Evaluating Environmental Effects in Early-Stage Food Innovation: A Life Cycle and Actor-Network Perspective on Upcycling Brewery Spent Grain

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June 2025

Title Page

Thesis title: Evaluating Environmental Effects in Early-Stage Food Innovation: A Life Cycle and Actor-Network Perspective on Upcycling Brewery Spent Grain

Institution: Aalborg University, Copenhagen

Program and semester: MSc Sustainable Design Engineering, fourth semester

Project: Master Thesis

Project Period: February 5th, 2025 - June 17th 2025

Submission date: 28th of May 2025

Supervisor: Louise Laumann Kjær

Number of characters: 98.713

Number of standard pages: 41

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AALBORG UNIVERSITET

Abstract

Climate change represents an urgent challenge that calls for more sustainable management of land and resources. This thesis investigates the potential of circular economy principles and the waste hierarchy as tools to address this issue, focusing on an empirical case study of a Danish startup working with the upcycling of brewers' spent grain (BSG) – a by-product of beer production – into bakery products. The case is part of a value chain collaboration under the Closing Loops initiative, involving a bakery, a brewery, and the startup, with the goal of reducing waste and CO_2 emissions through circular partnerships.

Data collection is grounded in ethnographic methods, enabling close observation of the practical and logistical challenges associated with handling wet BSG, including issues related to food safety, economics, and scalability. Actor-Network Theory (ANT) is used to map the complex network of human and non-human actors involved in the value chain, expanding the analysis from internal company processes to a more systemic understanding of innovation in practice.

A critical screening-level Life Cycle Assessment (LCA), including both attributional (aLCA) and consequential (cLCA) perspectives, highlights the environmental consequences of diverting BSG from animal feed to human food. This approach assesses not only the direct effects, but also the methodological potential and limitations of LCA in early-stage innovations.

To strengthen the evaluation of circular innovation in practice, the thesis develops supplementary criteria that reflect the complexities identified in the case study. Informed by both empirical findings and theoretical perspectives, these criteria expand the current evaluation beyond quantifiable outcomes to include practical dependencies, system-level effects, and the risk of unintended consequences within the value chain.

Finally, a systemic analysis using the Multi-Level Perspective (MLP) situates the case in a broader context, examining how regulations and political frameworks shape the treatment of BSG. The analysis shows how EU regulations and support schemes can unintentionally promote fragmented solutions and regime shifts that oversimplify decision-making processes. The thesis argues for a holistic approach, integrating environmental and socio-technical perspectives to support sustainable innovation from the earliest stages.

The main contribution of this thesis is a nuanced, system-oriented understanding of circular economy practices, emphasizing the importance of considering material flows, network dynamics, and potential rebound effects in decision-making and policy for sustainable innovation.

Resume

Klimaudfordringen kræver, at vi gentænker vores omgang med ressourcer og affald, særligt i fødevaresektoren. Denne afhandling tager udgangspunkt i et konkret casestudie af en dansk startup, der sammen med et bryggeri og et bageri forsøger at opgradere mask – et restprodukt fra ølproduktionen – til nye fødevareprodukter. Projektet indgår i det nationale initiativ Closing Loops, hvor samarbejde på tværs af værdikæden skal bidrage til at mindske både madspild og CO_2-udledning.

Gennem etnografiske metoder og feltstudier har jeg fulgt processen tæt og fået indblik i de praktiske og logistiske barrierer, der opstår, når våd mask skal håndteres under hensyntagen til fødevaresikkerhed, økonomi og mulighederne for opskalering. Med Actor-Network Theory (ANT) som analytisk ramme belyser specialet, hvordan materialer, aktører og teknologier gensidigt former innovationen og stiller krav til samarbejde og organisering.

For at vurdere de miljømæssige konsekvenser har jeg gennemført en screening-baseret livscyklusvurdering (LCA), hvor både attributionelle og konsekvensbaserede tilgange er anvendt. Analysen viser, at omdirigering af mask fra dyrefoder til menneskeføde kan have både fordele og ulemper, alt efter hvordan værdikæden organiseres, og hvilke substitutionsvalg der træffes.

På baggrund af caseanalysen introducerer specialet et sæt supplerende vurderingskriterier, som tager højde for de praktiske afhængigheder, systemiske effekter og mulige utilsigtede konsekvenser, der ofte overses i konventionelle evalueringsrammer. Endelig perspektiveres casen ved hjælp af Multi-Level Perspective (MLP), som sætter fokus på, hvordan politiske rammer og støtteordninger kan påvirke udviklingen af cirkulære løsninger – ofte med utilsigtede eller begrænsende følgevirkninger.

Specialets hovedbidrag er et nuanceret indblik i, hvordan cirkulær økonomi kan fremmes i praksis, og en opfordring til at tænke helhedsorienteret, når bæredygtige løsninger skal vurderes og implementeres.

Preface

This thesis originates from my internship in 2024, during which I had the opportunity to gain an in-depth understanding of a startup's efforts in upcycling food waste. For the purposes of this thesis, the company is anonymized and referred to as The Case Company. The Case Company focuses on upcycling spent grain (a by-product from beer brewing) in collaboration with a local brewery and a bakery.

At the time of my initial involvement in 2024, the project remained in its early development phase, characterized primarily by desk research and efforts to secure funding for practical implementation. My motivation to continue engaging with the project increased as the startup succeeded in obtaining funding, enabling the transition from concept to actual implementation. This development allowed me to follow the project's progression in parallel with my thesis work, wherein I have investigated the environmental implications of the upcycling process in practice.

In this study, I examine the environmental aspects of upcycling and storing wet spent grain, while shedding light on the complexities of a value chain collaboration, where multiple actors work together to promote sustainable waste management. The results of this thesis are intended to inform decision-makers and stakeholders who are involved in the early stages of innovation processes related to upcycling food by-products and improving environmental performance in value chains.

Acknowledgement

This thesis would not have been possible without the support and input from a number of individuals, to whom I would like to express my gratitude for their contributions to my knowledge gathering and process.

First and foremost, I would like to extend a huge thank you to my supervisor, Louise Laumann Kjær, for her ongoing commitment, sharp questions, and ability to create reflection and overview, especially during the periods when I found it all overwhelming.

A big thank you also goes to The Case Company for welcoming me into their office community, allowing me to attend meetings, ask questions, and access data throughout the process. Likewise, I would like to thank their collaborators, The Case Bakery and The Case Brewery, for their openness and willingness to share knowledge and provide insights into their processes.

I would also like to express my sincere thanks to Conny Hanghøj from Food & Bio Cluster Denmark, who showed interest in my project from the start and has provided valuable feedback along the way.

Thanks to my fellow students and professors for professional advice, support, and guidance throughout the process. A special thank you also goes to the librarians at Aalborg University, who have assisted me with literature searches and reference management when I needed it.

I am deeply grateful for the warmth, curiosity, and support I have received from all of these individuals throughout my work on this thesis.

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Chapter 1: Introduction and problem definition

1.1 Background and Problem Context

Climate change and biodiversity loss have created an urgent need for more sustainable production and consumption patterns. In this context, the circular economy has gained increased political and societal attention, particularly considering the European Green Deal and the EU Circular Economy Action Plan (European Commission, 2019; 2020). These ambitions are alligned at national level, where Denmark's climate policies aim to reduce greenhouse gas emissions by 70% by 2030, with circularity identified as a key strategy (Klima-, Energi- og Forsyningsministeriet, 2019).

One sector where this challenge is particularly pressing is the food industry, which is responsible for significant greenhouse gas emissions and land use – while at the same time holding great potential for circular solutions. Recent estimates show that global agrifood systems account for nearly 30% of total emissions, underlining the sector's dual role as both problem and opportunity (FAO, 2023).

A growing part of the circular economy debate focuses on food loss and waste. These can be grouped into three overarching categories:

1. **Surplus food** refers to edible excess, often resulting from overproduction.
2. **Unavoidable residuals** are by-products generated during food processing, such as pulp, peels, or spent grain.
3. **Post-consumer leftovers** are food wastes originating from households or the foodservice sector (Jain & Gualandris, 2023).

Upcycling targets especially the second category: unavoidable residuals. The aim is to reintegrate these materials into the food system by converting them into valuable inputs in new production cycles (Jain & Gualandris, 2023). This thesis focuses on a specific example of such upcycling: the reuse of Brewers' Spent Grain (BSG), a by-product of beer production. BSG is the solid material left after extracting sugars during the brewing process. It accounts for approximately 85% of the industry's total by-products and is generated in large quantities worldwide (Mussatto, 2014).

1.2 Case Description

This thesis is based on a case study of a startup (The Case Company) that seeks to develop a circular food value chain by upcycling brewer's spent grain (BSG). The case is part of Closing Loops, a national initiative led by Food & Bio Cluster Denmark and co-financed by the EU and the Danish Business Promotion Board. The initiative aims to promote circular value chain collaborations and support Denmark's 2030 climate goals (Closing Loops, n.d.).

In this case, The Case Company collaborates with a local brewery (The Case Brewery) and a bakery (The Case Bakery), both located in the Copenhagen area. The aim of the partnership is to establish a circular value chain in which BSG from beer production is upcycled and incorporated as an ingredient in bakery products.

The initiative has received funding from Closing Loops, a national program that supports the development of circular value chains across multiple sectors. Closing Loops focuses on promoting resource efficiency, reducing CO_2 emissions and waste, and accelerating Denmark's transition to a more circular economy. One of the program's key targets is to achieve a reduction of 235,000 tons of CO_2 emissions and 42,000 tons of waste over three years (Closing Loops, n.d.). As highlighted in the interviews with Food & Bio Cluster Denmark (Appendix 4 and 5), projects in the Closing Loops programme are evaluated according to established criteria, where side streams such as BSG are only considered as waste if they do not have an economic value animal feed or biogas.

1.3 Evaluation Criteria for Closing Loop

To receive support and funding from the Closing Loops program, projects must meet a set of established criteria. These are intended to support the program's goal of promoting circular value chains and delivering measurable environmental benefits. The following section outlines the criteria used to evaluate all participating projects.

Evaluation Criteria for Value Chain Collaborations in Closing Loops

Projects involving value chain collaboration are evaluated based on four equally weighted criteria, covering both technical feasibility and environmental impact.

1. **Relevance and Volume of the Value Chain:** Projects must present a clear description of the relevant circular value chain and the volume of the resource stream that the project addresses.
2. **Expected Environmental Impact:** Projects are evaluated on their potential to achieve significant CO_2 reductions and/or waste minimization, in line with the program goals.
3. **Feasibility and Realism:** The proposed solution must be well described and realistically achievable within the specified timeline.
4. **Expertise and Partnerships:** It is evaluated whether the involved companies and organizations represent the necessary links in the value chain and possess the required expertise to realize the project's ambitions.

Each criterion is assigned up to 25 points, for a maximum total of 100 points. To qualify for funding, projects must achieve a minimum of 65 points in total and at least 50% of the points in each criterion (Closing Loops, 2024). For a detailed description of the specific evaluation criteria and the associated evaluation scale, see Appendix 6.

1.4 Identified Research Gap

Although interest in upcycling brewery by-products and developing circular food solutions is growing, there is still limited research that systematically evaluates the environmental consequences of different uses of BSG. Existing studies often focus on technological optimisation or specific biorefinery pathways but rarely compare these to current baseline practices, such as using BSG as animal feed. In addition, many rely on fixed system boundaries and methodological assumptions that overlook the complexity and uncertainty of early-stage innovation.

A noticeable gap remains in the integration of environmental assessment methods, such as Life Cycle Assessment (LCA), with qualitative analyses of actor roles, network dynamics, and institutional frameworks.

To address this gap, this thesis applies a combined approach of LCA and Actor-Network Theory (ANT) to a case study on BSG upcycling, aiming to explore both the environmental implications and the socio-technical dynamics that shape circular innovation in practice

1.5 Research Scope

This thesis explores how environmental impacts and network dynamics in early-stage food innovation can be analyzed through a case of upcycling BSG into bakery products in a Danish context.

The main objective is to investigate how emerging circular food solutions can be evaluated in the early stages of innovation, where the solution is still under development and data availability is limited. By combining LCA with Actor-Network Theory (ANT), the thesis analyzes both the environmental implications and the technical and organizational negotiations shaping the innovation process. Rather than conducting a full quantitative LCA, a screening-level environmental analysis is applied, drawing on existing literature and qualitative insights from the actor network.

The aim is not to develop a finalized assessment tool, but to explore the possibilities and limitations of integrating environmental and socio-technical perspectives in sustainability evaluation.

While economic and social dimensions of sustainability are acknowledged, they are not systematically addressed in this study. Accordingly, this thesis should be understood as a first step toward identifying and understanding the environmental impacts and potential unintended effects of circular innovations in practice, with the possibility of further developing the evaluation criteria toward a more holistic approach.

1.6 Research Questions

This thesis explores how environmental and systemic impacts can be assessed in early-stage circular food innovations. The focus is on a concrete case where brewers' spent grain (BSG) is upcycled into bakery products through a collaboration between a startup, a microbrewery, and a bakery.

In innovation programs such as *Closing Loops*, assessment frameworks often prioritize quantifiable results such as CO_2 savings and waste reduction. However, in early-phase projects where solutions are still emerging, these effects are difficult to measure. This raises the need for supplementary approaches that can capture environmental and systemic dynamics even when data is limited.

To address this, the thesis combines Life Cycle Assessment (LCA) and Actor-Network Theory (ANT). LCA provides an environmental screening of different handling options for BSG, while ANT offers insights into the collaborative and material dynamics that shape the innovation process. Based on this dual perspective, the following research questions guide the analysis:

Main Research Question (MRQ):

How can environmental impacts and actor-network dynamics be assessed in early-stage circular food innovations, using the upcycling of brewers' spent grains (BSG) as a case?

This overarching question aims to investigate not only the environmental performance of a specific circular food innovation but also the systemic and organizational conditions that shape its development. The ambition is to contribute to more nuanced evaluation practices in contexts where conventional tools may fall short.

Sub-question 1:

How is BSG transformed and negotiated as an actor in the collaboration between The Case Brewery, The Case Company, and The Case Bakery, and what socio-technical conditions shape the network?

While BSG is technically a by-product, it plays an active role in shaping the collaboration. By applying ANT, this question investigates how materials like BSG are assigned different meanings and how technologies, standards, and infrastructures influence what is possible within the network.

Sub-question 2:

What environmental consequences arise from upcycling BSG into food products rather than animal feed, and how are the results influenced by different LCA approaches?

Through attributional and consequential LCA, this question compares the environmental performance of BSG upcycling scenarios and reflects on how methodological choices affect the interpretation of sustainability outcomes.

Sub-question 3:

How can insights from ANT and LCA analyses inform assessment practices in innovation programs such as Closing Loops?

Building on the two previous questions, this sub-question links empirical findings to practical application. It considers how existing evaluation criteria could be complemented by more context-aware approaches that better account for complexity in early-stage circular innovations.

1.7 Reading guide

This thesis is structured according to a classic report format.

Chapter 1 introduces the background, problem statement, case description, research gap, scope, and presents the main research questions of the thesis.

Chapter 2 presents the theoretical foundation for the analysis. Here, ANT and LCA are introduced and applied respectively to analyze the social and technical dynamics of the network and to assess the environmental impacts of different uses of BSG. Additionally, concepts such as systems thinking, absolute sustainability, and the Multi-Level Perspective (MLP) are included and used in the discussion.

Chapter 3 describes the methodological approach, including the case study design, the use of ethnographic methods, literature review, and the development of a screening-level LCA. This chapter forms the basis for the analysis and explains how data have been collected and integrated into the following chapters.

Chapter 4 addresses Sub-question 1. Here, ANT is used to map the relations between actors and to identify the material and institutional conditions that support or challenge the development of the circular value chain.

Chapter 5 addresses Sub-question 2. This chapter presents the results from both attributional and consequential LCA, which are analyzed with respect to system boundaries, substitution assumptions, and methodological choices.

Chapter 6 addresses Sub-question 3. Based on the case, a set of supplementary assessment criteria is developed to strengthen the current evaluation framework in Closing Loops, particularly in early-stage projects with limited data.

Chapter 7 presents a discussion where the main findings are discussed in relation to broader structural and institutional contexts and reflection about my methods.

Chapter 8 concludes the thesis by summarizing the research questions and synthesizing the main findings of the report.

Chapter 9 presents a reflection on my role as a design engineer and discusses relevant perspectives for future work.

Chapter 2: Theoretical Framework

This chapter presents the theoretical framework that supports the thesis' analysis and interpretation of circular food innovation in an early-stage context. Two main analytical approaches are introduced: Actor-Network Theory (ANT) and Life Cycle Assessment (LCA). ANT is used to explore how materials, actors, and technologies interact and negotiate meaning in the formation of a circular value chain, while LCA provides a methodological basis for assessing the environmental impacts of alternative valorisation strategies for BSG.

In addition to these core perspectives, the chapter draws on selected concepts from systems thinking, including the distinction between relative and absolute sustainability and the risk of rebound effects. These perspectives help bridge ANT's relational focus and LCA's systemic orientation and inform the development of more nuanced evaluation criteria.

To further contextualise the thesis within existing research, a review of academic studies on BSG upcycling and environmental assessment is included. This review highlights current technological and environmental approaches to BSG valorisation and identifies gaps related to early-stage innovation, limited data availability, and systemic considerations.

Finally, the chapter introduces the Multi-Level Perspective (MLP), which is applied in the discussion chapter to reflect on the broader structural and institutional dynamics shaping current treatment pathways for BSG. MLP provides a socio-technical lens that helps position the case study within a wider transition context and understand why biogas remains the dominant outlet for BSG despite circular alternatives.

Together, these perspectives form the analytical foundation for the thesis and guide the research design and methods presented in the following chapter.

2.1 Actor-Network Theory (ANT)

In this thesis, ANT is used as an analytical approach to examine how the network shapes the practice of upcycling BSG. ANT makes it possible to analyze the dynamics that emerge in socio-technical systems, where both human and non-human actors play a role. The theory is applied to explore how the social and technical system is created and shaped through ongoing negotiations (Latour, 2005). I have used ANT to zoom in on the case and to gain an overview of the actors involved, including those affected by the project and those whose engagement is necessary to ensure its implementation.

A key principle in ANT is to "follow the actors" (Latour, 2005). This means that actors are not analyzed based on predefined roles, but through the meanings they generate and the connections they form in practice.

In connection with this, I incorporate Latour's (2004) concept of *"matters of concern"*, which in this project refers to the value and significance that key actors attribute to BSG within the collaboration. By analyzing these concerns and interests, it becomes possible to understand what drives the actors' actions and where potential tensions may arise within the network.

Another important analytical tool in ANT is is the examination of controversies in the network. These are situations where actors disagree, or where relations may become unstable and potentially destabilise the system. According to Venturini (2010), it is in such moments that the social becomes most visible, as actors are forced to reveal their positions, alliances, and interests. In this thesis, controversies are used to identify where relationships in the network are challenged, for example in relation to noise complaints from neighbors, access issues involving The Case Brewery, or the role of the municipality.

The purpose of applying ANT in this thesis is not to simplify reality, but to uncover and understand the complexity that arises when different actors come together and collaborate. ANT allows for the investigation of how networks formed, maintained, and transformed over time, and under what conditions cooperation or resistance occurs. By analyzing tensions and negotiations among actors, it is possible to understand what contributes to the stability of the system and where potential breakdowns may occur.

Part of the empirical foundation for the ANT analysis is based on my internship at the case company during the autumn of 2024, where I conducted observations and interviews with central actors. This data collection has been supplemented by additional research conducted throughout the thesis project.

ANT has also supported my work with LCA, as the mapping of the network and the insight into actors' practices has provided valuable input for screening their current activities and identifying relevant environmental trade-offs.

2.2 Life Cycle Assessment as an Analytical Framework

LCA is not only a method for quantifying environmental impacts, but also an analytical framework that structures how environmental problems are understood and assessed. By evaluating resource use and emissions across all life cycle stages of a product or service, from raw material extraction to final disposal, LCA supports systemic thinking and highlights how environmental burdens may shift between processes, over time, or across geographical locations (Hauschild et al., 2018).

LCA is formally structured into four phases, as defined in ISO 14040 and 14044. These phases include goal and scope definition, inventory analysis, impact assessment, and interpretation. Together, they guide the assessment process and shape what is considered environmentally relevant (Hauschild et al., 2018).

LCA does not simply provide objective results. It reflects a way of thinking that involves both methodological and normative choices. For example, decisions regarding system boundaries, the functional unit, or the treatment of biogenic CO_2 emissions influence the outcome and interpretation of sustainability assessments. Likewise, the distinction between attributional and consequential LCA illustrates two fundamentally different approaches. Attributional LCA describes the environmental profile of a system as it exists, whereas consequential LCA focuses on the broader environmental consequences of changing that system (Weidema, 2003; Bjørn et al., 2018). These perspectives reflect different understandings of responsibility and causality in environmental decision-making.

In this thesis, LCA is used both as a practical tool and as a conceptual lens. On a practical level, it provides a screening-level assessment of handling BSG in the case-study, as described in section 3.4 and analysed in chapter 5. On a conceptual level, LCA is used to examine how methodological assumptions, such as choices about system boundaries, substitution effects, and data sources, influence the sustainability narratives that emerge from such assessments. As discussed in the literature review in section 2.4.2, these methodological choices play a key role in shaping how upcycling initiatives are perceived and evaluated in relation to sustainability.

In this way, LCA is not only a measurement tool but also a means to critically question and frame environmental impacts within the context of innovation and circular economy strategies.

2.3 Supplementary Sustainability Perspectives

2.3.1 Circular Economy and the Waste Hierarchy

The circular economy challenges the traditional linear model, where products are produced, used, and discarded after use. This model is often described as “take-make-dispose.” In contrast, the circular approach seeks to establish closed loops in which resources are kept in use for as long as possible through strategies such as reuse, repair, recycling, and upcycling. This involves both design and business model innovations, aiming to narrow, slow, and close resource loops (Bocken et al., 2016). Closing the loop, for example, means reusing by-products multiple times, thereby reducing the demand for new materials. A practical example of this is the use of BSG in bakery products. In this context, BSG remains within the value chain and reduces The Case Bakery’s need to purchase wheat flour. In doing so, BSG avoids becoming waste and replaces wheat flour, which is a virgin material.

This type of practice is closely related to the waste hierarchy (see figure 1), which prioritizes waste handling based on environmental benefits. At the top of the hierarchy are prevention and reuse, followed by recycling and energy recovery. Disposal is placed at the bottom (Teigiserova et al., 2020). In the past, the spent grain from The Case Brewery was used for biogas production, which corresponds to energy recovery in the waste hierarchy. Today, the grain is used as animal feed, placing it higher in the hierarchy under “reuse,” although still below direct use for human consumption.

The circular economy is also a core element of the European Union’s green strategy. One important aspect is the transition to a circular bioeconomy, where organic residual streams such as by-products from food production are utilized more efficiently. The aim is to minimize waste, reduce greenhouse gas emissions, and generate new economic opportunities (Klitkou et al., 2019). In this context, cross-sectoral collaborations, often referred to as industrial symbioses, play a key role in developing value chains in which waste from one industry becomes a resource in another.

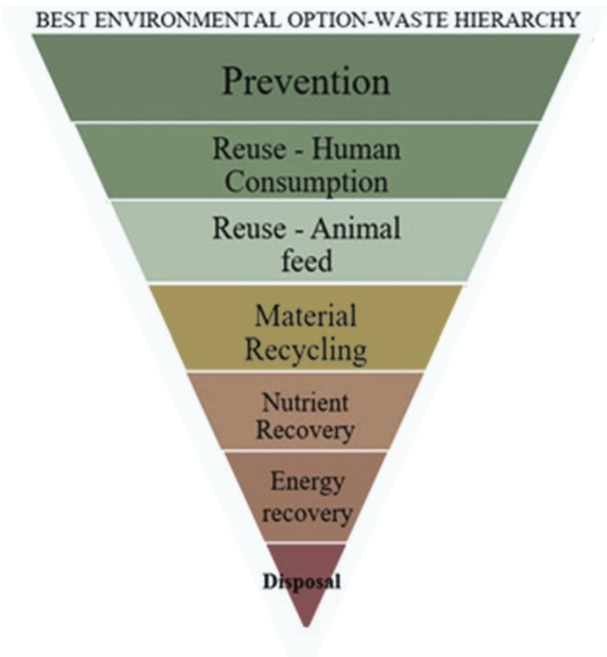

Figure 1Waste Hierarchy: Figure adapted from (Evensen, 2023), based on Teigiserova et al., 2020.

2.3.2 Systems Thinking

To understand and assess circular innovations in their early stages, a systems thinking approach is essential. Systems thinking involves analysing relationships, dependencies, and feedback loops between different actors and elements within a complex system, rather than evaluating them in isolation (Meadows, 2008). In the context of this thesis, this means that a solution such as the upcycling of BSG must be considered not only in terms of material flows, but also in relation to the broader network of actors, including breweries, bakeries, logistics systems, consumers, and policy frameworks.

This perspective is particularly important in circular contexts, where the value and impact of a solution often depend on how well it integrates into existing or emerging loops and infrastructures. Drawing on Meadows' systems thinking, the thesis thus views innovation not as an isolated technical fix, but as part of a dynamic and interdependent system. This approach informed both the design of the empirical study and the development of evaluation criteria.

Systems thinking is operationalised through the use of ANT, which helps trace how technologies, materials, and institutions co-evolve. It also highlights the importance of reflecting on system-level conditions such as feasibility, institutional lock-in, and long-term change dynamics. By doing so, the thesis supports a more holistic approach to sustainability assessment in innovation programs, where early choices may have lasting systemic effects.

2.3.3 Relative vs. Absolute Sustainability

In sustainability assessment, new solutions are often compared with existing alternatives from a relative perspective. This typically means evaluating whether a solution reduces CO_2 emissions or resource use compared to the status quo. Absolute sustainability shifts the focus away from product-level comparisons and instead examines whether the total environmental impact remains within planetary boundaries (Hauschild et al., 2020).

In this report, the environmental assessment of upcycling BSG is primarily based on relative comparisons. However, from an absolute sustainability perspective, it is necessary to ask whether upcycling truly reduces the overall environmental impact to a level that supports climate goals. It should be noted that absolute sustainability is not used here as a quantitative method, but rather as a reflective theoretical framework

Reflections on absolute sustainability can serve as a reality check, helping to decide whether the solution provides improvements only at the product level or whether it is part of a broader and necessary transformation. This perspective also raises questions about whether the solution risks creating lock-in, where it indirectly perpetuates existing, less sustainable practices instead of contributing to genuine system change (Seto et al., 2016).

2.4 Literature Review

To contextualise the case and methods, this section reviews existing research on BSG upcycling and its environmental assessment. The review outlines key strategies for revalorising BSG in food systems, including technological and practical approaches, and summarises the findings and limitations of previous LCA studies. This helps identify current gaps in the literature, particularly concerning early-stage innovations, limited data conditions, and the systemic effects of circular solutions.

2.4.1 Utilization of BSG and Sustainability

BSG is the most prominent by-product from beer production, constituting up to 85% of the total waste generated by breweries (Mussatto, 2014). Globally, it is estimated that up to 36.4 million tons of BSG are produced annually (Nyhan et al., 2023), representing a significant environmental and logistical challenge.
The increasing focus on circular economy and bioeconomy has promoted research into BSG utilization. BSG was traditionally seen as a waste product but is now increasingly regarded as a resource-rich biomass that can be exploited in various industrial and food-related contexts (Jackowski et al., 2020).

Composition and Potential
According to Belardi et al. (2025), BSG consists mainly of fiber and protein, highlighting its nutritional potential. Typically, BSG contains approximately 23% protein and 57% fiber. The fiber content is significantly higher than that found in unmalted barley or wheat, making it well suited for value-added food applications (Nyhan et al., 2023). BSG has traditionally been used as animal feed, which is considered to have low economic and environmental value (Mainardis et al., 2024). For this reason, research has intensified into alternative uses, especially since BSG is cheap, widely available, and can contribute to food security and the fight against hunger, particularly in developing countries (Nyhan et al., 2023).

Examples of alternative uses include the incorporation of BSG into bread, pasta, snacks, and fermented products to increase their protein and fiber content (Petit et al., 2020). Biorefining can also extract valuable compounds such as antioxidants, phenolics, and prebiotics, as well as produce bioethanol, biogas, and biohydrogen (Errico et al., 2023; Pérez-Barragán et al., 2024). At the same time, the fiber-rich structure and biopolymer content of BSG make it suitable as a filler in bioplastics, composites, and building materials. Compared to fossil resources, BSG is considered to have a significantly lower environmental impact in these applications (Visco et al., 2022).

Barriers: Logistics, Shelf-life, and Technological Limitations
The high moisture content of BSG (70–85%) (Mussatto, 2014) represents a major barrier to effective utilization. Because the chemical composition of BSG can vary, and there is a risk of mold and bacterial growth, thorough documentation and process control are required if it is to be used in food products (Lopes et al., 2023). The regulations are strict, which is particularly challenging for small breweries. The short shelf-life (8–10 days) also imposes significant demands on logistics, preservation, and storage (Belardi et al., 2025; Mainardis et al., 2024). Drying can extend the shelf-life but is often energy-intensive and economically challenging. Especially microbreweries often lack the necessary equipment and incentive to develop new uses, as it is still easiest and cheapest to dispose of BSG as animal feed (Bugge et al., 2019).

Additional challenges include variation in chemical composition between batches and beer types, making it difficult to achieve consistency in food production (Belardi et al., 2025; Nyhan et al., 2023). Sensory properties (taste, texture) are also affected, and consumer acceptance is low at high concentrations of BSG in products. Studies indicate that 10–15% BSG in, for example, bread is optimal (Nyhan et al., 2023; Mainardis et al., 2024).

Solutions and Future Perspectives
To realize the potential of BSG as a valuable resource, it is necessary to develop more efficient and sustainable preservation methods, such as using excess heat from brewing for drying (Jackowski et

al., 2020), or fermentation, which can improve both taste and shelf-life (Belardi et al., 2025). Review articles recommend reusing BSG as close to the source as possible to minimize transport and CO_2 emissions. In particular, craft breweries can benefit from technological solutions and partnerships that enable local and sustainable utilization of BSG (Mainardis et al., 2024). Several companies, such as the Danish company Agrain, have already developed foods based on BSG (Nyhan et al., 2023).

Circular Economy and Upcycling: Argumentation and Critique
The increased focus on the circular economy has significantly influenced both research and practice concerning BSG. Where BSG was previously regarded as waste, it is now described as a valuable resource in the transition to a bioeconomy (Errico et al., 2023). Mainardis et al. (2024) argue that craft breweries can increase their sustainability through BSG valorization and integration of renewable energy. However, the articles show considerable variation in how methodically circular economy and upcycling are substantiated. Some studies (e.g., Petit et al., 2020; Jain & Gualandris, 2023) systematically use LCA data to document environmental effects, while others primarily use the circular economy as a visionary or political argument (Visco et al., 2022; Errico et al., 2023).
Jain & Gualandris (2023) emphasize, however, that the climate impact of upcycling BSG and similar by-products cannot be assessed in isolation but depends on several local factors, particularly energy use and transport distances. The article also recommends that companies and decision-makers should not simply follow the waste hierarchy, which places upcycling at the top, when assessing their solutions, but rather consider these local factors and conduct specific LCA analyses to ensure that the solution actually delivers a lower CO_2 footprint than current uses.

2.4.2 Environmental Assessment of BSG Utilisation

Although BSG is a large waste streams in food production and holds significant potential as a resource in the circular bioeconomy, there are still relatively few studies that conduct proper LCA analyses of its utilisation. The few studies that exist explore various applications and have methodological differences, making it difficult to directly compare results. This review examines five selected studies, each of which uses LCA to assess the environmental impacts of BSG utilisation, focusing on which applications are explored, what the results show, and how methodological choices, such as system boundaries and product status, influence the conclusions.

The potential applications of BSG range from traditional uses like animal feed to more technically complex applications like chemicals or food ingredients. In the literature, animal feed is often referred to as a low-value use, but several of the analysed LCA studies show that it is, in many cases, the most sustainable solution in terms of climate impact and resource consumption. This raises the question of whether the current valuation and technological ambition truly reflect the real environmental benefits.

In the study by González-García et al. (2018), a biorefinery model is explored where BSG is used as a raw material for the simultaneous production of bioethanol and xylooligosaccharides (XOS). This solution is highlighted as a high-value use, partly because BSG is cheap and available in large quantities. In contrast, the current use as animal feed is considered a low-value utilisation and is not included in the LCA analysis. This suggests that the authors have judged that technological upgrading is a better solution than animal feed, without directly comparing this in their analysis.

A similar approach is found in Tiwari et al. (2023), where BSG is fermented with microorganisms to produce 2,3-butanediol (BDO), a platform chemical with application potential in industries such as plastics, cosmetics, and pharmaceuticals. BDO is traditionally produced from fossil resources, but the authors highlight that BSG can serve as a more sustainable source of the same substance. Here, BSG is also seen as an underutilised resource, with its current use as animal feed considered economically limited, estimated at around 50 USD per ton, compared to the significantly higher value of BDO. Economic value creation thus forms a central argument for upgrading.

However, the LCA in Tiwari et al. (2023) shows that the production of 1 kg of BDO from BSG results in a climate impact of 7.25 kg CO_2 equivalents when biogenic CO_2 is included. Since biogenic CO_2 is typically considered climate-neutral in life cycle assessments, an alternative result is also reported without this component, where the emissions are reduced to 0.9 kg CO_2e per kg of BDO. The result shows that methodological choices, particularly regarding how biogenic CO_2 is handled, have a significant impact on the environmental assessment. When biogenic CO_2 is included in the analysis, the process appears much more climate-intensive, while the emissions are markedly reduced if it is excluded. This raises the question of whether biogenic CO_2 should always be considered climate-neutral, particularly in systems where biomass is used with high energy consumption or where carbon is only temporarily sequestered.

Other studies attempt to directly compare several different applications of BSG in their analysis, including food, feed, and energy scenarios.

Petit et al. (2020) conducts an extensive LCA of methods for preserving BSG for use in human food, as an alternative to feed or waste management. The study compares ten different stabilisation scenarios, including freeze-drying, freezing, dehydration, lacto-fermentation, and cooling. Reference uses, such as animal feed (for cattle and pigs), biogas, and composting, are also included. The results show that freezing has the highest CO_2 emissions per functional unit, while use as animal feed for cattle results in the lowest impact.

The total energy consumption, particularly in connection with drying and freezing, is identified as the primary driver behind the emissions. Lacto-fermentation is identified as a compromise, as it both provides a relatively low climate impact and better preserves the protein and fiber content of BSG compared to methods like drying. The study shows that the chosen preservation method (e.g., freezing, drying, fermentation) has a significant impact on the overall environmental effect of using BSG as an ingredient in food. At the same time, the analysis reveals that while animal feed is the most climate-friendly solution in this case, it is often overlooked in evaluations of high-value uses, even though it can be both environmentally efficient and practically useful.

Fonseca et al. (2024) assesses the environmental impact of various technological solutions for upgrading BSG, which is at an early development stage (TRL 3). The study uses a prospective LCA approach to identify which technologies have the greatest potential for further development. The analysed platforms include the production of volatile fatty acids (VFA), protein isolates, and biofertilizers, and the results are explicitly compared with a business-as-usual scenario, where BSG is used as animal feed.

The aim is to identify environmental hotspots and assess which parameters need to be improved before the technologies can potentially be scaled up. The analysis points to electricity consumption, chemical inputs, and transport as key impact factors in the new scenarios. At the same time, the results show that animal feed, in its current context, is still the solution with the lowest climate and resource impact. Nevertheless, Fonseca et al. argue that the new technologies are worth further developing, as they potentially offer higher economic value and better nutrient recovery in the long term.

Tiwari et al. illustrates how the inclusion or exclusion of biogenic CO_2 can significantly alter the results. Fonseca also shows that biogas production and the use of BSG as a substitute for natural gas play a crucial role in making the utilisation scenarios appear as sustainable solutions. At the same time, Scherhaufer et al. (2020) points out that the composition of a country's electricity mix is highly significant. A process that is climate-intensive in one geographic area may therefore have a significantly lower impact elsewhere.

However, the results do not only depend on technology or energy consumption. The methodological choices made in the LCA itself also have a significant impact on how the environmental effects are assessed. A central methodological question is whether BSG is considered waste or a by-product. If classified as waste, no environmental impact is typically assigned to the processes that generated it, since waste is traditionally treated as "burden-free" material in LCA (according to ISO 14044). However, if it is considered a valuable product, part of the upstream emissions (e.g., from grain production and brewing) must be allocated to BSG. This significantly affects the overall CO_2e footprint. Of the five studies, only Scherhaufer et al. (2020) explicitly discusses this issue and explains how market value can change a material's status from waste to by-product, requiring changes in the allocation method. However, in their own analysis, BSG is treated like in the other studies as waste, and the environmental impact is only assessed from the point at which the biomass is received.

Finally, it is worth noting that all five studies use an attributional approach to LCA. However, several of them also incorporate assumptions about substitution, where BSG is assumed to replace other products like soy, corn, or fossil fuels. This is particularly seen in the analyses by Fonseca et al. (2024) and Scherhaufer et al. (2020), where the calculated environmental benefits heavily depend on what BSG is assumed to replace. Substitutions of this type are typically part of a consequential approach, which is designed to assess the consequences of changes in the system.

2.5 Multi-Level Perspective (MLP)

While the main analysis is based on ANT and LCA, this thesis also draws on the Multi-Level Perspective (MLP) to discuss the broader structural and institutional conditions that influence the fate of BSG. MLP is a theoretical framework for understanding socio-technical transitions, which explains how changes in complex systems emerge and evolve over time through interactions between three analytical levels (Geels, 2012):

- **The macro level (landscape)** refers to broad structural conditions such as political trends, global climate agendas, and shifts in societal values. These conditions are difficult to influence directly but can create 'windows of opportunity' for new solutions.

- **The meso level (regime)** represents the dominant system, including established practices, policies, technologies, and actors' behavior. Regimes tend to be stable and self-reinforcing but can be destabilized by pressures from both the landscape and niches.

- **The micro level (niches)** is the arena for innovation. Here, new technologies and practices are developed, which under certain conditions may grow and challenge or complement the existing regime (Geels, 2012).

To understand how niche innovations can grow, I include Strategic Niche Management (SNM). SNM is an approach that focuses on the conditions that must be present in niche experiments for them to evolve and eventually challenge the established regime. According to SNM, this requires especially (1) clear and shared visions, (2) the development of strong networks, and (3) opportunities for experimentation and learning in practice (Geels & Schot, 2008).

In the discussion, MLP is applied to situate the case-study within a broader political and societal context and to analyze how different factors have shaped current management practices for BSG. The aim is to place the empirical findings within a broader structural and societal context and to examine which forces at the landscape, regime, and niche levels have influenced current practices.

Chapter 3: Methods

3.1 Research Design

This thesis adopts a qualitative case study design combined with a mixed methods strategy. The starting point is a concrete and practice-oriented innovation project, in which The Case Company seeks to establish a circular value chain based on the upcycling of BSG in collaboration with a local The Case Brewery and The Case Bakery. The case study enables a contextual and in-depth analysis of both environmental and network dynamics in the early phases of circular food innovation.

Methodologically, the thesis combines qualitative and quantitative elements. The qualitative data were collected through ethnographic methods, including participant observation and semi-structured interviews, supplemented by document analysis. These data are analyzed using ANT, which is applied to understand how actors, materials, and infrastructures interact and negotiate meanings in the construction of the value chain. Simultaneously, LCA is used as a quantitative method to examine the environmental consequences of different uses of BSG. The LCA model was developed iteratively and reflects the evolving nature of the case.

The research design is exploratory and practice-oriented, informed by a participatory approach. I have followed the project closely over an extended period and engaged in ongoing dialogue with key actors. Certain aspects resemble action research, particularly in terms of continuous interaction with the involved stakeholders, but the approach is primarily analytical rather than interventionist. A more in-depth reflection on my role and the degree of participation is provided in the reflection (Chapter 9). This participatory approach has provided access to deeper insights into network dynamics, decision-making processes, and implementation challenges that would not have been accessible through classical desk research alone.

By combining ANT and LCA with empirical insights from the case, this thesis contributes to the development of new evaluation criteria for circular innovation projects that better account for system effects, network dependencies, and uncertainties in early-stage innovation.

The Combination of ANT and LCA in Existing Research

There are only a very limited number of studies that combine ANT and LCA. A targeted search in Scopus identified five articles, of which two are relevant for this project as they attempt to integrate the methodological approaches in relation to the circular economy. Niero et al. (2021) argue that LCA alone is not able to make unintended effects of circular economy initiatives visible and actionable. They therefore propose a combination with ANT and practice theory to analyze how socio-technical networks shape both outcomes and unintended consequences. In continuation of this, Niero (2023) presents a conceptual framework that combines LCA, Material Flow Analysis and ANT for the assessment of packaging solutions. Here, it is highlighted how ANT contributes to understanding actor dynamics and conflicts in the implementation of regulations.

As outlined in Chapter 1, there is a clear gap in the existing literature regarding the integration of environmental assessment methods such as LCA with qualitative analyses of actor-network dynamics in early-stage circular food innovations. By combining ANT and LCA in this thesis, I address this gap and provide new empirical insights into both the environmental and socio-technical dimensions of circular value chain development. This combined approach not only responds to recent calls in the literature but also contributes methodologically by operationalizing this integration in a concrete empirical context.

3.2 Ethnographic Methods

Ethnography is a qualitative method used to gain in-depth insights into people's practices, experiences, and social contexts (Coffey, 2020). In this study, I have used ethnographic methods such as participant observation and semi-structured interviews to understand the social and organizational conditions surrounding the use and valuation of BSG. The practical challenges and decisions that arise due to food safety requirements, for example, have directly impacted the environmental impact of the project. The ethnographic observations have provided insights into logistical and social barriers related to the upcycling of BSG, which would not have been accessible solely through literature studies.

Fieldwork has been conducted in collaboration with The Case Company, which I have followed closely throughout my thesis. I have had access to the company's office and partners, and we have had ongoing contact via email, phone, and Slack. My fieldwork has included participation in meetings, visits to the project's freezer container, attendance at the Loop Forum, and conducting semi-structured interviews (see Appendices). The interviews are inspired by open and exploratory questions focusing on gathering data about the actors' experiences, values, and actions regarding BSG and circular economy.

I have observed both physical and online meetings, where I took field notes, which were handwritten during physical meetings and either handwritten or digital for online meetings. These notes have been an important part of my data foundation and have helped me identify practices, decision-making processes, and challenges in handling BSG.

My role has alternated between being a passive observer to understand the participants' perspectives and being more active in other contexts where I asked clarifying questions and provided feedback. In some cases, I have thus acted as 'The Observer as Participant', and in others as 'The Participant as Observer'(Coffey, 2020).

My relationship with the case goes back to the fall of 2024, when I interned at the same company. Here, I gained insight into the local conditions and the project's original idea of upcycling BSG into food production. At that time, the project was mainly at the conceptual stage. Throughout spring 2025, I have been able to follow how the project gradually moved from idea to practice and the barriers that arose along the way.

Data from interviews and observations have helped shed light on the systemic conditions and have supported both the development of evaluation criteria for the Closing Loops project and the development of the LCA screening (see Appendix 2, 3, 4 og 5)

3.3 Literature Search and Review Approach

The literature search in this thesis has been an iterative and central part of the overall project process. The aim of the search was to identify previous research related to BSG, upcycling, circular economy, and the environmental assessment of novel applications, with a particular focus on LCA studies.

I primarily used the Scopus database for the literature searches and RefWorks as a reference management tool to sort and select materials by screening abstracts. Primo was mainly used to access and retrieve the full texts for reading. The search strategy was refined continuously throughout the project, and I also employed snowballing to identify additional relevant literature—i.e., reviewing the reference lists of key articles and authors to locate related work.

Two main searches form the backbone of my literature review:

- **Search 1**:
  "spent grains" OR BSG OR "brewer's spent grain" AND "circular economy" AND upcycling OR valorization OR valorisation
  This search yielded 61 results and was conducted to explore academic applications and the potential for BSG-based upcycling.

- **Search 2**:
  "life cycle assessment" OR LCA AND "brewer's spent grain" OR "spent grains" OR BSG
  This narrower search generated 20 results, of which five articles were selected for in-depth analysis. The focus here was to identify studies that had conducted explicit LCA analyses of BSG in various contexts, such as food ingredients, raw materials for biochemicals, or in biogas production.

The literature search provided a solid foundation for the analysis and served as a way to map the field of research, identify gaps in the existing literature, and position my own contribution in relation to current knowledge.

3.4 Life Cycle Assessment Methodology

In this thesis, a screening-level Life Cycle Assessment (LCA) was conducted to evaluate the environmental consequences of upcycling BSG at The Case Brewery, compared to the current practice of giving it to a local farmer as animal feed. The purpose of the LCA is to provide indicative insights during the early stages of innovation, where data is limited and uncertainty is high. The results are not third-party verified and are primarily intended to support internal reflection and future decision-making.

Two complementary LCA approaches were applied:

- **Attributional LCA (aLCA)** was used to quantify the direct environmental impacts associated with handling BSG for human food production. This includes collection at The Case Brewery, packaging in plastic containers, short-distance transport to the freezing container and electricity consumption for freezing (see Appendix 7).

- **Consequential LCA (cLCA)** was used to assess the broader environmental consequences of diverting BSG from its current use as animal feed to human food. The model reflects the current baseline, in which a local farmer collects BSG in reusable plastic containers and transports it to a nearby farm for use as livestock feed. In the upcycling scenario, this collection is avoided, but the associated feed value of BSG must be replaced within the animal feed system. To account for this, the model includes two substitution scenarios:
  (1) one where BSG is replaced by a mix of rapeseed cake and corn silage, chosen to match its

protein content, and
(2) another where it is replaced by soybean meal.
The latter scenario includes a marginal input modelling approach, where Argentina is assumed to supply the additional soybean meal, and Brazil is included in a sensitivity analysis.

The substitution scenarios used in the LCA are based on information from interviews with farmers, who states that BSG typically replaces the protein component in the feed, such as soy or maize (see Appendix 2 and 3), as well as VKST (2022), who describes an alternative composition.

These approaches reflect different perspectives on environmental causality and system boundaries, as described in section 2.2. Using both allows for a more nuanced understanding of the environmental implications of changing how BSG is handled.

The LCA model was developed using the software tool SimaPro, with background data sourced from the Ecoinvent 3.9.1 database. Where available datasets were selected based on geographical relevance to Denmark or Europe. The analysis follows a gate-to-gate approach in both models.

The declared unit in this study is 1 kg of dry-weight stabilized BSG. While the analysis does not define a fully functional unit across different end uses, adjustments have been made in the consequential model to match the protein content of BSG with that of the substituted feed components. This allows for a more functionally relevant comparison in terms of nutritional value within the animal feed system.

Excluded Processes

Several supporting processes have been excluded from the model due to lack of available data. These include cleaning and disinfection of containers, brewery-level sanitation processes, noise insulation materials for the freezing container (see Chapter 4), and the production and delivery of the container itself. While these exclusions are consistent with the screening-level scope of the study, it is worth noting that most of them relate to the logistics associated with upcycling, and that cleaning requirements are likely more intensive in the human food scenario than in the animal feed scenario, where containers are typically only rinsed with water.

Marginal Input Modelling

In the consequential LCA, marginal input modelling is used to reflect likely market responses to changes in feed demand resulting from the upcycling of BSG. Following the principles of consequential modelling (Weidema, 2003), the marginal supplier is defined as the actor most likely to expand production in response to increased demand.

Argentina is selected as the primary marginal supplier of soybean meal, based on both established literature and recent trade data. Dalgaard et al. (2008) identify Argentina as a likely marginal producer due to its large export capacity, rapid historical expansion of soybean cultivation, and use of transgenic no-till farming systems.

To validate this choice with current data, recent trade reports show that Argentina's share of EU soybean meal imports increased by 117% between 2023/24 and 2024/25, rising from 20.5% to 35.8%. In the same period, Brazil’s share declined, suggesting that Argentina is becoming a more responsive supplier to the European market (SunSirs, 2025).

In addition, a sensitivity analysis is conducted using soybean meal from Brazil (Scenario B2). This reflects the approach of recent attributional LCA studies, such as Fonseca et al. (2024) and Scherhaufer et al. (2020), where Brazilian soybean meal is used as a reference product in substitution calculations. Including both regions allows for a more robust understanding of how marginal assumptions influence the results.

Iterative Model Development and Case Integration

The development of the LCA model followed the practical evolution of the case. As the project progressed from the idea stage to real-world implementation, the model was continuously updated with new information and more precise data. Close contact with the case-study and ongoing data collection made it possible to adjust both assumptions and system boundaries. This iterative process aligns with the flexible nature of LCA, where findings from one phase often inform revisions in earlier stages (Hauschild et al., 2018).

Chapter 4: Analysis Part 1 - Network Dynamics (ANT)

In this chapter, I apply ANT to examine how BSG is negotiated and transformed as an actor within the network of the value chain collaboration, and which socio-technical conditions that shape it. The analysis is structured around sub-question 1 and constitutes the answer to this question. The answers to the identified sub-questions are gathered and discussed in the synthesis and conclusion chapter.

4.1 Actor-Network Theory (ANT) Analysis

This section presents an ANT-based analysis of the value chain collaboration that has developed between the The Case Bakery, The Case Brewery and The Case Company. The analysis builds on a comprehensive network mapping (see Appendix 1) that identifies key human and non-human actors involved in the upcycling of BSG. The analysis follows how actors engage, translate and negotiate their roles in the network. Two figures are used to support the analysis. Figure 2 presents how different actors value BSG according to their respective positions in the network. Figure 3 highlights the controversies related to the logistics and handling of BSG.

BSG as an Active Actor and Translation Point

BSG is not merely a by-product in this network but an active actor whose role is continuously being negotiated. At the The Case Brewery, BSG is primarily seen as a material to be disposed of quickly and cheaply, often through donation to a local farmer. At the The Case Company, BSG is viewed as a valuable resource and the foundation for a new business model. At the The Case Bakery, BSG becomes an ingredient for producing nutritious and flavourful bread. Prototypes have been tested, and the The Case Bakery has selected one specific BSG composition, referred to as BSG-H (where H stands for human consumption), to incorporate into sourdough bread, with the intention of scaling up to other baked goods.

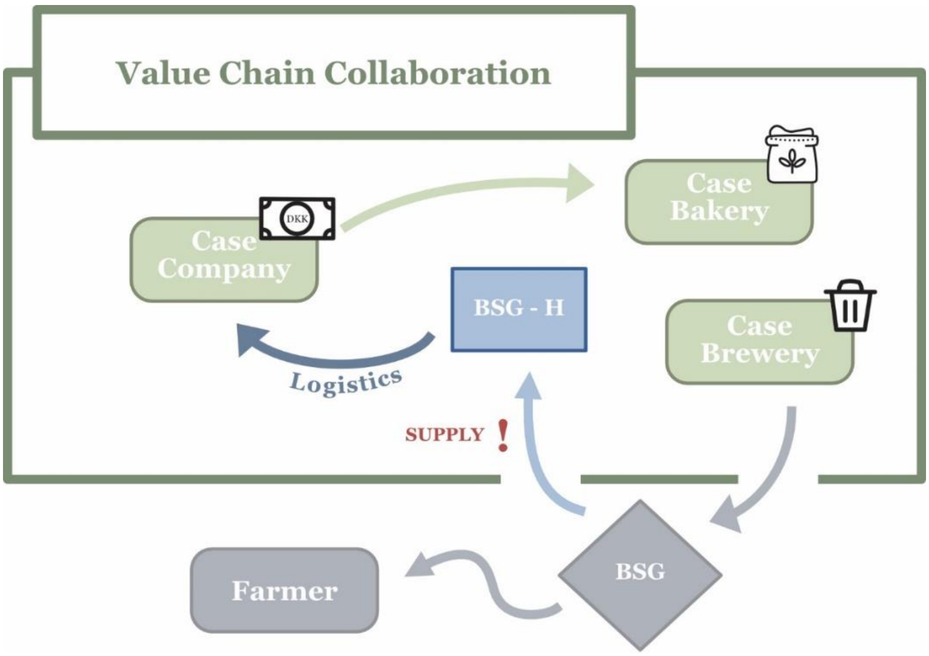

Figure 2 ANT- Value Chain Collaboration

Figure 2 illustrates how the three key actors attribute different values to BSG depending on their position in the network. It also highlights an emerging controversy related to supply, as the The Case Bakery only accepts BSG-H and not all other variants (see Appendix 7).

BSG is thus translated variously as waste, opportunity, food ingredient and occasionally as a problematic actor, for instance when its handling leads to complaints from neighbours due to noise. These translations are not just discursive but have direct practical implications. They shape requirements for handling, define which actors must be involved and influence how the network is organised around the material.

Non-Human Actors as Boundary Objects and Limiting Factors

ANT allows non-human actors to be viewed as co-shapers of action. Technologies such as freezer container, storage units and collection bins are not passive infrastructure but active elements that determine what can or cannot happen. BSG leaves The Case Brewery hot and moist, at around 65°C, and must be cooled below 10°C within four hours to avoid mould growth. This creates logistical and infrastructural demands.

Figure 3 maps the key controversies surrounding BSG logistics, including infrastructure, regulation and local resistance.

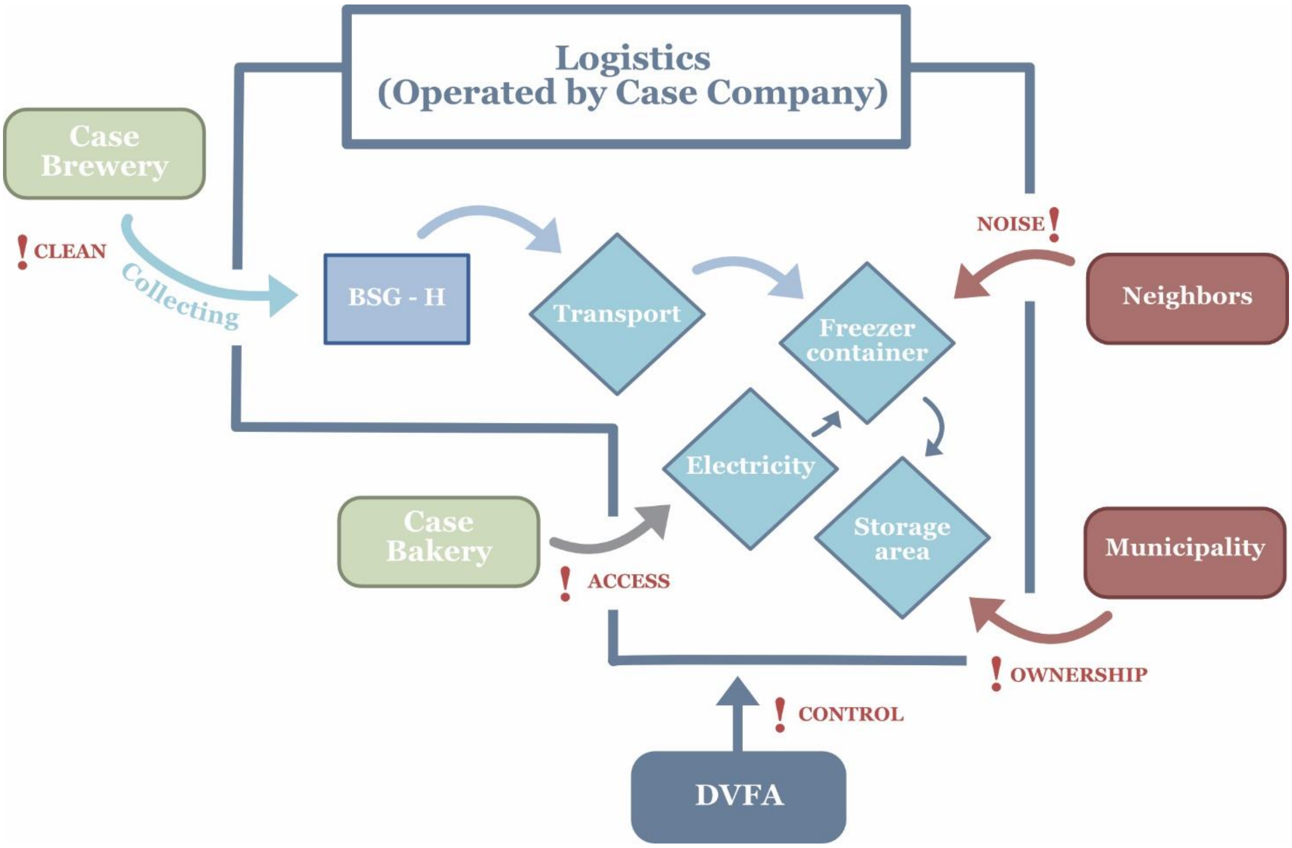

Figure 3 ANT- Logistics

Food safety requirements shape the network in significant ways. The Danish Veterinary and Food Administration (DVFA) sets hygiene standards for human consumption that directly influence how the logistics around BSG must be organised. These regulations include procedures for cleaning, the ability to disinfect all surfaces that come into contact with BSG, and ensuring that the material is cooled to below 10°C within four hours after leaving the The Case Brewery.

To meet these requirements, specific technologies must be in place. The The Case Brewery's infrastructure must therefore support not only production but also regulated hygiene workflows. Similarly, the The Case Company s entire logistical setup, from cooling containers to transport, must comply with these standards. This places material and procedural demands on the network, limiting which breweries can participate and constraining how the system can scale.

Rather than serving as background rules, food safety regulations function as active non-human actors that condition what is possible within the network. Their presence reinforces how logistical infrastructures and institutional frameworks co-shape the collaboration

Furthermore, local complaints about the noise from the cooling container show how technological solutions can activate new controversies and bring in unexpected actors. Neighbours living close to the logistics site have complained about noise levels, which has prompted The Case Company to develop a physical design intervention around the cooling container to reduce the sound impact. The site on which the container is located is owned by the municipality, and although current use is permitted, there are future, not-yet-finalised development plans for the area that could require The Case Company to relocate or redesign its logistics setup in 2026.
This creates a dual vulnerability. On one hand, local residents may escalate pressure if the noise issue remains unresolved. On the other, municipal decisions about land use could force changes to the logistics infrastructure. The result is that the network's logistical node is embedded in a material and regulatory uncertainty, with both social and institutional actors having the power to destabilise or transform it.

Scaling and the Fragility of Translations
These infrastructural and social dependencies illustrate how fragile the network can be. Although the value chain collaboration has been formalised through Closing Loops and supported by project funding, the network is still in a process of continuous change. ANT highlights how networks must be constantly maintained through coordination and translation. This is especially evident in this project where the flow of BSG is closely tied to The Case Brewery's production cycles and The Case Bakery's needs.

The Case Bakery only wants BSG-H, a specific composition that meets quality requirements for human consumption. This introduces a supply-related controversy, as not all BSG produced by The Case Brewery qualifies as BSG-H. As a result, The Case Brewery must continue producing certain types of beer, even if these are not in current market demand. This adds tension to the system. The Case Company's plan to scale up deliveries increases the dependence on the The Case Brewery's production capacity and creates potential instability. If new breweries are to be included in the network, their routines, materials and hygiene practices might differ, requiring a new round of negotiation and coordination.

It is important to clarify that BSG is not surplus waste but rather an unavoidable residue. This matters especially when discussing sustainability outcomes. If BSG gains value as a resource, there is a risk that beer is produced not because it is needed but because the by-product is wanted. This could unintentionally encourage overproduction or prevent more radical rethinking of beer production methods. In this way, sustainability goals may be undermined by market incentives to preserve or even increase the waste stream.

In addition, The Case Company relies on The Case Bakery for electricity to run its cooling infrastructure, having physically tapped into The Case Bakery's power supply. This creates a dependency beyond logistics, as The Case Company is reliant on The Case Bakery's ongoing goodwill. This infrastructure-sharing adds a layer of social and operational vulnerability to the collaboration, where personal relationships and continued alignment become crucial for maintaining the network.

Conclusion: A Network in Constant Translation

The ANT analysis demonstrates that the collaboration around upcycling BSG is not a linear or purely technical process but a network in constant negotiation. Materials, technologies, regulations and actors interact to shape what is possible, and what becomes problematic. BSG itself plays multiple roles ranging from waste and ingredient to point of conflict and cannot be understood in isolation from the network that supports and constrains its movement.

Upcycling only becomes possible when the material, social and institutional conditions are aligned. This alignment, however, is temporary and constantly tested by logistical constraints, regulatory demands, actor interests and environmental factors. The network is thus never stable but must be actively maintained and adjusted, with stability emerging only through the continuous coordination of people, technologies and practices.

Chapter 5: Analysis part 2 - Environmental impacts (LCA)

5.1 Life Cycle Assessment (LCA) on Case-study: BSG valorisation

Building on the screening-level LCA methodology described in Section 3.4, this section presents the results of both attributional and consequential models developed for the upcycling of BSG. The attributional LCA quantifies the direct environmental impacts of handling BSG for food use, while the consequential LCA assesses broader market-based consequences of diverting BSG from animal feed to human consumption.

5.2 Attributional LCA

This section evaluates the direct environmental impacts associated with handling and processing BSG into food ingredients. A gate-to-gate approach is used, which includes the collection of BSG at the The Case Brewery, transport to a freezing container, electricity usage for cooling, and the use of plastic containers for storage and delivery.

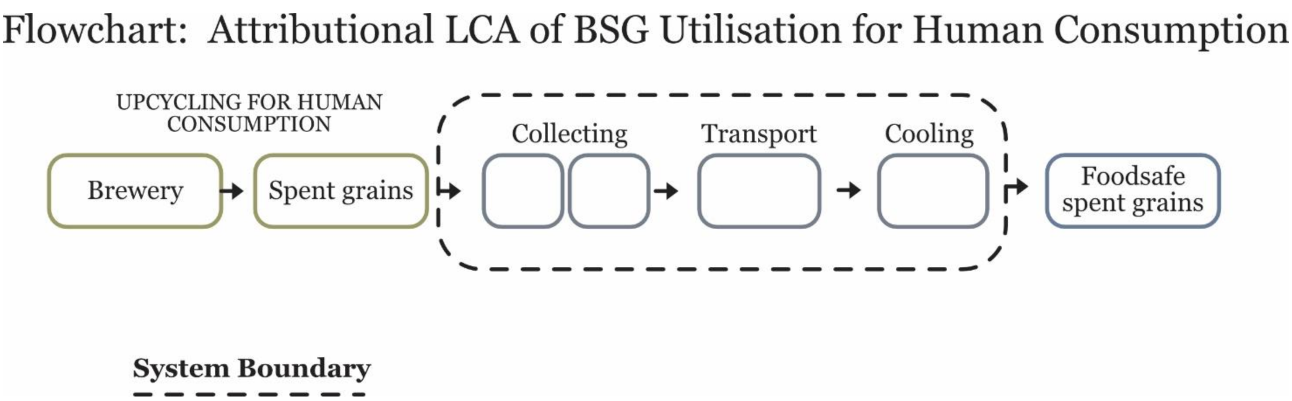

Figure 4 Flowchart: aLCA

Declared unit: 1 kg dry-weight stabilized BSG.

Data and Assumptions

- **BSG quantity:** An average monthly volume of 650 kg wet BSG corresponds to approximately 162.5 kg dry matter, based on an estimated dry matter content of 25%.
- **Transport:** BSG is transported by passenger car over a distance of 1.1 km per trip (two trips per collection).
- **Plastic containers:** Two large HDPE containers (50 kg each, 200-use lifespan) and smaller PP boxes (900 g, 75-use lifespan) are used. The weight of the large containers is based on a datasheet, while the small containers are estimated.
- **Electricity use:** Estimated based on The Case Company's monthly budget, as no electricity meter is yet installed.

Results

The total climate impact of upcycling BSG in the attributional LCA is 2.05 kg CO_2-eq per kg dry BSG, of which 2.01 kg CO_2-eq stems from electricity consumption for freezing.

Although the attributional LCA does not allow for a comparative assessment, it is worth noting that BSG is intended to partially replace wheat flour in bakery applications. For context, wheat flour has an average climate impact of 1.04 kg CO_2-eq per kg dry matter. However, these values are not functionally equivalent, and attributional LCA cannot be used to assess the consequences of such a substitution.

5.2.2 Consequential LCA

The consequential LCA assesses the broader environmental impacts of diverting BSG from its current use as animal feed to food production. It accounts for the market-based consequences of removing BSG from the feed system and the need to substitute its nutritional value with other feed components.

The model includes the same transport and freezing steps as in the attributional approach. The farmer's handling and transport are not part of the upcycling scenario but are credited as an avoided burden in the consequential model. Instead, the system accounts for the production and transport of substitute feed. A gate-to-gate boundary is applied, and electricity is modelled using long-term marginal data to reflect a future shift toward lower-carbon technologies

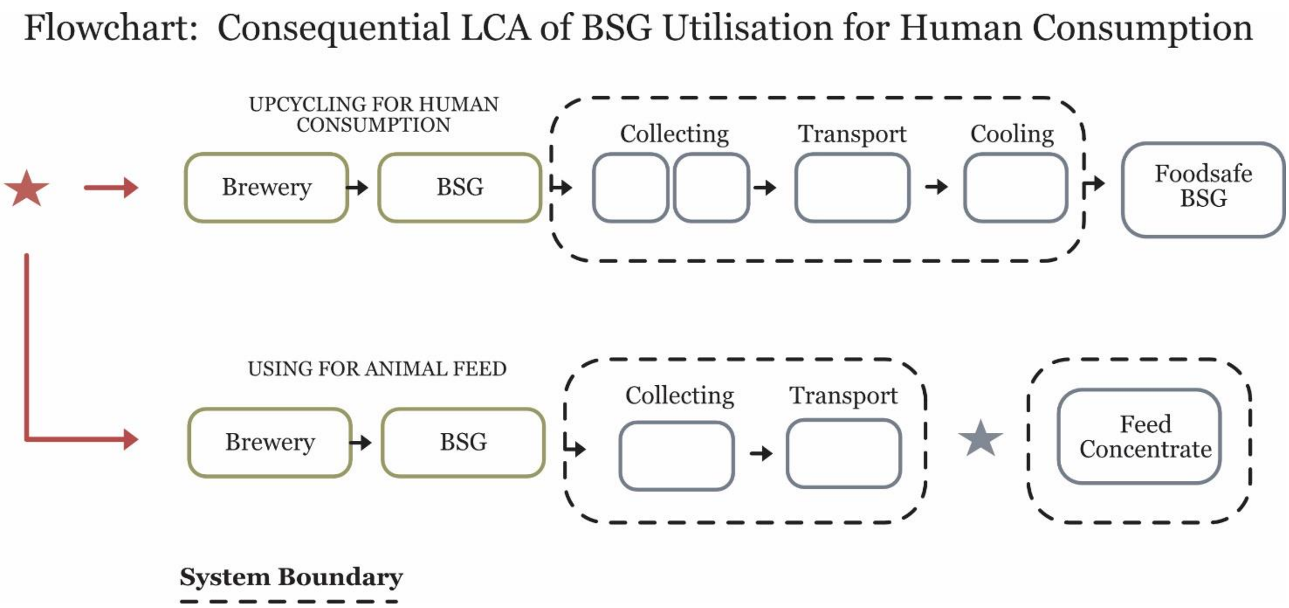

Figure 5 Flowchart: cLCA

Declared unit: 1 kg dry-weight stabilized BSG.

Data and Assumptions

- **Electricity and containers:** Same assumptions as aLCA.
- **Substitution scenarios:**
    - **Scenario A:** Substitution with 2/3 rapeseed cake and 1/3 corn silage (approx. 23% protein).
    - **Scenario B1:** Substitution with soybean meal from Argentina, based on marginal input modelling (see Section 3.4). To ensure comparability with Scenario A, the protein content of soybean meal has been adjusted to match 23 percent.
- **Farmer handling:** Modelled as 20.7 km transport with a small truck and use of large 50 kg HDPE containers.

Results

- **Scenario A** results in 1.34 kg CO_2-eq per kg BSG, primarily from feed production.
- **Scenario B1** results in 3.41 kg CO_2-eq per kg BSG, largely driven by soybean production and associated land use change. Electricity contributes only 0.426 kg CO_2-eq, showing that power use plays a smaller role due to greener marginal electricity assumptions.

As in the attributional model, it is relevant to consider that BSG replaces flour in The Case Bakery. Wheat flour has a reported emission of 0.64 kg CO_2-eq per kg dry matter (RoW average). However, BSG and flour are not functionally equivalent, and the amount of BSG needed depends on specific recipes. A meaningful comparison would require modelling a full bread recipe and defining a functional unit based on product performance when data is available.

Sensitivity Analysis: Brazil as Alternative Supplier

To explore the effect of marginal supplier choice, a sensitivity analysis was carried out where soybean meal from Brazil was used instead of Argentina (Scenario B2). Brazil is commonly used as a reference country in attributional LCA studies (see Section 2.4.2) and is among the major exporters of soybean meal globally. Although Denmark imports soybean meal from Brazil and Argentina, much of the trade occurs through re-exporting countries such as the Netherlands, Germany, and the UK (Energistyrelsen, 2022), making the true country of origin difficult to trace. This introduces uncertainty, especially in modelling transport distances, which may be underestimated in Scenario B2.

For Scenario B2, additional transport was modelled to reflect a more complete supply chain: 10,000 km of ocean freight from Brazil, followed by 300 km of truck transport from Aarhus Port to Copenhagen. In contrast, Scenario B1 (Argentina) is based on a RoW dataset that includes embedded transport.

- **Scenario B2** results in a total climate impact of 0.994 kg CO_2-eq per kg BSG, which is substantially lower than in Scenario B1.

The significant difference in climate impact between soybean meal from Argentina (Scenario B1) and Brazil (Scenario B2) can be primarily attributed to differences in land use change emissions. In Scenario B1, 2.81 kg CO_2-eq per kg BSG stem from land transformation, while the same figure in Scenario B2 is only 0.387 kg CO_2-eq.

Although Argentina was selected as the marginal supplier based on literature (Dalgaard et al., 2008) and datasheets, which highlights the use of no-till farming and a high export capacity, the Ecoinvent data used in this study indicate significantly higher land use change (LUC) emissions for soybean meal from Argentina compared to Brazil.

While no-tillage systems are commonly used in Argentine soybean production and can reduce emissions related to soil disturbance during cultivation, they do not eliminate emissions from land use change if soybean expansion occurs on land with high carbon stocks. In this study, the Ecoinvent dataset attributes significant LUC emissions to Argentine soybean meal, suggesting that the production is assumed to occur on previously uncultivated land, such as natural grasslands. Thus, the environmental advantage of no-till practices is outweighed by the impact of initial land conversion in the consequential modelling. This illustrates how modelling assumptions in life cycle inventory databases can deviate from published assumptions or national farming practices, highlighting the importance of sensitivity analysis in consequential LCA.

Chapter 6: Development of Supplementary Assessment Criteria

6.1 Development of the Assessment Criteria for Closing Loops

The current assessment criteria in Closing Loops focus primarily on measurable effects such as CO_2 reduction, waste minimization, and likelihood of implementation (see section 1.3). This approach works well for more mature projects with clearly documented outcomes but often falls short in innovation projects where solutions are still under development and effects are not easily quantifiable.

There is therefore a need for additional qualitative and systemic assessment frameworks that can account for factors such as the level of innovation, scaling barriers, and potential unintended system effects. Findings from the case study in this thesis show that circular solutions which initially appear sustainable from a narrow, effect-based perspective may, upon closer analysis, lead to rebound effects, lock-ins, or shifts elsewhere in the value chain. This underlines the need to expand the assessment framework to better capture the dynamics and complexities of early-stage innovation projects.

Based on the case study and analysis, I have developed a set of supplementary assessment questions that translate the complex issues from ANT and LCA perspectives into a format that can be used in practice by applicants and review panels. These questions are designed to be scored on a high/low scale and can be integrated into the existing points system of Closing Loops. The aim is not to replace the current criteria but to complement them, so they better reflect the types of effects seen in early innovation efforts.

6.2 Justification for the Selection of Assessment Categories

Network maintenance and dependencies

The ANT analysis shows that collaboration in circular innovation projects is not something that is established once and for all. It is an ongoing process of negotiation between people, materials, technologies and infrastructures. The case study illustrates how even small changes in production, logistics or partner requirements can disrupt the network the solution relies on.

In the BSG project, the network was influenced by several factors. The The Case Brewery's production schedule, variations in the composition of BSG, food safety regulations and storage needs all had an impact on how the collaboration could function. These factors highlighted that value chain cooperation requires continuous coordination and adjustment. A good idea and clear division of tasks are not enough if the actors involved are not prepared to manage practical interdependencies and mutual adaptation.

There is therefore a need for an assessment criterion that focuses on the project's understanding of its collaborative foundation. This criterion should support the evaluation of how the network is maintained and whether the actors are aware of the dynamics and vulnerabilities that may affect the stability and feasibility of the collaboration.

Holistic environmental impact

The LCA screening in the case study shows that environmental impacts are not necessarily tied to the material being recycled, but often to the resources and practices required to make the solution work. In the BSG project, it was not the by-product itself that caused the environmental burden, but rather the need for freezing, transportation and the consequences of shifting BSG from one value chain to another.

This points to an important perspective in assessing circular solutions. It is not enough to focus on what the solution replaces or how much waste it reduces. It is also necessary to consider what is required to implement it. Energy-intensive technologies, work processes and supporting infrastructure can contribute significantly to the overall environmental footprint, even if these elements are not always considered in estimates of CO_2 or waste reduction.

There is therefore a need for an assessment criterion that supports a holistic understanding of environmental impact. This criterion should emphasize both the environmental benefits the solution generates and the resources it requires to function in practice.

Systemic consequences

The consequential LCA and the analysis of system boundaries show that environmental gains in one part of a system can lead to environmental burdens in another. When a resource already in use is redirected to a new value chain, this creates shifts that may have significant ripple effects. In the case study, BSG was already being used as animal feed. When that waste stream is instead used for food production, its original function must be replaced, often by other resources that may carry a higher environmental footprint.

This issue becomes especially important when the solution is scaled up. The more BSG is used in food production, the greater the pressure on its original use, and the more significant the indirect consequences become. What may seem like a minor shift in a pilot project can have real impacts on the market, environmental load and overall resource allocation when scaled.

There is therefore a need for an assessment criterion that emphasizes the project's ability to identify and reflect on systemic consequences. This criterion should support the evaluation of how the solution affects other parts of the system and whether it unintentionally displaces existing functions that have environmental value.

Rebound effects and lock-in

The ANT analysis and the reflections on absolute and relative sustainability show that circular solutions do not automatically lead to real sustainability, even if they reduce waste or improve certain parts of a value chain. When waste gains economic value, it can create new incentives that maintain or even reinforce the production processes that originally generated the waste. Instead of transforming the system, there is a risk of stabilizing it in a new form.

In the case study, demand emerged for a specific type of BSG that only results from brewing certain types of beer, which are currently produced in small quantities. The solution therefore risks creating incentives to maintain or increase the production of that specific type of beer, not due to demand for the beer itself, but because of the value attached to the resulting waste stream in the circular project. In this way, BSG becomes not just an unavoidable by-product, but a desirable resource in its own right.

There is therefore a need for an assessment criterion that encourages reflection on whether the project is driven by demand for waste streams and whether it risks reinforcing production systems that should be challenged. This criterion should support the evaluation of whether the solution contributes to genuine system change or inadvertently becomes part of the problem it seeks to address.

Presentation of the assessment criteria
The table below presents each criterion along with guidance for assessment and practical reflection questions for applicants.

Assessment Criterion	**Evaluation Guidance (for scoring)**	**Applicant Questions (guidance)**
Network maintenance and dependencies	**High score**: The project demonstrates concrete insight into dependencies and necessary collaborations, and shows understanding of how the network must be coordinated and maintained. **Low score**: The project assumes that the network is stable and does not explain how collaboration will be sustained.	Which actors and technologies does your solution depend on? What happens if one actor changes their practices? How do you ensure coordination and adaptation within the value chain collaboration?
Holistic environmental impact	**High score**: The project considers total environmental impacts throughout the entire process, not only the expected savings at the end stage of the solution. **Low score**: The focus is solely on expected CO_2 or waste reductions, without reflection on the resources and technologies required to implement the solution.	What resources and processes does your solution require to function in practice (e.g., energy, transportation, refrigeration, packaging or cleaning)? Are there environmental impacts associated with your solution that may not be reflected in CO_2 or waste reductions, such as energy use, toxicity, resource consumption or effects on biodiversity?
Systemic consequences	**High score**: The project demonstrates awareness of whether materials or by-products are already in use elsewhere and understands the potential shifts and indirect environmental effects that may result. **Low score**: The project ignores whether it redirects resources from existing uses or creates imbalances in other value chains.	Do your materials already serve a function today, such as animal feed, fuel or inputs in another value chain? If so, what happens when you redirect the material to your solution? Could this create new needs, imbalances or environmental burdens in the system the material is taken from?

Rebound effects and lock-in	**High score**: The project demonstrates an understanding of how the solution may influence consumption and production in the long term. It reflects on whether the solution depends on waste or by-products that may eventually disappear, be avoided or reused in other ways in a more sustainable future. The project considers whether it contributes to long-term transformation or risks locking in systems and resources that should be phased out. **Low score**: The project does not consider how it may affect future waste or by-product streams and does not reflect on whether the solution is viable in a system where these residual resources are reduced or eliminated.	Is your solution dependent on waste or by-products from another production process? What role does your solution play if the waste stream you work with is reduced or managed differently in the future? Does your solution contribute to a transition toward less waste and fewer by-products over time?

Chapter 7: Diskussion

7.1 Regime transition and support for biogas

In recent years, there has been a significant shift in how BSG is used in Denmark. While it was previously mainly used as animal feed in local agriculture, an increasing share is now directed toward biogas production, particularly by larger industrial breweries (VKST, 2022). This development can be understood as a regime transition, where a former niche technology, namely biogas, has entered the established system. To analyse this movement, the Multi-Level Perspective (MLP) is used in combination with Strategic Niche Management (SNM), which illustrates how technologies mature through access to networks, experimentation and political support (Geels & Schot, 2008).

In Denmark, these three conditions have largely been fulfilled for biogas. The 2020 Climate Action Plan and the EU's Green Deal have established clear visions for phasing out fossil fuels and set quantitative targets for the role of biogas in the energy transition. At the same time, biogas projects have gained access to research funding and subsidy schemes, including a 20-year support period, which has made investments attractive (Klima-, Energi- og Forsyningsministeriet, 2020). Networks across industry, politics and research have actively worked to disseminate the technology. Altogether, this has created a "window of opportunity" for biogas, making it possible for the technology to move from niche to regime.

The Russian invasion of Ukraine in 2022 has reinforced this development, as it has led to increased focus on energy security and the need for independence from foreign natural gas (IEA, 2022). This has given biogas a strategic role in the phase-out of natural gas and the promotion of energy security.

At the same time, economic incentives have contributed to making biogas production more competitive than other uses of BSG. As gas prices rise and attractive subsidy schemes are introduced, biogas plants are increasingly able to pay high prices for organic residues. According to VKST (2022), several farmers find it difficult to compete for the price of BSG, which in practice means that the agricultural sector is being displaced as a recipient. This results in a shift in use, where the feed role is weakened in favour of energy extraction (see Appendix 3).

This shift can be seen as the result of structural and political drivers, where for example the EU's Green Deal and the desire for energy independence following the war in Ukraine have created a 'window of opportunity' for biogas.

As illustrated in Figure 6, these macro-level developments have reinforced the movement of biogas from niche to regime, supported by investments, subsidy schemes and clear climate policy visions. The figure also shows how the previously dominant use of BSG as feed has been challenged, and how biogas is increasingly dominating as a use, while food applications still represent only a limited and experimental pathway.

System effects, value logic and sustainability

With the implementation of the EU's Corporate Sustainability Reporting Directive (CSRD) and the associated reporting standards, new ways of measuring and documenting sustainability have emerged. The focus is largely on measurable improvements in companies' own CO_2 accounts, particularly within Scope 1 and 2. This creates incentives to promote solutions that appear green in accounting but do not necessarily reduce the overall environmental impact.

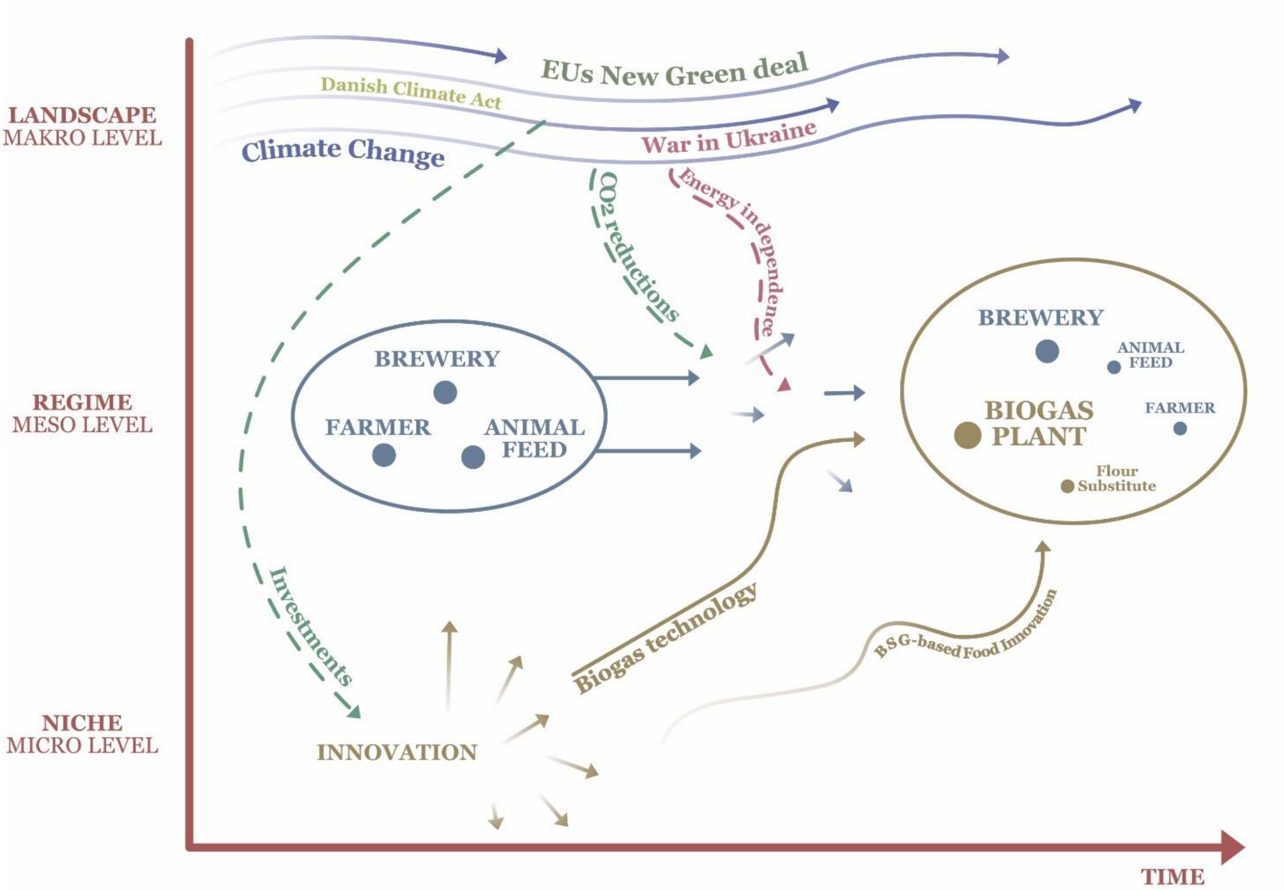

Figure 6 MLP-analysis on BSG utilisation

An example is Royal Unibrew, which has restructured production at a factory in Finland and now uses BSG as biofuel (Royal Unibrew, 2023). This reduces the company's consumption of fossil energy and improves its internal climate accounting. At the same time, BSG is removed from the feed chain, which increases the need for alternative animal feed, often with a higher climate footprint, such as imported soy. Since these indirect effects are not reflected in the company's official reporting, the solution appears more sustainable than it actually is. This is an example of a rebound effect, where an apparent improvement is accompanied by hidden burdens elsewhere in the system.

This issue is linked to a broader development in which BSG is increasingly functioning as a market commodity. When biogas plants can pay higher prices than farmers, a shift occurs in its use, changing the balance between the food and energy systems. This leads to increased imports of protein feed such as soybean meal from South America, which is associated with deforestation, biodiversity loss and significant CO_2 emissions. These emissions are not included in Denmark's official climate accounts, as they are classified as Scope 3 emissions. The Danish Council on Climate Change and other actors have criticised this, as it removes the incentive to choose solutions with lower overall consequences.

According to the EU's waste hierarchy, the use of organic by-products such as BSG for feed should be prioritised over energy use. Food and feed purposes are placed higher in the hierarchy because they utilise resources more efficiently and reduce the need to produce new raw materials. When BSG is used as animal feed, local resource loops are supported and the need for imported protein feed is reduced. Despite this prioritisation, current economic and political frameworks are more supportive of energy recovery such as biogas.

The LCA screening indicates that using BSG as feed could have a lower climate footprint than using it as food, especially when usin handling with high energy consumption and when the substitution effects are considered. Existing literature (see Section 2.4.2) also points out that using BSG for biogas may have higher overall environmental impacts than feed use, especially because it indirectly increases demand for high-emission feed sources.

These insights raise the question of how sustainability should be understood and assessed. If the goal is to stay within planetary boundaries, we must focus on solutions that reduce overall resource consumption and global emissions and not just local improvements or improvements in reporting. When we only focus on what can be documented internally, we lose sight of the systemic consequences. In this context, biogas does not necessarily appear as a final solution, but rather as a displacement of problems within a complex value chain.

It may therefore be relevant to reconsider how feed applications such as BSG are valued in sustainability assessments. Recognising their potential to reduce imports and prevent indirect emissions could offer a more accurate picture of their climate benefits. Such an approach could help guide decision-making toward mitigating environmental burdens at a global scale.

7.2 Backcasting as an Alternative Approach to Sustainable Food Innovation

In this thesis, I have chosen to work with a combination of LCA and ANT to analyse the environmental and network-related aspects of upcycling BSG at an early stage of innovation. An alternative approach could have been to apply backcasting as a methodological framework. Backcasting is particularly relevant in sustainability analyses, where one starts with a desired future scenario and then analyses what societal and systemic changes are necessary to reach that goal (Vergragt & Quist, 2011).

Had I based the analysis on a backcasting approach, it could have been grounded in a future scenario where food consumption remains within planetary boundaries. According to a recent study by researchers at DTU, such a scenario would only allow consumption of around 255 grams of meat per week, equivalent to approximately two chicken legs (Gebara et al., 2025). This limit illustrates how significantly our dietary habits need to change if we are to ensure both health and environmental sustainability.

This thesis has not explicitly addressed current consumption patterns, neither in relation to meat nor beer. However, it is relevant to note that my findings indicate there is no saturation in the system regarding the use of BSG as animal feed. My interviews and additional research instead suggest that farmers are interested in using BSG for feed. This implies that, if BSG continues to be produced, it may contribute to increasing the resource efficiency of existing food production. At the same time, we are facing a growing global population and a projected increase in food production, which makes it necessary to both optimise production systems environmentally and promote changes in consumption behaviour.

As Ceschin (2014) points out, it is not sufficient to improve products and production technologies in isolation. Achieving real sustainability requires radical changes in the systems that underpin our consumption and production. From this perspective, a solution like BSG upcycling risks reinforcing existing structures unless accompanied by a broader reflection on how we consume.

Had I employed a backcasting approach, the analysis might have taken a very different direction. Rather than focusing on how BSG can be utilised, the question might have been how to avoid producing BSG in the first place. This could have prompted more fundamental reflections on whether we should rethink beer production altogether. Should we significantly reduce our beer consumption, or develop new production methods that do not involve grain and therefore do not generate this by-product? These types of questions relate to the top level of the waste hierarchy, where prevention is prioritised over recycling.

Such an approach would have allowed for the inclusion of more normative considerations about what a sustainable food system should be, rather than just how we can improve the current one. Backcasting could thus have opened up for a more fundamental systemic critique, where both meat and beer consumption are brought into question. Instead of focusing on how to best utilise existing by-products, the perspective could have shifted towards reducing or even avoiding them entirely through changes in production and consumption systems.

Chapter 8: Conclusion

This thesis has investigated how environmental impacts and actor-network dynamics can be assessed in the early stages of circular food innovations, with a particular focus on the upcycling of brewers' spent grain (BSG) as a case study. Through a combination of Life Cycle Assessment (LCA) and Actor-Network Theory (ANT), both the environmental and socio-technical dimensions have been analysed to achieve a more nuanced understanding of sustainability in practice.

Answer to Sub-question 1: Network dynamics and roles of actors
The analysis shows that BSG is not merely a technical by-product, but acts as an active agent whose role and significance are continuously negotiated among the involved parties. The ANT analysis highlights how humans, technologies, and regulations function as governing elements in the network, and how the collaboration between the brewery, startup, and bakery is shaped by interdependencies, vulnerabilities, and constant adjustments. The stability of the network depends on ongoing coordination, which underlines the importance of incorporating socio-technical aspects in the assessment of circular food innovations.

Answer to Sub-question 2: Environmental consequences
The life cycle analysis of BSG upcycling demonstrates that the environmental consequences are highly dependent on local and contextual factors, especially energy consumption for freezing and the choice of substitute products in the feed chain. The results indicate that upcycling BSG for food products does not necessarily result in a lower climate footprint compared to its current use as animal feed. Factors such as electricity use, feed substitution, and assumptions regarding transport and raw materials significantly influence the results, which points to the need for context-sensitive and systemic assessments rather than general assumptions about the sustainability of upcycling.

Answer to Sub-question 3: Implications for the evaluation of innovations
Based on the analyses, supplementary evaluation criteria have been developed that can strengthen existing evaluation practices in innovation programs such as Closing Loops. The new criteria address network maintenance, holistic environmental impact, systemic consequences, and the risk of rebound effects and lock-in. By incorporating these reflexive dimensions, assessment processes are better equipped to embrace the complexity of early-stage circular innovations and to support solutions with greater long-term transformative potential.

Overall answer to the main research question
The thesis demonstrates that a comprehensive assessment of circular food innovations requires an integrated approach, where technical, environmental, and network-related dimensions are analysed in conjunction. The combination of ANT and LCA has made it possible to reveal both the direct and indirect consequences of new solutions and to identify the institutional, technological, and collaborative conditions that enable or constrain their implementation. The analysis shows that circular strategies such as upcycling cannot be evaluated in isolation based on individual environmental parameters or simple effect metrics, and the assumption that upcycling for human consumption is automatically more sustainable than other uses does not necessarily hold true in practice. Only by integrating systemic, actor-oriented, and environmental perspectives is it possible to achieve a more realistic and accurate picture of sustainability, which is essential to avoid unintended consequences and promote long-term solutions in the circular economy.

Chapter 9: Reflection

Through my ongoing collaboration with the case actors, I developed a close relationship with the project and gained insight into decision-making processes, actor relations and practical challenges. In certain situations, I contributed with input when asked, but I did not actively intervene in the project. I did not suggest alternative preservation methods or question the choice of by-product, even though there might have been opportunities to introduce other waste streams into the process. This was due to my role as a student without formal affiliation to the company, and my focus was therefore on following the process rather than attempting to change it. This non-interventionist approach clearly distinguishes my work from action research, where intervention and change are central elements.

Accordingly, the thesis is grounded in a case study approach with mixed methods as the primary research design, while action research is used reflectively to discuss my own position and relationship to the field. The decision not to take a critical stance towards the actors' foundational setup also reflects my awareness that excessive critique can create distance and limit access to valuable insights, something I have experienced in previous projects. At the same time, I have been conscious of the difference between being employed to carry out a sustainable development task and being granted access as a student to follow a project from within. This consideration also informed my decision to anonymise the actors.

Working on this thesis has strengthened my understanding of the conditions and limitations that small companies operate under, including how factors such as economy, logistics and food safety often determine what is practically feasible. My academic background as a Sustainable Design Engineer has enabled me to think systemically and apply life cycle perspectives in the analysis, but the experience has also shown me the importance of translating these perspectives into concrete actions within a resource-constrained context.

The use of Actor-Network Theory has sharpened my understanding of how both material and human actors contribute to shaping sustainable solutions. It has demonstrated that sustainability is not merely a matter of technical data and calculations but is also deeply rooted in networks, negotiations and social practices. Moving forward, I will carry this recognition with me. Sustainable design is not solely about product optimisation, but also about engaging with and shaping the complex structures and relations in which innovation is embedded.

Chapter 10: Future work

This report has developed a set of supplementary evaluation criteria and conducted a screening-level LCA of a specific case within circular food innovation. Based on the identified opportunities and limitations, the following areas point to relevant future work.

Further development and testing of evaluation criteria
The evaluation criteria developed in Chapter 6 represent an initial attempt to address systemic and environmental complexities in early-stage innovation projects. An important next step will be to test and validate these criteria in practice, for example through application in other cases or as part of the official evaluation framework in the Closing Loops program. In addition, the design and formulation of the questions in the table should be revised to improve precision, usability and clarity for both applicants and evaluation panels.

Expansion to include economic and social dimensions
As this report has primarily focused on environmental and network-related aspects, there is a need to further develop the evaluation framework so that it also includes economic and social sustainability dimensions. This could include indicators related to job creation, local anchoring, food security and distributional consequences. An interdisciplinary approach could strengthen the overall coherence of the criteria and make them more relevant in broader political and societal contexts.

Strengthening and further development of the LCA model
The screening-level LCA conducted in this report is based on simplified assumptions and uncertain input, which is typical of innovation projects in early stages. Future work could focus on further developing the model to support more robust analyses. This could include collecting more detailed data on electricity consumption, as well as expanding the model with a functional unit that enables comparison between the use of BSG and wheat flour in bread production.

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