated for each farm that is part of the program. The calculation is based on production data that the farmers submit to Danish Crown. In return, the farmers' carbon footprint is calculated, and they can compare their carbon footprint to a national benchmark. Behind the calculation is an LCA model that was developed in 2020. The LCA model is an in-house and site-specific life cycle modelling tool and database that covers the meat product system of the focal company. It was developed in collaboration between the case company and consultants and is used to assess GHG emissions for the product chains in Denmark, Sweden, Poland, and Germany. The model assesses the climate impact of the production of beef and pork from the farm, including feed production, to the processing gate. The assessment is based on primary data from farmers, abattoirs, processing plants, and logistics. The LCA model of the meat production of the company is meant to be used as a tool to support the green transition and specify climate impacts for the farmers, the company, and the customers. Data is collected every year and a new carbon footprint is calculated for Danish Crown's products and for each farmer. A data hierarchy is applied with farmer data at the top, sector specific data is second and national data is third. Sector specific data and national data are only used when farmer specific data is unavailable. The LCA model is regularly updated to fix issues and improve the application possibilities of the model. A central focus is to increase the number of products that the LCA model can calculate results for. This has led to the development of a separate module where Danish Crown can use their recipes for sausages and other processed products to calculate an endless number of LCA results. The company is also working on including other product chain companies in the LCA model, e.g., tanneries and external processing facilities.

CHAPTER 4. RESEARCH DESIGN AND METHODS

The research design and methods used for this thesis are presented in this chapter.

4.1 RIGOR AND RELEVANCE

Manufacturing Academy Denmark (MADE) is a Danish cluster for advanced manufacturing, which creates and supports world-class Danish manufacturing through research, innovation, and education. Knowledge is generated through industrial research and development and the testing of new solutions and technologies in close collaboration with industry. The activities are centered on applied research within a range of thematic domains defined by the current needs of Danish manufacturing companies. This project is part of the research platform MADE FAST (Flexible, Agile, and Sustainable production enabled by Talented employees) the aim of which is to develop the next generation of advanced Danish manufacturing capabilities. This project belongs to the research track of developing sustainable manufacturing operations with a reduced environmental footprint.

This project took place at the large Danish meat manufacturer, Danish Crown, and Aalborg University (AAU). My time was divided between AAU and the company, where I was involved in the development and implementation of an LCA model in their sustainability work. I became a part of the EHS&S department, where I was given the task of supporting the work connected to the LCA model.

The tasks included collecting data from cattle abattoirs, presenting the LCA model to other departments at Danish Crown and a farmer panel, developing and prototyping an LCA tool for assessing the climate footprint of food waste, a tool for packaging materials, and a processing facility tool, writing internal communication papers about LCA methods and comparisons of different LCA methods, participating in development work with LCA consultants, and supporting decisions regarding the selection of LCA methods and tools. In my position, I was able to observe and participate in an environmental department that works with LCA, which gave me access to potential interviewees and company specific data that I could use in my LCA model. I also had the opportunity to observe the company's approach to LCA and learn about their understanding of what LCA is useful for and see how they work with the results. These observations inspired me and steered the direction of the research together with the challenges that the company was experiencing. Amongst other things, this led to a change in the focus of the paper on LC work.

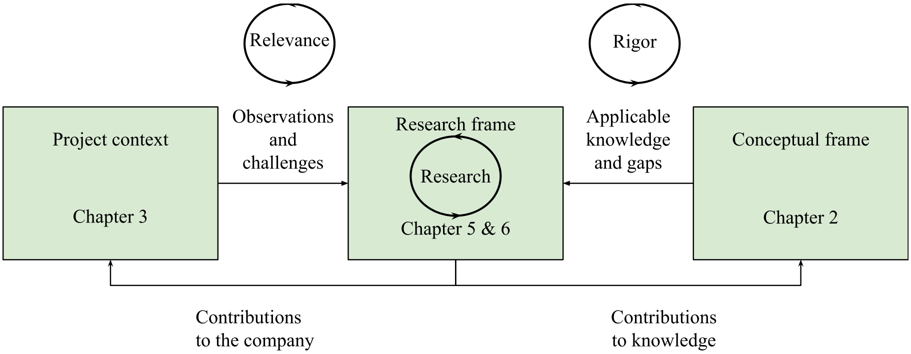

Figure 4-1 Research framework and chapter contributions, inspired by (Skelton, 2017; Kristensen, 2020), based on (Hevner et al., 2004; Hevner, 2007)

4.2 RESEARCH DESIGN

The main research question is broad and can be answered in many ways. The sub-research questions address some of the aspects from different angles. The research design developed as a means to answer the research question and it builds on different research strategies such as quantitative and qualitative methodologies.

The qualitative research has an interpretivist orientation, which asserts that the social world is constructed through the perceptions and interpretations of the participants in the world (Bryman, 2012). The goal of the research is to understand actors' perceptions and how they interpret LCA. The work with LCA is also investigated as part of organizational behavior and practice.

The quantitative research takes a positivist orientation whereby numerical measurements can be made. The aim is to explain phenomena through causal explanation.

As this research aims to contribute to both the practical and theoretical knowledge in the LCA field, an abductive research strategy was selected to operationalize the interplay between theory and practice. The focus of the study is found in the relationship between the context of the project and the gaps in the scientific field. In this way, the research is steered by the existing knowledge but is also based on observations in the organization.

4.3 METHODS

The research design provided a framework for data collection and analysis. Data was collected through four qualitative methods and one quantitative: Literature review, case study, interview, involvement in company, and LCA (Table 4-1). Each of the methods is described in the following sections while a more detailed description can be found in each paper.

Table 4-1 Methods used in the scientific papers.

	Challenges with Product Environmental Footprint: A review	**Transforming the meat sector towards net zero greenhouse gas emissions: The role of life cycle work**	**Testing different modelling of by-products in the Product Environmental Footprint in cattle abattoirs**
Research orientation	Qualitative	Quantitative	Qualitative
Literature review	Structured literature review of 140 research papers.	Literature review was performed to identify approaches used to model multifunctionality in beef abattoirs.	Knowledge on life cycle management was identified in a literature review.
Case study		One of Danish Crown's beef abattoirs is used as the case.	Danish Crown is used as a case.
Interview			Interviews with 8 actors from the meat production chain.
Observations at company		The observed process in the abattoir is used to develop alternative production scenarios.	The work performed in the company was observed throughout the PhD.
Life cycle assessment		Four LCA models are developed for assessing the effect of modelling choices.	

4.3.1 INVOLVEMENT IN COMPANY

The backbone of the research in this PhD thesis is the involvement and collaboration with Danish Crown. I was working at Danish Crown's headquarters 1-2 days per week during most of the PhD period. This involvement and fieldwork included discussions with employees in the case company's Environment, Health, Safety & Sustainability (EHS&S) department, collecting data for the LCA model, communicating internally in the company with other departments and externally to farmers. During this involvement, it was possible to observe the employees' daily work in the EHS&S department, the planning, and the challenges the department experienced during the observation period. My involvement also contributed to building trust between the employees in the company and the researcher, which opened access to internal documents and facilitated access to interviewees in the company and the product chain.

The work performed during my involvement had two purposes. The first was to complete the tasks given to me by Danish Crown and help them resolve any LCA-related challenges. These tasks were focused on LCA-related activities and involved collaborating with employees in the EHS&S department. The second purpose was to use my involvement at the company for research as a form of data collection.

The dual-purpose approach has similarities to the action research, where research and practice follow two parallel cycles. In action research, these cycles are repeated, and the researcher plays an active role in introducing an initiative and conducting structured follow up and assessment of the impact resulting from the initiative. Some of the tasks performed during this involvement involved developing LCA tools and facilitating their introduction and further development. The research involvement can best be described as participant observation as the aim of the research was to gain knowledge about the work performed by the employees, or partially participant observation when interviews are also used for data collection (Bryman, 2016). The participant observation was conducted in an overt way as the company and the employees knew about the research and its focus. The company would normally be a closed setting, but access was gained to the company because of the PhD project and the promise of providing Danish Crown with an LCA. This access was ongoing and developed into broader access to departments other than the EHS&S in the three years that the project was active. The employees in the EHS&S department acted as key informants and sponsors by helping gain access to actors and places both inside and outside the organization.

4.3.2 CASE STUDY

The research performed in this project was framed by the context of Danish Crown. The company was used as the case for some of the research and data was collected from some of the company's abattoirs and employees. It was used as the case in the research on LC work and the empirical material used for this paper was collected at the company. It was interesting to work with this topic in the context of Danish Crown because the company has worked with life cycle thinking and climate impacts for close to 10 years. The company is not new to working with LCA, which make it useful for studying how to strengthen LC work and focus on emission reductions (Pedersen and Baumann, 2023). Danish Crown's abattoirs were also used as the case productions for the LCA, see section 4.3.5.

4.3.3 INTERVIEWS

Interviews were used to collect data for *Paper II*. Eight individuals at Danish Crown and in the beef production chain were interviewed including farmers, farmer consultants, and employees in the dairy sector. The selection of one focal company and a few companies in their production chain made it possible to collect extensive empirical material (Pedersen and Baumann, 2023). The interviews were semi-structured, which made it possible to follow topics that were brought up by the interviewees during the interviews. The purpose of the interviews was to gain insights into the actors' work as well as into strategies related to LCA and sustainability.

4.3.4 LITERATURE REVIEW

A literature review was conducted throughout the project to collect knowledge. In the initial stage of the PhD project, several literature reviews were performed to establish a knowledge base for the initial formulation of the research questions. The scope of this literature review was broad and included topics within circular bioeconomy, sustainable business models, business model experimentation, and LCA. Some of these topics were later excluded as they did not align with the aim of the research.

In the papers, literature review was done with a varying degree of structure. For *paper I*, a systematic literature review was used as the primary method of data collection. First, a screening of the literature in the databases ProQuest, ScienceDirect, and Scopus was performed. The scope of the search were articles in English published in the period 2014 to 2020. The search words were "Product environmental footprint", "Product environmental footprint category rules", and "PEFCR". 140 publications were identified, and each abstract was screened for any results, discussion, or conclusions addressing methodological issues or challenges connected to the use of PEF. For the two other papers, a literature review was performed by an initial search on the specific subject followed by a *snowballing* process whereby relevant papers were identified through citations in other papers. This method was chosen because the aim of the literature reviews was to identify trends in the literature and gaps that may have been relevant to study.

4.3.5 LIFE CYCLE ASSESSMENT

A life cycle assessment was conducted for two of Danish Crown's cattle abattoirs using the PEF method. The abattoirs are in Holsted and Aalborg, and they slaughter approximately 300,000 cattle each year. The abattoir in Holsted is Danish Crown's largest cattle abattoir and it produces 350 tons of minced beef per week.

Goal and scope

The primary goal of conducting an LCA for each of the abattoirs was to assess the environmental impact of the beef production. The results were mainly for internal use in Danish Crown, although some of them are also used in *paper III*. The scope of the LCA is to study the production system for beef in Denmark.

The functional unit is 1 kg of output for human consumption.

The system boundary is set when the meat leaves the abattoir gate. The use stage and end-of-life stage are not included in this study. The study includes company specific data from two of Danish Crown's abattoirs in Denmark. Background data is used for the processes that the company does not control, e.g., feed production, cattle rearing, and energy production. The cut-off is where elementary flows leave the system. Capital goods and services are not included in the study.

The model was built to assess all 16 environmental impact categories from the PEF method, but a decision was made to only use the climate impact category in the final paper as it made the communication of results and conclusions clearer.

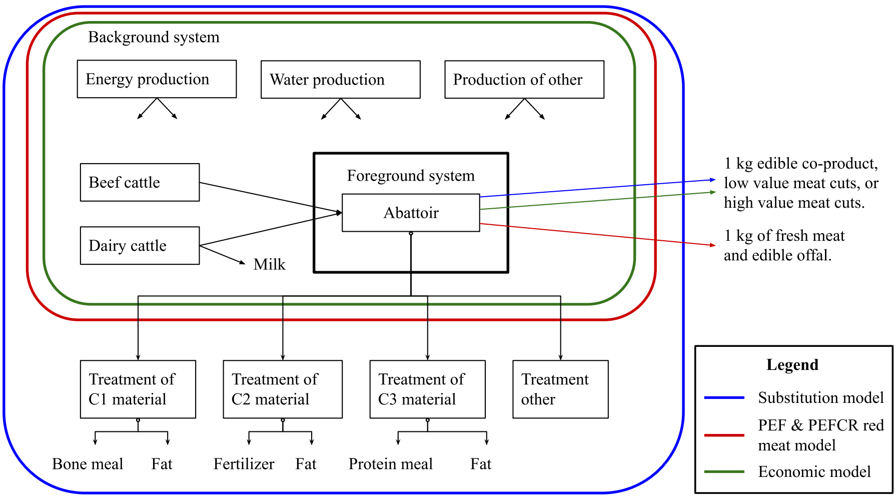

Figure 4-2 System boundary of the LCA (Pedersen and Schmidt, 2023)

Life cycle inventory

Data was collected during a three-year period from 2019 to 2021. The data collection covered all the energy and raw material inputs and outputs of products, co-products and waste from the abattoirs.

Life cycle impact assessment

The impact assessment is based on the PEF method. In the model, it is possible to assess the environmental impacts based on 16 environmental impact categories.

4.4 QUALITY OF RESEARCH

The research conducted for this project includes qualitative and quantitative methods. The quality of the research was ensured using different strategies. For both the qualitative and quantitative research, the data collection process and analysis were documented in detail and a procedure for the research design was presented in each of the three papers. All collected data was documented and archived. Interviews were recorded and transcribed, and notes were taken to ensure that the meaning of what was said was recorded. The findings of the interviews were presented to the employees at the sustainability department. The literature review process was documented and described to ensure a structured research approach. LCA data was archived, and the method was described.

The quality of the research was also ensured through feedback from and sparring with the PhD supervisors on the framing of the project and the choice of data collection methods and analysis. Informal sparring with peers such as fellow PhD students, colleagues in the research group and a steering group committee organized by MADE also took place. This collaboration and sparring ensured the rigor of the research. Collaboration with peers from Chalmers Technical University was also completed to ensure that the research was of international quality.

The quality of the quantitative research was ensured by archiving the company specific data and describing in detail how the LCA was modelled. The reliability was ensured by data quality control of company specific data and by ensuring that the secondary data was representative for the modelled processes. The validity of the results was ensured by checking that the tests and success criteria were in line with the research question.

The quality of the qualitative research was ensured by describing the data collection and processing method. The analytical process was also described in detail. Reliability was ensured by method triangulation in the case study of LC work in Danish Crown as both participating observation and interviews were used to collect data. Data source triangulation was also used as several actors in Danish Crown and the product chain of Danish Crown were interviewed.

Investigator triangulation was used in both qualitative papers as two authors were involved in the analysis and interpretation of data. Data triangulation was ensured by collecting data from different sources and periods in both the qualitative and quantitative research. Several concepts, e.g., LCM and LC work were used to ensure theory triangulation. Method triangulation was used in the qualitative research, where interviews, observations, and literature review were conducted. The validity of the results in the case study was ensured by limiting the conclusions to the case company and not generalizing the results.

CHAPTER 5. TRANSFORMING THE MEAT SECTOR TOWARDS NET ZERO GREENHOUSE GAS EMISSIONS: THE ROLE OF LIFE CYCLE WORK

This chapter contains paper I: Transforming the meat sector towards net zero greenhouse gas emissions: The role of life cycle assessment (Pedersen and Baumann, 2023), which is submitted to *The International Journal of Life Cycle Assessment*.

The aim of this paper is to explore how life cycle (LC) work in a company is linked to reductions in GHG emissions in the product chain. The research on LCM mainly focused on developing tools for companies to use or analyzing rationales for and barriers to implementing LCM in a company. A new stream of research focuses on LC work performed in companies. In this research, there is a gap in the form of the link between LC work and interest in effectively reducing emissions. This research gap leads to the research question: How is the life cycle work in a company linked to reductions of GHG emissions in the product chain?

The research takes the form of a qualitative case study of a product chain organization from the perspective of a company within its product chain. The case concerns a meat production chain in which the focal company is a meat producer. The theoretical concept of life cycle work is applied to structure the account and analyze the empirical data. The links between life cycle work and GHG reductions and environmental transitioning are the focus of the analysis. Data was collected through interviews with employees and suppliers of the company, combined with observations over a 2-year period made by the lead author at the company 1-2 days per week. The observations were made while the lead author was involved in developing the company's LCA model.

The analysis shows that many types of LC work are performed by the company, and some of them are performed in relation to the farmers. However, the company faces challenges in this LC work since some farmers are unwilling to work with GHG emissions and are skeptical of the LCA model. Also, the employees with closest contact with the farmers have limited knowledge of LCA and GHG emissions, which makes it difficult for them to advise farmers. Low data quality from the farms and difficulties experienced by the farmers working with GHG emissions as they cannot see them in their daily work at the farm adds to the challenges for the company. While the aim of some LC work is to create value for the focal company through, for example, branding and partnerships, it is unclear how it will result in reduced GHG emissions from the product chain.

This paper provides a first description of the organization of LC work in a company with that reach out in the product chain. This facilitated an analysis of LC work for GHG reductions in the product chain. The present study of LC work in a meat production chain concluded that LC work played a limited role in reducing GHG emissions, despite a stated LC-based ambition of net-zero. Instead, we find that LC work mainly had a role for the company's communication to customers and for developing partnerships with potential commercial value. The focus of the activities related to the LCA model is on ensuring the model calculates in the "right" way and on calculating footprints for all products so they can be communicated to customers and consumers. This leads us to conclude that there is need to examine the organization of LC work regarding the effect on environmental performance, as well as better understand the operational role of LC work for business strategy.

This study contributes with the conclusion that working with LCA in a company does not necessarily mean that the company will reduce its GHG emissions. We contribute insights into how companies work with LCA, and from our findings we conclude that what hinders action on reducing GHG emissions is missing organizational links between the LC work and the points in the product chain where GHG reductions are made.

CHAPTER 6. CHALLENGES WITH PRODUCT ENVIRONMENTAL FOOTPRINT: A REVIEW

This chapter contains paper II: Challenges with the Product Environmental Footprint: A review (Pedersen and Remmen, 2022), which is published in *The International Journal of Life Cycle Assessment*.

Within the scientific community, there has been some resistance to and criticism of the PEF method during its development and testing. The critique is levelled at the suitability of the method itself as it prescribes a way of conducting an LCA with which not everyone agrees. The latest update of the PEF method was made available with the publication of suggestions for updating the product environmental footprint method (Zampori & Pant, 2019). The aim of this paper is to highlight the issues that are still relevant and, based on the results, identify the challenges to using the PEF method in the identified policy application areas and how they can be resolved. This paper answers the following research questions:

1. What have the methodological issues been in the discussion on PEF, and how do the suggested updates address them?
2. What are the challenges of using PEF in policies and how can these be resolved?

The first research question was answered through an extensive review of the literature on PEF. The search was conducted as a systematic review based on the following three databases: Scopus, ProQuest, and ScienceDirect, using the search words "Product Environmental Footprint," "Product Environmental Footprint Category Rules," and "PEFCR". The initial search identified 234 publications, and after the removal of duplicates, 140 publications remained. Each abstract was screened for any results, discussion, or conclusions that addressed methodological issues related to PEF or any challenges to using PEF. The final number of publications matching the scope of this paper was 68. The second research question was answered by conducting an analysis of the challenges for each of the three policy application areas. The challenges were identified by analyzing how the issues that are still relevant may affect the policy application area.

The methodological issues in the PEF method have led to ongoing discussions. Some of the identified issues have been addressed by a subsequent update to the PEF guidance, but some significant issues remain. These are as follows: 1) The defined functional units in the Product Environmental Footprint Category Rules (PEFCR) are inadequate for ensuring a fair comparison between products; 2) Impact categories for biodiversity and indirect land use change are still being developed; 3) The existing and new PEFCR need to adopt a benchmarking method; 4) Uncertainty exists about how the costs of making an LCA study are affected by PEF and 5) It is unclear how the results of a PEF study should be communicated.

With the European Commission as the facilitator, the PEF method could play an essential role in developing a market for green products. The review made it clear that there are still some open issues that need to be resolved to make PEF more suitable for policy implementation. If PEF is to be be used for background studies in existing policies or for business-to-consumer communication, the fact that PEF can only be used to assess environmental impacts and does not include social aspects represents a potential problem. A PEF study should, therefore, not be conducted in isolation, but rather it should be supplemented by other types of information. Another challenge is that the quality of products is not considered in some of the PEFCR. This aspect should be part of the functional unit that is defined in the PEFCR. A third challenge for PEF in business-to-consumer communication is that a framework for communicating environmental impacts does not currently exist. The initiative Made Green in Italy could be used as inspiration for the development of a communicative framework. If PEF were to become mandatory for substantiating green claims, the first challenge would be that the costs of conducting a PEF study could be too high for SMEs. Reducing the costs of performing a PEF study so that it is possible for SMEs to make green claims should, therefore, be a focus in the future development of PEF. Another challenge to using PEF to substantiate green claims is that the credibility of some green claims cannot be confirmed through use of PEF. Therefore, the use of PEF should only be mandatory for claims the credibility of which can be validated by the method. There are most likely other challenges that will need to be resolved before PEF can be used in policies, but a key takeaway from this study is that PEF can be applied in different policy areas, although some challenges still remain in all of them.

CHAPTER 7. TESTING DIFFERENT MODELLING OF BY-PRODUCTS IN THE PRODUCT ENVIRONMENTAL FOOTPRINT IN CATTLE ABATTOIRS

This chapter contains paper III: Testing different modelling of by-products in the Product Environmental Footprint in cattle abattoirs (Pedersen and Schmidt, 2023), which has been submitted to *The International Journal of Life Cycle Assessment*.

This paper explores how the results of an LCA study on beef from cattle are affected by changes made to the modelling of multifunctionality, which is an important step in developing an LCA. The modelling of multifunctionality also receives a lot of attention when negotiating calculation rules in the Product Environmental Footprint (PEF) Guidelines. First, an analysis of the results of an LCA on beef is conducted to determine how sensitive they are to changes in the modelling of multifunctionality. Second, each model for multifunctionality is analyzed to answer the following two questions: 1) do the models adequately represents the actual difference in environmental impact 2) are environmentally relevant differences in quality of the co-products detected by the methods and are the obligatory properties of the meat considered.

This study was carried out by performing tests of different modelling assumptions in connection with an LCA on beef products. The environmental impact category used in this study is climate change (GWP100). The study is based on an LCA of a cattle abattoir in Denmark. The product studied is beef at abattoir gate from cattle produced at farms in Denmark. The main life cycle stages of this production are the farming stage and the slaughtering stage. Four LCA models with different approaches to the modelling of multifunctionality are used for this paper: A PEF compliant model, which follows the general PEF guideline, a model that follows the guidelines from the discontinued PEFCR for Red Meat, a model that uses economic allocation, and a model that uses substitution. Four tests were performed to assess the four modelling approaches.

The PEF compliant, PEFCR Red Meat, and Economic models were not successful in any of the tests. The results show that the substitution model was the only model that was successful in every test. The model produced results that reflect the environmental consequences of changing production processes, it had a good functional unit and is consistently modelled at farm and abattoir. Therefore, the modelling of multifunctionality should apply a substitution approach when the purpose of the LCA is to assess the environmental impact of changing the demand for a product or changing the production process. This also includes benchmarking different product alternatives because this relates to changing the production volumes of product alternatives. Four further recommendations are also given regarding the modelling of multifunctionality in the production of beef: 1) the mass fractions should be based on company specific data, so it is possible to show the effect of making changes to the production process in an abattoir; 2) the relative prices used in the model should be market-based and not company specific; 3) the relative prices should be based on the average prices over a longer period, and 4) the results should be presented for different cuts instead of only one category of product.

CHAPTER 8. DISCUSSION

With an aim to further broaden academic research, this PhD dissertation focuses on the use and application of LCA and LCM for decarbonizing beef production by Danish Crown, issues in the modelling of an LCA for beef production, and the application of LCA in policies.

This chapter is structured around four key problems identified in this dissertation. The first section of this chapter discusses some of the challenges with the LCA method. The second section focuses on how companies use LCA internally when working with GHG emissions. The third section focuses on the role of LCA for collaboration on decarbonizing the product chain. The fourth section presents opportunities for using LCA in policies aimed at reducing GHG emissions from beef product chains. The final section of this chapter discusses the future of beef production and its contribution to climate change.

8.1 THE LCA METHOD

In Chapter 6 and Chapter 7, it is concluded that the PEF method still has some issues that should be addressed before it can be used for conducting an LCA for beef. The chapters provide conclusions on how an LCA method should handle different issues. Some relevant themes from those chapters are discussed here.

Product characteristics

The nutritional aspect of different food products is important when discussing what constitutes a sustainable diet, as a sustainable diet should also be a healthy diet. When performing an LCA on a food product, it is important to consider the function of the product. The most obvious function is that it should satisfy a person’s hunger and meet their nutritional requirements. Other functions are that the food product should look and taste delicious. The inclusion of product characteristics in the PEF method is discussed in Chapter 6, where it is suggested that the function of satiating a person should be used as the functional unit for PEFCR on food products. However, the function of satiating a person for a certain period could be difficult to quantify in an LCA. This issue has also been identified in other studies that point towards a solution whereby the product characteristics, e.g., kcal, essential amino acids, or omega-3 fatty acids are included in the functional unit (McAuliffe et al., 2022; McLaren et al., 2021; Heller et al., 2013). The inclusion of these characteristics in an LCA provides a more nuanced picture of the environmental impacts related to the food product and thereby a more nuanced basis for decisions. The inclusion of product characteristics could also enable comparisons between food products from different product categories, e.g., meat products and plant-based alternatives. This type of comparison is already taking place, but if these comparisons are made based on the weight of the product and without the inclusion of product characteristics, then it could be argued that they are unfair as 1 kg of cucumber does not have the same nutritional value as 1 kg of beef.

Impact categories

The theme of this PhD dissertation and the focus of Danish Crown's work with LCA is GHG emissions. For Danish Crown, this focus is driven by pressure from customers and consumers to reduce GHG emissions from their products. From a business perspective, it is this pressure that should steer the focus of Danish Crown's work. However, from an environmental perspective, the emissions of GHG from Danish Crown's product chain represent only one impact category among many other relevant impacts. It introduces a risk for suboptimization and does not give a comprehensive evaluation of the environmental impact from beef production. The discontinued PEFCR for meat products identified terrestrial eutrophication and acidification as relevant impact categories along with climate change. Other studies have also included land occupation, non-renewable energy, and biodiversity loss as relevant impact categories (Nguyen et al., 2010; Mogensen et al., 2015b). In Chapter 6, it is argued that biodiversity and indirect land use change should be included as impact categories for LCAs on food products. Here, it is important to keep in mind that biodiversity is included indirectly in eight of the existing impact categories (and as additional environmental information), which means that there is a risk of double counting. However, considering the impact that agriculture has on biodiversity, it could be argued that biodiversity should be included more directly in the PEF method as there is a risk of burden shifting. There is also a risk that the impact of beef production on biodiversity will be overlooked when it is assessed as other environmental impacts.

Dealing with uncertainty

The results of an LCA are sometimes presented as being indisputable, but LCA results are more uncertain than LCA practitioners usually acknowledge. In a recent study, it was found that less than 20% of LCA studies published five years prior to the study reported any kind of uncertainty analysis (Bamber et al., 2020). Some practitioners do acknowledge the uncertainty of the results and here Monte Carlo sampling is the most popular method for communicating uncertainties. The uncertainty of the results of an LCA as a theme is not discussed previously in this dissertation despite its importance for understanding LCA results. While other studies have focused on the uncertainty of the results in prospective LCA or the risk of overlooking certain conditions that affect the environmental impact of products (Pizzol et al., 2021; Jouannais and Pizzol, 2022; Sohn et al., 2019), the results in this dissertation demonstrate that the results and the analysis of improvement options is highly dependent on the choice of method, which confirms the findings in other papers (Igos et al., 2019; De Rosa et al., 2018; Huang et al., 2013).

8.2 DECARBONISATION - USE OF LCA AS A MEAN

The analysis of Danish Crown's use of LCA and their work with managing their transition towards net zero GHG emissions for their products broadened the understanding of how a company can use an LCA. How LCA is used internally at Danish Crown as a means for decarbonization is discussed in the following.

Strategy development

The findings of this PhD dissertation add to a more nuanced understanding of how companies use LCA in their work with reducing GHG emissions. A common theme in LCA research is the use of LCA for decision-making for strategy development (for examples, see Frischknecht et al., 2017; Borghino et al., 2021). The results of this dissertation demonstrate that LCA was not used directly for decision making in Danish Crown's work with reducing GHG emissions from the product chain. It could be argued that the work with LCA is still at an early stage at Danish Crown as not using LCA for decision-making is typical for early-stage implementation in companies (Frankl and Rubik, 1999). As the work with LCA becomes more embedded in Danish Crown, it is expected by Danish Crowns employees the number of decisions where LCA is involved will increase. However, Danish Crown has used LCA to identify which solutions could be implemented to reach their goal of halving GHG emissions from its product chain by 2030 such as optimized feed efficiency and feed production, increased biogas production, and the use of deforestation free soy (Danish Crown, 2022).

Internal learning

A theme not highlighted in Chapter 5 is the role of LCA for internal learning at Danish Crown. In Danish Crown's work with the LCA model, they have applied two modelling approaches with the first following the PEF method and the second following a consequential method. Danish Crown chose to develop two methods as there was uncertainty in the organization about which of the two methods would become the most widely used in the future. Developing the model with two methods was seen as a safety net against future LCA method development and policy, but it also provided Danish Crown's employees an opportunity to discuss LCA methods with consultants and researchers as it became clear to the employees that the two models produced different results from the same analysis. Having two methods provided employees insights into the LCA method and the underlying assumptions, which they would not have gotten if they only had the results from one method. On the other hand, having two methods also created some confusion internally in the organization when the results were communicated.

In this way, LCA became a learning tool for the employees. The employees' learning was related to the modelling of LCA and knowledge about the most important indicators for environmental impacts. This supports the findings from other studies that propose applying an LCA to learn about the environmental impacts of products

(Hagen et al., 2020; Baumann and Tillman, 2004; Frankl and Rubik, 1999). An improved understanding of the assumptions behind the models also means that the models can be used to gain a deeper understanding of the assumptions behind the proposed mitigation options from NGOs' and competitors' initiatives to reduce GHG emissions. When using LCA for learning, it is possible to apply different assumptions to the model and thereby achieve a better understanding of uncertainties, when considering ways to reduce environmental impact, e.g., by conducting a scenario analysis of new mitigation options.

External communication

Being able to brand themselves as a sustainable company is one of the reasons that Danish Crown has set the target of having net-zero GHG emissions. In 2020, the company launched a marketing campaign in which they communicated a message directly to consumers about their perception of the climate benefits of pork. This marketing campaign became the subject of a lawsuit against the company filed by NGOs as they accused Danish Crown of greenwashing. Other companies besides Danish Crown struggle with communicating environmental messages to consumers (Potter & Röös, 2021; Vizzoto et al., 2021; Iovino et al., 2023), but they should not find it that difficult to communicate these messages if they adhere to the guidance on environmental marketing published by the Ombudsman (Forbrugerombudsmanden, 2021). The issue in Danish Crown seems to be that the communication department is eager to communicate anything related to sustainability as it has a positive impact on Danish Crowns image, but the message tend to be exaggerated at the expense of the credibility.

While this study has focused on the company perspective, other studies have focused on the consumers. These studies find that only some consumers are interested in the green claims made by companies and that those consumers are skeptical of the claims made by the companies if they are not supported by recognized schemes (Ulusoy and Barretta, 2016; Akaichi et al., 2014; Gadema and Oglethorphe, 2011). This points to the need to develop an environmental label or scheme that increases the credibility of a company's green claims. The EU Commission has proposed a guideline for how green claims shall be supported by evidence, e.g., by the PEF method or other scientifically sound methods. However, in line with the conclusion in Chapter 6 and Chapter 7, the EU Commission recognizes that there are some issues with the PEF method that need to be corrected. The Commission prioritize the assessment of impacts on biodiversity, carbon storage and removal, biogenic carbon, resource dissipation, and updates of the existing impact assessment methods.

8.3 PRODUCT CHAIN COLLABORATION

Missing organizational linkages between the LC work performed at Danish Crown and the socio-material interaction points where GHG emissions occur hinders action on reducing GHG emissions. In beef production, more than 98% of the GHG emissions come from the farming stage. The following sections discuss how LCA is used as a tool to create the necessary changes towards reducing GHG emissions from their product chain.

Collaboration across departments

The LCA model is part of the promotion of the sustainability strategy and decarbonization at Danish Crown. When the employees from the sustainability department talk with other departments about their work, they highlight the motivation for why the company is investing resources in LCA and decarbonization. The importance of having one or more employees that promote the LC perspective in environmental work by, e.g., creating interest in life cycle thinking, developing life cycle efforts that blend in operationally, or relating the life cycle perspective to the business logic, has been highlighted as being important for the successful integration of a life cycle perspective in multinational corporations (Nilsson-Linden et al., 2019a; Bianchi et al., 2022). The importance of sharing the rationale for the work has also been highlighted by others (Bianchi et al., 2022). While previous studies have focused on the need for communication among group members and at the organizational level for knowledge sharing (Bianchi et al., 2022), it is identified in Chapter 5 that the employees should become involved in the action nets they are part of by teaching, engaging and sharing knowledge with colleagues and other actors.

Collaboration with farmers

Danish Crown faces some challenges in their collaboration with the farmers that supply cattle to their abattoirs. Danish Crown collects data from farmers and supports research and technological development aimed at mitigating GHG emissions from the farms. They are also planning to develop concrete recommendations for the farmers on how they could mitigate their GHG emissions. However, some farmers are skeptical of the work with reducing GHG emissions and do not trust the results from the LCA model. This indicates the need for trust between the farmers and the employees that work with the LCA model.

This supports the findings of Alig et. al., (2008), who found that the farmers need to understand the evidence behind the recommended mitigation options. This points to the need for an even greater effort on the behalf of the employees at Danish Crown to educate the farmers about how they can mitigate their GHG emissions and to use the LCA model as a learning tool for the farmers. Close collaboration on LCA has previously been found to lead to improvements in both competitiveness and environmental performance for the companies involved (Testa et al. 2022).

The need for concrete recommendations on how farmers can mitigate their GHG emissions is highlighted by the employees in Danish Crown, who have regular contact with the farmers and by the farmers themselves. The work to reduce GHG emissions from the farms is intangible for the farmers as the results of climate mitigation are not visible to the farmer in his day-to-day work. Being presented with the results of an LCA once a year does not lead to any action by the farmers. In contrast to Alig et al., (2008), who found that the farmers need more information about where the emissions occur, but more information does not necessarily lead to any changes as they find it difficult to translate the information into action.

This highlights the important role Danish Crown plays in helping the farmers to reduce their GHG emissions through detailed descriptions of what each farmer should do. Danish Crown has previously taken on a similar role when the farmers needed to improve the animal welfare for some types of cattle. Therefore, the employees in Danish Crown are not completely unfamiliar with the role as consultants and facilitators for the farmers. Danish Crown also has all the data needed to identify what the farmers who produce cattle with less GHG emissions are doing. The results of an LCA have a lot of potential for learning more about the farmers, and which type of recommendations the farmers should receive to reduce their GHG emissions. These recommendations should be linked with an economic compensation to the farmer to increase the farmers motivation.

Collaboration with customers

Collaboration with customers is identified in Chapter 5 as a business value created for Danish Crown by the work with LCA. Their customers are mainly retail stores and other food production companies. The LC work is used to create partnerships between Danish Crown and commercial partners by sharing LCA results and engaging in strategic partnerships. An example is the work performed in Danish Crowns subsidiary company called Scan-Hide where the traceability of the hides is used to promote the sustainability initiatives of the farmer where the hides are produced. The life cycle practitioners become facilitators of partnerships and collaboration with other companies. LC work is performed in action nets and is not limited to the product chain but also includes the wider system of which Danish Crown is part. The LC work affects business-to-business relations in a positive way for Danish Crown as they can provide their customers with insights into their product chain. This supports the findings of Nilsson-Lindén et al., (2019b), which indicate that the adoption of a product chain LCM is driven by both self-interest in the business case and a collective interest in the product chain.

Collaboration with other companies in the agri-food sector

The Danish Agri-food sector is characterized by large cooperative companies owned by farmers. The most well-known of these companies are Danish Crown, Arla, and DLG. The companies work in different parts of the sector (meat, dairy, and feed), but they all share the goal of achieving net-zero GHG emissions in their production by 2050, which is also in line with the Danish Agriculture and Food Council's goal that Danish food production should be climate neutral by 2050. Their goals for 2030 have differing ambition levels as DLG only include scope 1 and 2 in their targets where Danish Crown and Arla include scope 1, 2, and 3.

The companies collaborate to some degree by sharing experiences from their work, investing in the same research projects, and exchanging some LCA results. However, the companies could benefit from even closer collaboration in their work to achieve net-zero GHG emissions by 2050. Closer collaboration on the cattle could be especially beneficial as many of the cattle slaughtered by Danish Crown come from farms that supply Arla with milk. Any initiatives implemented at the farms would benefit both companies and if the two companies coordinated their efforts to a higher degree, the burden for the farmers could be reduced. The collaboration could focus on the sharing of farm data, educating farmers about sources of GHG emissions and the mitigation options, or developing products that focus on environmental sustainability. However, this kind of collaboration has some limitations for both Arla and Danish Crown. First, the companies are reluctant to sharing the data they have gathered which leads to a lack of transparency in the product chain. Second, for Arla, the issue is that Danish Crown's beef division is mainly based in Denmark and Northern Germany, while their farmers are spread out in several European countries. The company is, therefore, not interested in investing heavily in collaboration with a mainly Denmark-based abattoir. From Danish Crown's perspective, the issue is that if they collaborate with Arla on reducing GHG emissions from the farmers who supply milk to Arla, there is a risk that some of Danish Crown's competitors will also benefit from the initiatives, e.g., Tican or Himmerlandskød. Therefore, Danish Crown focuses their efforts on the farmers who primarily produce beef cattle and then rely on Arla to reduce GHG emissions from the dairy farms.

8.4 LCA IN POLICY

In Chapter 6, three policy options for the use of the PEF method as part of an integrated product policy are analyzed. In this section, the options for using LCA in policies aimed at meat production and consumption are discussed.

Background study

The simplest application of an LCA is as a tool for deriving quantitative insights into the change in pollution that might result from adopting an innovation (Rajagopal et al., 2017). Adoption of less polluting practices and/or technologies is one of the policy options that could benefit most from LCA-based data (Gava et al., 2018).

In the EU, the largest livestock facilities are regulated by the Industrial Emissions Directive, which targets harmful emissions to air and water. These farms are required to operate in accordance with a permit, which is granted by the national authorities and is based on the concept of Best Available Techniques (BAT). LCA can be used as a background study to the development of BAT requirements to identify the best available techniques.

Performance benchmark

A more challenging use of LCA in policy is to establish performance standards based on a life cycle footprint of a product (Rajagopal et al., 2017). In the Danish building sector, a limit value of 12 kg CO_2-e / m^2/ year was introduced on the 1st of January 2023 for all new constructions larger than 1000 m^2. A similar limit value could be set for food items based on their assessed climate impact from an LCA. Such a limit value could be set for each type of food, e.g., a limit value of 15 to 30 kg CO_2-e / kg beef depending on the underlying method. However, such a policy would be challenging to implement as it would require all food producers to conduct an LCA of their products. These LCAs should be calculated using a similar method, e.g., the PEF method, and all the data and the LCA results should be verified by a third party.

Production tax

Another potential use of an LCA is as a foundation for a tax (Rajagopal et al., 2017). The purpose of such a tax could be to internalize the externalities associated with GHG emissions (Metcalf and Weisbach, 2009). The issues connected with such a tax are assessing the tax base (including possibilities for tax reductions), setting the tax rate, and ensuring trade. LCA could be used to assess the tax base and possible tax reductions but that would again require all producers to conduct verified LCA studies. Another approach could be to tax the production based on average impacts of the product groups. That will mean that all beef productions will have the same tax rate. It can be based on existing LCA studies which makes it easier to implement, but the motivation to reduce GHG emissions will be limited for the individual farmer, as the tax rate will be independent of the actual emissions from the farm.

Business-to-consumer communication

Business-to-consumer communication was addressed in Chapter 6. Environmental labeling of food products based on LCA has been discussed at the national and regional scale in the EU. In Denmark, work is ongoing to find a way to make a climate label based on LCA. There are different issues when developing a label, e.g., how it should look, which LCA approach it should be based on, and how detailed the data used in the LCA should be (national averages or company specific).

In France and Italy ecolabels for food products have already been introduced on the market. Compared to the Danish initiative, these labels are further ahead in their development and include more parameters, e.g., biodiversity and animal welfare. In the recently published recommendations from the workgroup under the Danish

Veterinary and Food Administration (Ministry of Food, Agriculture and Fisheries of Denmark, 2023), it is suggested that a Danish Climate label should to some degree be based on the PEF method and only include climate impacts. The Danish label will thereby be less adequate for guiding consumers towards the most sustainable products as it only includes one environmental impact. Therefore, it could be argued that a better strategy for an ecolabel for food products in Denmark would be to adopt an already existing ecolabel developed by another EU Member State.

The recent inflation in food prices and the following change in consumption away from organic products shows that the potential of voluntary means is limited as they are based on consumers' willingness to pay a premium for products with a better environmental performance. Consumers' willingness to pay for premium products with a lower climate impact varies and depends on their socio-demographic background and attitudes (Akaichi et al., 2014). A study from the UK found that 72 percent of consumers wanted a climate label on their food products, but also that 89 percent were confused by the proliferation of labels and had difficulty understanding the labels (Gadema and Oglethorphe, 2011). More recent studies have highlighted the need for being able to compare the climate effect between product groups and not only within narrowly defined product groups, i.e., comparing beef with beans and not only beef with pork (Edenbrandt and Nordström, 2023).

Consumption tax

Another way to use LCA in changing the consumption of beef is to introduce a climate tax on consumption. This is again a more challenging use of LCA in policy (Rajagopal et al., 2017), but it could have a significant effect on the beef consumption. A Danish study from 2013 found that a climate tax that increased the price of beef by 25 percent could lead to approximately a 30 percent reduction in beef consumption (Edjabou and Smed, 2013). Others highlight the need for additional policies that also subsidize less carbon intensive foods (Tiboldo et al., 2022).

Aarhus Municipality has introduced an internal tax on food items such as beef with a high climate impact. The tax is 32.5 DKK per kg and is added to the price of the food products. It has led to a reduction in the consumption of beef products of more than 30% (Brandt, 2023). If a producer can prove a lower climate impact than the average production or introduce an environmental improvement with a positive effect on the climate impact, the tax could be refunded as part of the scheme (Gren et al., 2021). However, this is not possible in the scheme introduced by Aarhus municipality.

Push and pull policies

Several of the above options are aimed at regulating and incentivizing cleaner beef production. The use of new techniques and technologies for nitrification inhibitors and manure management has the potential to reduce GHG emissions from beef production by 22 to 44 percent in the EU (Bryngelsson et al., 2016). A production tax or a climate benchmark could motivate a more sustainable production of beef while the development of BAT requirements could push farmers to implement new techniques or technologies.

To stay within the EU's goal on climate change, it will be necessary to introduce dietary changes and reductions in the consumption of ruminant meat (beef and mutton). It has been estimated that consumption will have to be reduced by at least 50% (Bryngelsson et al., 2016).

A future policy should combine a focus on both consumption and production. A consumption tax on the products with the greatest climate impacts could be combined with the requirement for BAT for cattle farms. This could reduce the consumption of the products with high environmental impacts and ensure that the production has the lowest impact on the climate as possible. Both push and pull policies are needed as they can make a significant contribution to limiting the temperature increase over the next 100 years (Ivanovich et al., 2022). Demand side mitigation options in terms of shifting to a healthy sustainable diet and reducing food waste have the potential to reduce GHG emissions by 44% by 2050 (IPCC, 2023).

8.5 THE FUTURE OF BEEF PRODUCTION

From 2011 to 2020, global surface temperatures reached a level that is 1.1°C higher than in the period 1850 to 1900 (IPCC, 2023). In 2012, the warming directly attributable to livestock accounted for 23% of total warming (Reisinger & Clark, 2018). By the end of the century, global food consumption could contribute 0.7 ± 0.2 to 0.9 ± 0.2 °C above present-day warming levels, depending on population growth. Food consumption alone could bring us close to the 2°C threshold set in the Paris Agreement (Ivanovich et. al., 2023). In 2030, 33% of the contribution to mean global surface temperature from food consumption will come from the consumption of ruminant meat and 19% from the consumption of dairy products. In comparison, non-ruminant meat will account for 9% and vegetables for 3% (Ivanovich et. al., 2023).

To stay within the boundaries set by the Paris Agreement, the entire economy must become a net-zero CO_2-emitter and direct emissions of methane and nitrous oxide from livestock must be reduced by 40% compared to today. The demand for ruminant meat is expected to rise by 90% in 2050 due to an increasing population and wealth if no initiatives to reduce its consumption are implemented (Ivanovich et al., 2023). Even the best beef production systems have a climate impact that justifies efforts to limit any future growth in beef production (Pierrehumbert and Eshel, 2015).

Limiting the consumption of beef and meat, in general, would also have a positive effect on the health of the population. The official dietary guidelines in Denmark recommend that each person eat 350g of meat per week. However, the EU average is 4.1 times higher than this. A reduction in meat consumption could be implemented without having negative effects on the overall health of the EU population.

Technologies and techniques for reducing methane and nitrous dioxide emissions from enteric fermentation and manure management have the potential for reducing the climate impact of beef production. Some of the solutions with high mitigation potential are feed additives, manure treatment, manure storing, nitrification inhibitors, and a better nutrient balance in the feed (Gerber et al., 2013). Ensuring better management of cattle to increase the efficiency of the production and decrease the necessary space for feed production could reduce the need for land use changes. Reducing food waste should also be a focus in the future as 23% of meat products are lost and wasted (Karwowska et al., 2021).

Danish Crown and the employees in the sustainability department know that beef production has a high impact on the climate, and that it will be a challenge to reduce the climate impact of beef production enough to stay within the threshold of 2°C if the consumption of beef continues at the same rate as today. With Danish Crowns goal of halving the GHG emissions from their product chain by 2030, they have taken the first step in transforming the company in a more environmentally sustainable direction. Setting a goal is an important step but Danish Crown still has not taken significant actions to reduce the GHG emissions from the product chain.

In the past, the strategic focus of Danish Crown was on increasing the production of meat in Denmark and gain a larger market share. This focus has changed in recent years and with the adaption of the strategy called *Feeding the Future*, Danish Crowns focus shifted away from increasing production amounts towards increasing the economic value of the products through a higher degree of processing. The CEO of Danish Crown has also stated that he believes beef will get the same status as champagne in the future – meaning that it only will be consumed at special occasions (Svansø, 2021).

Danish Crown expects in other words that the consumption of beef will change from being an everyday commodity, where the cost of the product is an important parameter towards being something, where consumers are willing to pay a premium for a higher quality. If this scenario is happening in the future, then Danish Crowns work with reducing GHG emissions from beef could become a quality that consumers are willing to pay for. However, the future could also lead to another scenario where the perception of beef develops in a more negative way and becomes something that is perceived in the same way as foie gras.

For Danish Crown it is important that there continues to be a market for their beef production and they should therefore work on reducing the risk of negative perception of beef. However, this will be difficult when beef is produced at a scale worldwide where it has significant contribution to climate change. Therefore, Danish Crown should advocate for a lower consumption of beef to minimize the risk of beef getting a negative perception in the public, and DC could diversify their production even further by promoting their plant-based products.

CHAPTER 9. CONCLUSION

This PhD dissertation provides an analysis of the use of the LCA method to decarbonize Danish Crown's product chain. The analysis is based on the following research question:

To what extent can life cycle assessment be used to manage the transition towards decarbonizing beef production?

The research question was investigated from four angles. The first angle was to provide an overview of already identified issues with the European Commission's method for making LCA called Product Environmental Footprint (PEF). The second angle was to assess the feasibility of using the PEF method for conducting an LCA for beef. The third angle was to study the link between Danish Crown's work with decarbonizing their product chain and its use of LCA. The fourth angle was to analyze the limitations of the PEF method for policy use.

The LCA method

For LCA to be a management tool to facilitate the transition of a product chain towards decarbonization, it should provide results that reflect the environmental consequences of consumption and production choices and should point towards the potentials for improvements. This demands that the method can assess the environmental impacts of a product and can compare products fairly. The issues with the PEF method were analyzed in Chapter 6 and Chapter 7:

Research sub-question 2: What have the methodological issues been in the discussion on PEF, and how do the suggested updates address them?

Research sub-question 4: How does the modelling of multifunctionality affect the result of an LCA on beef?

The EU Commission has suggested that companies should use the PEF method when conducting an LCA. The implication is that the PEF method may have a significant role to play in a future green market in Europe. In this dissertation, a literature review of academic papers on the PEF method was conducted. It found that there are several problems with the PEF method in relation to using it to conduct an LCA – especially related to the food industry. Outstanding issues were identified for the chosen functional units, where some PEFCR did not involve necessary quality aspects such as nutrient value. There are also concerns about the lack of an impact category for biodiversity even though it is indirectly included in eight of the existing impact categories. This represents a limitation especially for agriculture products. Only a few of the developed PEFCR contain a benchmark that can be used for comparisons, which also limits the applicability of the method for communication purposes.

Furthermore, the feasibility of using the PEF method for making an LCA on a beef abattoir was analyzed. The aim was to assess the environmental impact of beef products and analyze how the results changed when the process in the abattoir changed. The climate impact of a low value cut of beef was calculated to be between 18 and 34 kg CO2e / kg beef, while for a high value cut of beef it was between 21 and 64 kg CO2e / kg beef. The differences in result were achieved through the application of different modelling approaches. Based on this assessment, it was concluded that the modelling of multifunctionality in meat production in the PEF method should be changed so that substitution is used instead of economic allocation.

Three additional recommendations were given regarding the modeling of multifunctionality in beef production. Firstly, the mass fractions, indicating how much of the cattle is used for human consumption versus other purposes, should be based on company-specific data, which allows companies to demonstrate the effects of changes made in the production process in an abattoir. This recommendation is relevant since the PEF guidelines do not permit companies to use their own mass fractions. Secondly, the relative prices for meat cuts used in the model should reflect market-based average prices over a longer period, rather than company-specific prices. The prices used for the meat cuts could be the average European sales price of a meat cut over a three-year period. Thirdly, the results should be presented for different cuts of meat, instead of only one product category, as it is described in the PEF guidelines. This will give a truer representation of the environmental impact from purchasing high value cuts compared to purchasing low value cuts.

LCA as a management tool for companies and product chains

Danish Crown has applied a life cycle perspective in their environmental work. The company developed an LCA model in 2021 as part of their strategy to become a net zero emitter of GHG emissions by 2050. Part of this dissertation investigated the link between the work with the LCA model and reductions in GHG emissions. The analysis was focused on LC work, which consists of activities performed by employees in the company with a life cycle perspective and in this case are linked to the work on the LCA model and the decarbonization of the beef production chain.

Research sub-question 1: How is the life cycle work in a company linked to reductions of GHG emissions in the product chain?

The analysis of the LC work in relation to the LCA model revealed that, at Danish Crown, the LC work mainly provided results to the farmers and customers and was used to develop partnerships of potential commercial value. The focus of the activities associated with the LCA model was on guaranteeing the accuracy of the calculations of the model and computing the climate footprints of all products, enabling their communication. The data collected from the farmers and the presentation of results to the farmers was conducted where more than 98% of the GHG emissions were located, but the company faced problems in the work with the farmers. Some of the farmers did not want to reduce their GHG emissions as they did not think it was important and they were skeptical about whether the LCA model calculated in the "right" way.

Danish Crown's employees, who had closest contact with the farmers, lacked knowledge about LCA and how to reduce GHG emissions, which meant they could not advise the farmers about what they should do to reduce their GHG emissions. The farmers highlighted the need for a more practical approach with concrete recommendations, so that the result of their efforts would be more tangible.

The LC work with the LCA model was also used to establish collaborations with some of Danish Crown's customers. These activities were performed to create value for the company in the form of a closer relationship with some customers, who had the same goal of decarbonizing their product chain. At the time of interviewing there were a few examples of this activity, but Danish Crown expect that there will be more in the coming years.

LCA in policies

Another strategy to managing beef production is through public policies. In Chapter 6 and Chapter 8, the opportunities for using PEF and LCA in public policies were analyzed and discussed.

Research sub-question 3: What are the challenges of using PEF in public policies and how can these be resolved?

The challenges to using PEF in public policies are numerous but they depend on the complexity of the policy. An option for using PEF in policies with minimal complexity is to use it for background studies to establish requirements in policies, e.g., assessing environmental impacts of new techniques for BAT requirements or eco-label criteria. If these background studies should include aspects other than environmental impacts, other methods should be used to assess these parameters.

A more complex use of PEF and LCA in policies is for communicating with consumers through green claims or environmental labelling. Here, the lack of a benchmark in most PEFCR is an issue as these could have been used in an environmental label based on a graduated score. The exclusion of some quality criteria in PEFCR could misguide consumers into choosing products of low quality and low environmental impact. The costs of conducting PEF studies could also become an issue for SMEs in particular. The possibility of using PEF or another LCA method as the basis for a consumption and/or production tax is also discussed.

Finally, returning to the title of the thesis, the decarbonization of beef production is necessary to ensure environmentally sustainable beef production in the future. New technologies and techniques have the potential to reduce GHG emissions from beef production. However, the pace of which it is happening today is slower than what is accomplished in other sectors. By 2030, it is expected that the Danish energy and industry sector will reduce its emissions by 80% while the agricultural sector will reduce its emissions by 32%. This means that the agricultural sector will account for 41% of national GHG emissions by 2030 compared to 32% in 2020.

CHAPTER 10. RECOMMENDATIONS

Recommendations for both Danish Crown and for further research are given based on the findings of this dissertation.

10.1 RECOMMENDATIONS FOR DANISH CROWN

Considering the urgent need to reduce GHG emissions, a company like Danish Crown should push their suppliers to reduce their GHG emissions significantly. The company have planned to develop concrete recommendations for farmers and are investing in the development of technologies for decarbonizing the product chain. To accelerate the implementation of better management practices or new technologies, Danish Crown should offer climate consultancy to farmers and support the implementation of new technologies by the farmers. Danish Crown could support these initiatives financially by paying a premium for the cattle if certain technologies or techniques are implemented or force the development by setting it as a minimum requirement for farmers who wish to be suppliers to Danish Crown. Suggestions for minimum requirements could be that the farmers should use a methane-reducing diet, send 50% of manure to biogas, and use acidification of manure. Premium criteria could be the use of nitrification inhibitors, restoring peat soils, applying low tillage practices, use green fertilizers, or send 80% of manure to biogas.

The transition in Danish Crown involves several departments. The member service department is especially important in the work with the product chain as they have direct contact with the farmers, but also procurement and production are of interest for Danish Crown's decarbonization work. The recommendation for the LC practitioners at Danish Crown is that they should emphasize their role as a knowledge center in Danish Crown and the beef product chain. Based on their work with LCA and the data from the farmers, the LC practitioners can develop concrete initiatives for each individual farmer. The company should collect best practices from the farmers and promote the knowledge to all the farmers in the product chain in all the countries where they source their animals.

This will mean that the LCA model which the LC practitioners work with shall be institutionalized. The current model is primarily set up to compute results based on average farm data and any changes to the input data are handled manually. The larger analysis of the data has been performed by a consultancy as they have more resources for that. In the future development of the LCA model, emphasis should be on developing the model for multiple purposes to enable actions for decarbonizing the product chain, e.g., internal learning, collaboration with partners, decision support, and communication.

Danish Crown's work with LCA focuses almost exclusively on GHG emissions. However, the company is beginning to invest resources into their impact on biodiversity, which is adversely affected in many ways, although Danish Crown's work mainly concentrates on the effect that grazing animals have on biodiversity at the farm level. Expanding the LCA model to also include the impact categories that affect biodiversity could give Danish Crown a better understanding of how the product chains affect biodiversity and thereby enhance their efforts to reduce this impact or even create a positive contribution to biodiversity.

10.2 RECOMMENDATIONS FOR FURTHER RESEARCH

This PhD project has provided some new insights into the connection between LC work and reducing GHG emissions in a product chain, but there is a need to examine the organization of LC work regarding the effect on environmental performance, as well as better understand the operational role of LC work for business strategy.

A few other researchers are active in this field, but there is a significant knowledge gap in terms of how companies link their work with monitoring and collecting data from their product chain to initiating strategies to reduce impacts. A company like Arla is more advanced in terms of linking the two, and could be a interesting case for future work. Other interesting cases could be companies that do not use LCA or have a minimal use of LCA in their strategies for decarbonization.

During this PhD project, the reputation and sophistication of the PEF method has increased. It is still considered as the future method of LCA in European policies. Nevertheless, it still has not been fully adopted. The research conducted for this project has focused on the method applied in the PEF guidelines and identified problems with the method. The future focus of research on PEF could continue this work to push for a continuous update of the PEF method to ensure that it incorporates the most recent scientific knowledge. Future research could also focus on developing tools for decreasing the costs of conducting PEF studies for companies – especially SMEs. This research could include the development of PEF tools based on the PEFCRs, so each company does not need to develop their own PEF model to calculate PEF results.

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