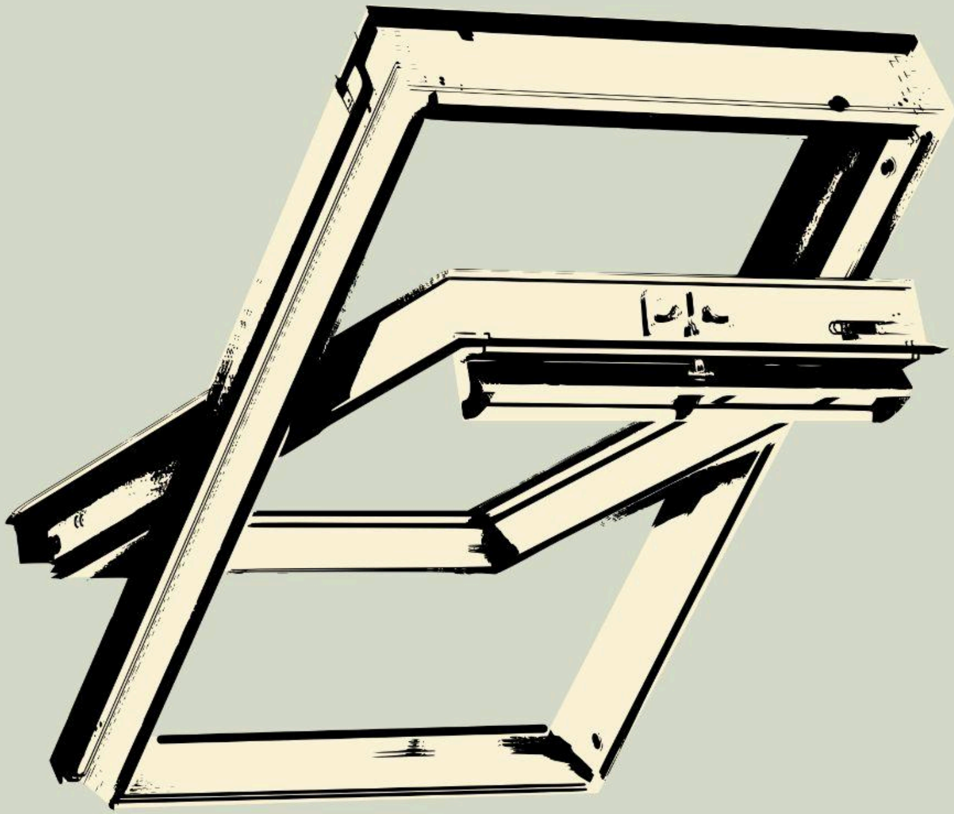
Strategies for Retaining the Environmental Value of Roof Windows

A master thesis in Sustainable Design Engineering

Aalborg University Copenhagen - 2024



A case study in collaboration with VELUX

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Abstract

Advancing sustainability in the building industry is crucial for meeting the European Green Deal's goals, given the industry's high carbon emissions and resource use. This issue is partly due to the industry's entrenched linear practices, which result in limited Circular Economy (CE) initiatives for Construction and Demolition Waste (C&DW), highlighting significant room for improvement. This thesis investigates circular business models for VELUX roof windows after their initial service life. Currently, there is a narrow focus on improving the energy balance of roof windows without considering the embedded CO2 equivalents (CO2e) in existing products, leading to wasted resources that could be better preserved. This is due to a limited life cycle approach that fails to assess solutions with the lowest environmental impact. The thesis argues that more circular initiatives for VELUX's current business model are feasible, which is a primary contribution of this study. By applying Carbon Lock-in theory and Actor-Network theory, the network involving VELUX roof windows was analysed to identify barriers and opportunities for integrating more CE into the system. Five design concepts were developed based on CE principles, offering more sustainable alternatives compared to the current business model. These concepts were evaluated using a life cycle assessment to provide actionable insights, aiming to interest, enrol, and potentially integrate these concepts into VELUX's operations.

Acknowledgement

The authors express sincere gratitude to Anja Gylling and Anne-Louise Terkelsen from VELUX for their generous support, which helped facilitate the case collaboration. Special thanks to Pernille Cuisy Svensson, Karsten Duer, Jesper Kolind Nielsen, and Marcel Vreeken for their invaluable contributions to our understanding of VELUX, encompassing product knowledge, company insights, and regulatory perspectives relevant to our study.

We also acknowledge the valuable insights provided by representatives of innovative companies involved in circular projects for roof windows, including Kenneth Vedel Hansen from J.Jensen Genbrug, Tom Jørgensen from Genbyg, Morten Risom from A:Gain, and Thomas Nordahl from Optoglas. Additionally, we appreciate the insights shared by both private and municipal recycling specialists, including Simon Halvarsson from Solum, Søren Løkke, and resource workers from Sydhavn Genbrugscenter, regarding current end-of-life treatment practices for windows. We extend our gratitude to Martin Visby Buchard from Roskilde University for his expertise in construction and demolition waste and circular business models. Special thanks are also due to Louise Laumann Kjær for her guidance and feedback on life cycle assessment modelling.

Our sincere appreciation goes to our supervisor, Jens Dorland, from Aalborg University, for his invaluable guidance and constructive feedback throughout the thesis process. Lastly, we are deeply grateful to our families and friends for their support and encouragement throughout this endeavour.

Glossary

AISL = After initial service life.

ANT = Actor-network theory.

BaU = Business as usual.

BMC = Business model canvas.

BR18 = Danish Building Regulations, as of 2024.

C&DW = Construction and demolition waste.

CE = Circular economy.

CO2e = CO2 equivalent, being the metric for global warming potential.

EoL = End-of-life. *“Point in time when a product is taken out of use and its resources are either recovered for processing or it is disposed of”* (The International Organization for Standardization, 2024, p. n.d.)

EPD = Environmental product declaration.

IGU = Insulating Glass Unit: Consisting of multiple glass panels spaced apart with a vacuum seal, usually bonded together within a metal frame.

KPI = Key performance indicator.

LCM = Life cycle management.

OPP = Obligatory passage point.

Roof windows = A window that is installed on the roof of a building, commonly flush with the roofing material.

SDE = Sustainable Design Engineering.

1. Introduction

1.1 Preface

This master thesis was made by two Sustainable Design Engineering (SDE) students (hereafter referred to as "the researchers") at Aalborg University in Copenhagen in the spring semester of 2024. Both researchers hold a bachelor's degree in the consecutively bachelor education "Bæredygtigt Design" at Aalborg University Copenhagen. Some of the key skills of Sustainable Design Engineering is knowledge within *"interdisciplinary components to satisfy the need for combining methods from social science and technology studies with technical subjects and design practices"* - (Aalborg University, n.d., p. 1). The aim of this thesis is to showcase the capabilities of SDE in exploring and designing solutions to address wicked problems often encountered in the linear economic Business as Usual (BaU) model, while aiming for long-term sustainable solutions.

1.2 Case Collaboration Partner

The thesis is executed in a case collaboration with Lead Product Sustainability Specialist, Anja Gylling, and Advanced Sustainability Advisor, Anne-Louise Terkelsen from VELUX Denmark.
VELUX is a Danish window manufacturer with a presence in 37 countries, production in 12 countries, and an annual revenue from 2023 of 21,670 million DKK, making them a well-established supplier in the market (VELUX, n.d.). VELUX defines their purpose as *"To create well-being for people and planet by transforming spaces using daylight and fresh air."* - (VELUX, n.d., p. 1). This aligns with targets from their company strategy presented in VELUX's Sustainability Report 2023, namely to promote a circular economy (CE) by decoupling resource use from value creation and removing the equivalent to the historical carbon footprint of VELUX by 2041 (The VELUX Group, 2024). The researchers see VELUX as a company with ambitious sustainability goals, presenting them with an opportunity to help VELUX achieve these objectives.
In November 2023, five project proposals were discussed with the collaboration partners from VELUX after the researchers reached out to them. The selected project aimed to determine whether implementing a take back system or other design solutions could enhance the environmental performance of VELUX roof windows post-sales, thereby improving the company's overall sustainability. How the project is approached necessitates an understanding of how sustainability and design is understood.

1.3 The Approach to Sustainability and Design

The researchers' understanding of *sustainability* is rooted in the definition of sustainable development from the Brundtland Report: *"meets the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland, 1987, p. 15). The definition indicates that humanity needs to consider the long-term effects of the current living practices, in order not to deteriorate the living conditions of future generations. From the researchers' background in SDE, they seek to have a holistic understanding of sustainability, avoiding burden shifting, mitigating rebound effects (Kjær et al., 2019), and leaving no person behind. The researchers understand this as the most optimal for developing actual sustainable transformation. Supporting this, the understanding of sustainability can be categorised into three legs: environmental, social and economic sustainability, which in a corporate context is inevitably and fundamental to ensure sustainable development (Geissdoerfer et al., 2016).

Design is another key term that needs elaboration in this thesis. By design the researchers refer to the process of conceiving, planning and making artefacts, often explained by a description (Cross, 2008). Design also regards the more intangible aspects elaborated by Ceshin (2014), *"from single products to services and Product-Service Systems and, more recently, to social innovation and large-scale socio-technical changes"* - (Ceschin, 2014, p. 4). Therefore, designing can address products and socio-technical elements consisting of both artefacts, social relations and institutional elements. The researchers see design as a strategic enabler to foster transformative and innovative change (Ceschin, 2014; Ellen MacArthur Foundation, 2023), which is needed to challenge the unsustainable practices in the BaU and aim for sustainable development.

Contributing to getting the building industry on a sustainable path is crucial for meeting the European Green Deal's sustainability targets (European Commission, 2019), given the industry's significant carbon emissions and resource usage. A transition towards a CE is regarded as essential for helping the building industry achieve sustainability. However, a review of case specific literature highlights that the industry is deeply rooted in take-make-dispose practices as a result of the incumbent linear economy. Consequently, current circular initiatives for Construction and Demolition Waste (C&DW) mostly involve low value retention strategies, leaving substantial room for improvement.

1.4 Research Question

Applying the competencies from SDE, the researchers aim to use their interdisciplinary capabilities to understand the field and its relevant actors, gain insight into the embedded barriers to sustainability transition, and employ their holistic approach to sustainability. They emphasise absolute decoupling and optimal environmental outcomes, guiding the design of concepts that could be effectively adopted by VELUX. This culminates in the following research question of this thesis:

Research Question:

How can roof windows be managed and utilised after their initial service life to enhance environmental sustainability?

After Initial Service Life (AISL) refers to when a product is removed or intended to be removed from its initial use setting, whether due to the end of its technical lifespan, aesthetic preferences, changes in requirements, or upgrades, even if it remains technically functional.

This study therefore focuses on the management and utilisation of procedures for handling roof windows that have reached the end of their initial service life within Denmark. The researchers hypothesise that the current end-of-life (EoL) handling of roof windows is unsustainable due to its linear approach, with room for environmental improvement. This hypothesis will be explored in the following analyses, with separate sub-questions guiding the focus into specific subsections.

1. ***What are the current barriers to implementing circular economy practices in the lifecycle management of VELUX roof windows?***

The researchers aim to map out the current downstream processes involving roof windows AISL, as well as the linear operations that sustain the existing system.

The second analysis focuses on the opportunities and drivers for circular initiatives that advance the CE agenda, highlighting potential ways to enhance the sustainability transition.

2. ***What opportunities and drivers exist for adopting circular business models for VELUX roof windows after their initial service life?***

Building on identified lock-ins, examples of circular pilots, and emerging drivers for a more CE, the third analysis focuses on VELUX roof windows. It examines how the system, of which these windows are part of, can be designed to enhance environmental sustainability.

3. ***How can design concepts for VELUX roof windows be developed to address identified barriers and reduce the environmental impacts throughout their life cycle?***

The final analysis applies life cycle assessment to evaluate the developed concepts from analysis 3, verifying the environmental sustainability performance claimed by the researchers.

4. ***How can circular design concepts be evaluated in terms of environmental performance?***

The researchers define environmental performance in terms of the total emitted CO2 equivalents (CO2e), considering it the most critical impact category related to climate change. Other impact categories are deemed too comprehensive to include given available data and time constraints. Additionally, CO2e serves as a well-harmonised metric for comparing different concepts. The discussion will encompass how well the research results address the research question, considering the analyses and the specific circumstances.

1.5 Thesis Structure

An overview of the thesis structure is illustrated in figure 1.

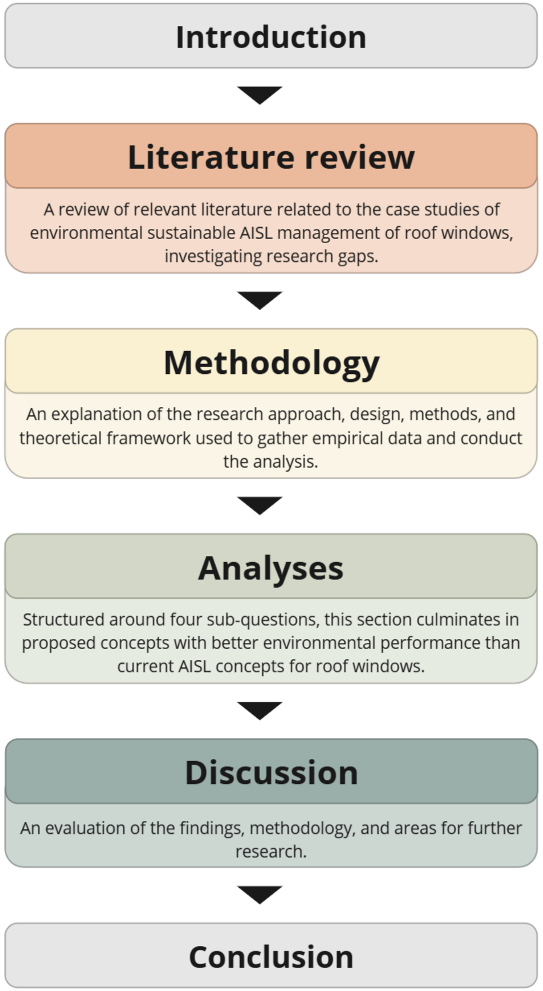

Figure 1 - Structure of the thesis

A more detailed overview of how the researchers will address the research question and sub-questions is provided in the research design in section 3.3.

2. Literature Review

A literature review was conducted to investigate the existing scientific literature on AISL management solutions for roof windows and related themes (appendix A). This method systematically gathers and synthesises research to provide a comprehensive understanding of the field (Snyder, 2019). An overview of the literature review can be found in figure 2. The search strategy employed a block search method in the Scopus database. The search string was refined until 425 scientific articles were identified. Among these, 38 articles were deemed relevant based on their titles. Subsequently, the abstracts were assessed for relevance, considering criteria such as their alignment with the research questions, focus on windows or other building materials, and relevance to reverse logistics, reuse, or similar circular business models. The following sections outline the findings from this review.

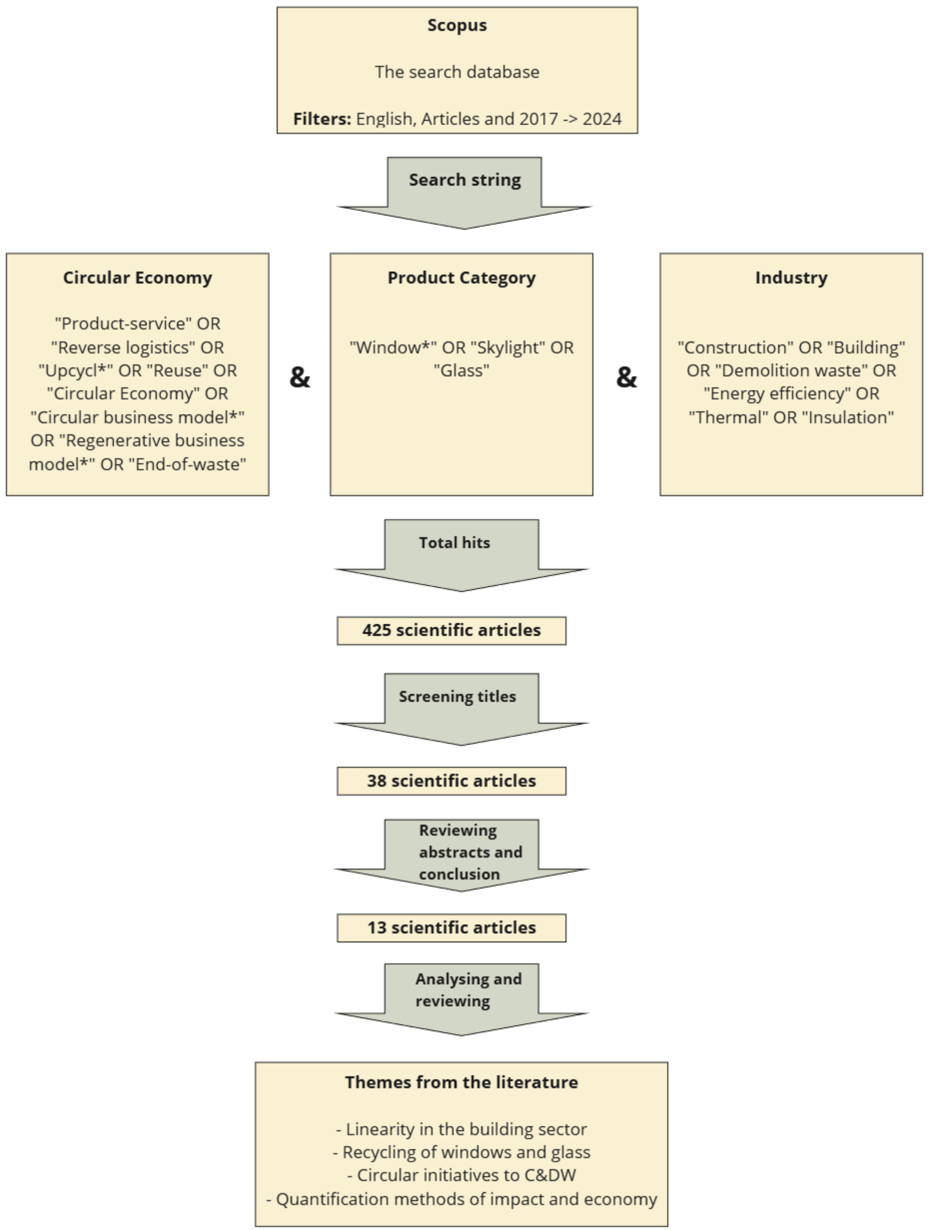

Figure 2 - Literature review strategy

2.1 The Impact of Windows and the Building Sector

The building sector emits up to 11% of the total human-induced carbon emissions globally (Eberhardt et al., 2020), while 20 to 40% of the total generated waste in Europe stems from the building and construction sector (Eberhardt et al., 2020; Fregonara et al., 2017; Geboes et al., 2023). This issue includes windows and its components. According to Geboes et. al. (2023) the production of flat glass emits globally 86 Mt CO2e annually, while only 11% of this glass is recycled in the EoL. In a study by Forslund & Björklund (2022), it was found that only 1% of flat glass is handled in circular or closed-loop supply chains in Sweden. This indicates a great potential for the improvement of circularity in this sector, and an area to investigate further.

C&DW in terms of glass is in some examples used as recycled aggregate for concrete (Tazi et al., 2021). A significant issue with this practice is that the glass is downcycled to a lower-grade material compared to its original use. This is a common problem in open-loop recycling, where challenges arise when glass is mixed with various types of glass and other materials during the recycling process. This mixing prevents the glass from achieving the necessary functionality required for use in flat glass for windows (Geboes et al., 2023). In other words, even though it may seem positive to recycle the glass, it is in many cases downcycled, which does not reduce the need for virgin glass in the production of windows. The distinction between low and high-quality recycling is relatively under-researched, leading to insufficient focus on maintaining the environmental integrity of products for as long as possible (Tazi et al., 2021). Consequently, individuals may perceive recycling glass positively without considering potential improvements to the treatment process.

One reason for the current linear approach to handling windows is that treating used windows differently is both more complex and costly (Geboes et al., 2023; Rota et al., 2023). Often windows from the building industry end up in relatively linear purposes such as landfills, or the wood is incinerated for energy recovery and the glass is downcycled into road backfilling purposes (Eberhardt et al., 2020; Rota et al., 2023). Most newer windows are created as an insulating glass unit (IGU), consisting of multiple layers of flat glass, and a space bar made of aluminium, all being sealed together (Geboes et al., 2023). *"Reusing an insulating glass unit (IGU) means dismounting it from a location and reinstalling it to another, but this operation makes sense only if weighted against its remaining service-life."* - (Rota et al., 2023, p. 236). Thus reuse is not always the best scenario, if the alternative is to keep the IGU in the window for the remaining service-life, to retain the environmental value as long as possible. Additionally, as IGUs are not designed for disassembly, separating the glass from the frame and its other materials is a time-consuming and resource-heavy process, which in most cases is not an economically feasible solution (Rota et al., 2023). This is not only due to technical challenges but represents a systemic challenge, due to a linear economic path dependency in the current system that reinforces the carbon-intensive need for window manufacturing.

According to Geboes et al. (2023) there are institutional challenges in reusing windows, as government energy policies set requirements for thermal insulation in the use phase of the buildings, and thereby promote virgin windows instead. This legislation is made to reduce the energy usage for heating the buildings, but is simultaneously making it hard to reuse older generations of windows for new buildings. The production of better insulating windows is more resource consuming, as more glass and resources is needed (Geboes et al., 2023).

2.2 Circular Economy Strategies for Windows

Some literature leans against CE describing circular strategies to close the material loop and minimise waste in the building sector (Arora et al., 2020; Forslund & Björklund, 2022; Geboes et al., 2023; Nußholz et al., 2020; Ploeger et al., 2019; Rota et al., 2023; Tazi et al., 2021). Circular business models such as take back systems based on reverse logistics, buy-back offering, and operational leases where the product is offered as a service, incentivise that the product design is more robust and is designed for extended product life (Ploeger et al., 2019). However, Ploeger et al. (2019) highlight a significant barrier in property law between fixtures and movables, specifically regarding building components. Windows, often considered fixtures, cannot easily be sold as a service, complicating the creation of a product service system for them (Ploeger et al., 2019).

Additionally, the strategies for the models identified in the literature, mainly focus on lower value retaining strategies, while only few examples of higher circular strategies are found in the literature. Moreover, the literature describing circular business models for windows is relatively limited. One source describes a pilot of a system where windows get remanufactured with the use of a reverse logistics system: "*Post-consumer windows are collected from demolition sites and dismantled to obtain the glass. Glass is assembled into new windows by adding customized frames and a second layer to comply with energy balance standards.*" - (Nußholz et al., 2020, p. 4). This example gives a tangible circular solution, which may sound promising. On the contrary, the difficulties in reusing building materials are highlighted as it requires a large amount of virgin material input and energy-extensive manufacturing processes to transform it to a usable condition that lives up to energy balance and construction safety (Nußholz et al., 2020; Rota et al., 2023). Additionally, the lack of guarantee of second hand roof windows, may limit their attractiveness (Rota et al., 2023). Moreover, in some instances, the pricing of reused materials serves as a barrier to further reuse, particularly when virgin materials are cheaper or priced similarly (Tazi et al., 2021).

2.3 Urban Mining

Arora et al. (2020) discuss urban mining as a promising concept for reducing the impact of the building sector. Urban mining involves gathering building materials from existing structures and reusing or repurposing them for new construction. This practice is driven by the concept of buildings serving as carbon and material sinks, contributing to a more sustainable resource utilisation. The researchers intend to investigate whether the case is the same for roof windows, and how they can contribute to new urban mining projects.

2.4 Assessment Methods for Circular Solutions

Gaining an understanding of the ideal and more sustainable solution can be challenging when developing circular business models that non-experts in sustainability within the building and construction sector can use. Therefore the importance of an assessment method to qualify the benefits of reusing or recycling windows is elaborated in multiple sources (Eberhardt et al., 2019, 2020; Kosanović et al., 2021; Saeed et al., 2023). A recognised method to assess environmental impacts is life cycle assessment (LCA), which considers all stages of a product or service's life cycle in its environmental assessment. It typically spans from resource extraction to EoL handling, essentially covering the entire lifecycle, from cradle to grave (Fregonara et al., 2017). Frameworks for assessing circular handling are presented in Eberhardt et al. (2020), offering a harmonised method for conducting LCAs in the built environment. Furthermore, other frameworks, such as economic-environmental indicators and life cycle costing, are suggested to support decision-making regarding the treatment of building materials in the EoL phase, thereby monetising potentials in EoL handling (Fregonara et al., 2017; Saeed et al., 2023).

2.5 Gap in the Literature

The literature emphasises significant sustainability issues in the building industry, which is also profound concerning the AISL management of windows. While there are circular innovations in this field, their implementation is hindered by barriers rooted in prevalent linear practices. Although the literature identifies both barriers to sustainable transformation and drivers that promote it, there is a lack of a comprehensive overview that combines these factors. Additionally, examination of these aspects related to AISL management of windows remains limited. Understanding these elements is crucial for designing solutions that effectively address barriers and leverage drivers. This thesis aims to identify the parameters keeping windows within a linear system and the drivers that can steer it towards a CE. By thoroughly understanding and addressing these parameters, the thesis seeks to promote circular innovation and contribute to sustainable transformation in the building industry.

The literature review highlight circular business models for C&DW generally exhibit a low level of value retention. This issue is also evident in business models related to windows, such as in the case of open-loop recycling of glass (Geboes et al., 2023). This lack of focus can be partly attributed to a general failure to distinguish between low- and high-quality recycling. There is limited research on high-value retention models, such as extending the service life of windows through reuse, repair, or upcycling. This scientific gap is explored in this thesis.

While frameworks for assessing environmental and economic aspects are suggested and evaluated in the literature (Eberhardt et al., 2019, 2020; Fregonara et al., 2017; Kosanović et al., 2021; Saeed et al., 2023), there is relatively limited research on frameworks being linked to physical and tangible CE design concepts, and how CE strategies can be utilised as a simple preliminary assessment method to prioritise the concepts with the lowest environmental footprint. Additionally, Rota et al. (2023) recommend future studies to investigate the embodied carbon in windows and its relation to remanufacturing processes. This thesis will explore these areas.

3 Methodology

The following section will outline how the researchers intend to uncover and address the research question.

3.1 The Meta-Theoretical Perspective

Being Sustainable Design Engineers, the researchers identify their meta-theoretical assumption aligned with the radical humanist paradigm, regarding how they perceive the social world related to the nature of science and society (Burrell & Morgan, 1979). This influences the researchers approaches, way of problematisation and the definition of solution spaces. Radical humanism can be defined as seeking radical change following a subjectivist perspective.

Following radical change, the researchers acknowledge a fundamental change of society is necessary to avoid further stressing planetary boundaries and achieving the targets set by the European Green Deal (European Commission, 2019). Implementing the needed long-term sustainable societal change, necessitates investigating the potentials of sustainable transformation while addressing the underlying conflicting forces that inhibit it.

Doing so from a subjectivist perspective, implies recognising individuals' subjective experiences having different understandings of reality (Burrell & Morgan, 1979). As this thesis is based on a case study, relevant actors who are a part of the network concerning VELUX roof windows, have been interviewed to find alternative solutions that can address their subjective concerns. Understanding the concerns of relevant actors and critically analysing the dynamics of the current system, creates conditions to design solutions that can contribute to fundamentally changing the sector towards sustainability.

3.2 The Methodological Approach

Following radical humanism, the project has employed a problem-oriented approach operationalised through the abduction method (Alvesson & Sköldberg, 2018). Grounded in practical, real-world problems needing solutions, the project uses iterative processes to refine problem definitions and conceptualise practical solutions while considering the complexities within the contexts.

While the abductive method aligns well with a problem-oriented approach, it is more theoretically grounded. It involves iteratively refining hypotheses and engaging with theoretical frameworks to interpret empirical data, leading to theory adaptation and possibly development (Alvesson & Sköldberg, 2018). This ensures that solutions are not only practical but also grounded in theoretical bases, enhancing their credibility and effectiveness.

This approach emphasises flexibility and dynamic adjustments of research focus and methods in response to new findings, which is essential when dealing with complex systemic problems and integrating new insights as they emerge. Therefore, the problem-oriented approach operationalised through abduction is deemed suitable for this case study, given its complementary nature, to provide real-world applicable solutions that are also theoretically robust.

3.3 Research Design

The researchers' approach to conduct this thesis is described in this section. The case study is based upon the AISL management of VELUX roof windows. As the building sector was a new area for the two researchers of this scientific article, an exploratory approach was applied where primary and secondary empirical material was collected to gain insights in the sector. The overall approach is pictured in figure 3.

Research Design

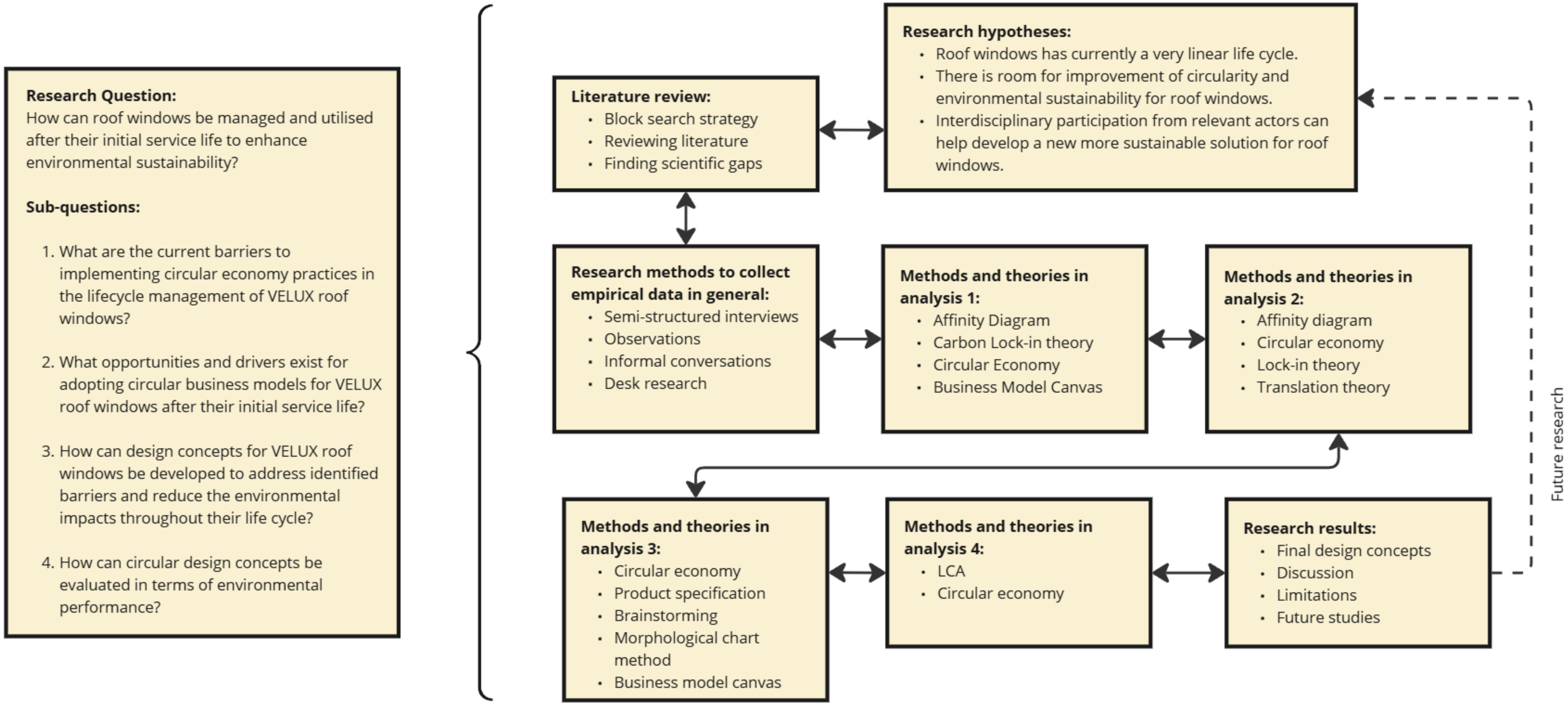

Figure 3 - Research Design - inspired by Ceschin (2014).

The research question originates from the work depicted on the right side of figure 3, with the sub-question numbers corresponding to the analysis steps. The arrows illustrate the project's workflow, beginning with the research hypotheses. An abductive approach was applied, allowing for iterations to refine and rescope elements throughout the project. Several general methods were employed to collect empirical data, including desk research, literature review, semi-structured interviews, observations, and informal conversations. In the four different analyses, specific methods and theories have been applied, chosen for their potential to contribute most effectively to each particular analysis.

In Analysis 1, the focus is on the BaU scenario for roof windows. Here, lock-in theory as defined by Seto et al. (2016), CE principles, an affinity diagram to structure the empirical data, and a business model canvas (BMC) to visualise the current business model for VELUX roof windows are applied. In Analysis 2, the focus is on drivers and opportunities for CE regarding roof windows. Besides the general methods for empirical data collection, the affinity diagram, CE principles, lock-in theory, and translation theory are applied. Analysis 3 concerns the conceptualisation of new CE concepts for VELUX, employing design methods such as brainstorming, product specification, the morphological chart method, and then repeating the BMC with the new concepts to indicate how they differ from the original BMC. The concepts from Analysis 3 are finally evaluated in Analysis 4 using a LCA, comparing the scenarios.

The final thesis aims to contribute to the field of Sustainable Design Engineering (SDE) by demonstrating how this profession can advance circular initiatives in the building industry. Additionally, the research aims to provide practical solutions for VELUX to adopt, while contributing to the scientific community by applying relevant theories and inspiring further research on the topic, as indicated by the dashed arrow in Figure 3.

4. Methods

As outlined in the research design, various methods were employed throughout this thesis to collect data and execute the project. A further elaboration of the methods is presented in the following section. Figure 4 provides an overview of the conducted interviews and conversations.

ChatGPT has been used for grammar corrections and translation of interviews as part of the thesis.

No.	Title for meeting	Organisation, Participant	Date	Location	Type of meeting	Purpose
1	Project collaboration initiation	**VELUX -** Anja Gylling	17/11/23	Online meeting	Informal conversation	A meeting to discuss potential projects for the Master Thesis.
2	Presentation of cases	**VELUX -** Anja Gylling, Anne-Louise Terkelsen	15/12/23	Online meeting	Informal conversation	Elaborating on selected cases and expectations for the project's progression.
3	Managing expectations and initial project definition	**VELUX -** Anja Gylling, Anne-Louise Terkelsen	18/01/24	VELUX's office	Informal conversation	Aligning expectations for the project and project focus.
4	Meeting with collaboration partners	**VELUX** - Anja Gylling & Anne-Louise Terkelsen	14/02/24	Online meeting	Semi-structured interview	Insights on VELUX operations and product chain.
5	Visit to retailer of building materials and timber, including roof windows	**STARK** - Sales and Sustainability Ambassador	16/02/24	Stark, Sydhavnen	Informal conversation	Gather insights from a retailer of Velux roof windows, to figure out how the sales process works regarding windows, as well as their capacity to sell reused materials in general.
6	Field research in municipal recycling centre	**Sydhavn Genbrugscenter** - Waste management workers	16/02/24	Sydhavn Genbrugscenter	Semi-structured interview	Insights on how windows are treated at municipal recycling centres.
7	Meeting at demolition company, which also retails reused building materials	**J. Jensen Genbrug** - Kenneth V. Hansen, Reuse Specialist	20/02/24	J.Jensen Genbrug's office	Semi-structured interview	Gather insights from a demolition company, specialised in selective demolition and retail of second hand building materials.
8	Treatment of windows at municipal recycling centre	**Amager Ressourcecenter (ARC)** - Resource Consultant, Casper Glottrup	22/02/24	Online	Mail correspondence	Insights in how windows are treated, and what criteria and procedures exist in sorting and treating them
9	Circular Business Models for C&DW	**RUC -** Martin Visby Buchard, External Lecturer	27/02/24	Online meeting	Semi-structured interview	Interview with Ph.D. researcher on circular business models for construction and demolition waste
10	Interview on Genbygs business model	**Genbyg -** Tom Jørgensen, Director, co-owner, and purchasing manager	28/02/24	Telephone meeting	Semi-structured interview	Knowledge on how Genbyg facilitates and executes their business concerning second hand building materials.
11	Meeting at Sydhavns Recycling centre with Project Manager	**Sydhavn Genbrugscenter -** Søren Løkke, Project Manager and Resource Worker	28/02/24	Sydhavn Genbrugscenter's office	Semi-structured interview	Interview with staff at municipal recycling centre on how they treat roof windows
12	Meeting with demolition company	**Kingo Karlsen -** Kim Møgelvang, Logistics manager	28/02/24	Online meeting	Semi-structured interview	Gather insights from a demolition company and retailer of reused building materials, to get a better understanding of the process and challenges of selling second hand building materials, like roof windows
13	Interview on product and regulation requirements for windows	**VELUX -** Karsten Duer, Manager for Standardisation and Product Regulation	01/03/24	Online meeting	Semi-structured interview	Gain knowledge on regulations that a window must live up to.
14	Interview with installer	**Installer** - Valdemar Zethner, Carpenter	07/03/24	Online meeting	Informal conversation	Insights on how an installer works with roof windows
15	Milestone 1 with collaboration partners	**VELUX** - Anja Gylling & Anne-Louise Terkelsen	08/03/24	VELUX's office	Milestone / Informal conversation	Presentaiton of initial findings and feedback
16	Interview with end-of-life specialist	**VELUX -** Pernille C. Svensson, Product Sustainability Specialist	08/03/24	VELUX's office	Semi-structured interview	Went through findings from Rambøll report on end-of–life recommendations for Velux, and relevant legislation.
17	Interview regarding the business model of Optoglas	**Optoglas** - Thomas Nordahl	19/03/24	Optoglas' office	Semi-structured interview	Interview to understand the products and business model from Optoglas
18	Interview with private recycling company	**Solum** - Simon Z. Halvarsson, Head of marketing	20/03/24	Online meeting	Semi-structured interview	Insights and implications on how a private recycling company works with windows as part of their end-of-life treatment
19	Take back pilot project	**VELUX (Netherlands)** - Marcel Vreeken, Manager of Public Affairs	22/03/24	Online meeting	Semi-structured interview	Introduction to inspirational case pilot of a take back system in the Netherlands
20	Upcycling / remanufacturing pilot project	**A:Gain** - Morten Risom, Head of Material Innovation	27/03/24	A:gain's office	Semi-structured interview	Interview regarding remanufacturing of IGUs for indoor wall panels
21	Short technical course on VELUX windows	**VELUX** - Jesper K. Nielsen, Technical Advisor	27/03/24	VELUX's office	Short technical course / Informal conversation	Technical course on how VELUX roof windows are constructed and the products' weak spots
22	Milestone 2 with collaboration partners	**VELUX** - Anja Gylling & Anne-Louise Terkelsen	26/04/24	Online meeting	Presentation of results / semi-structured interview	Presentation of Business Model Canvas on Velux BaU + Product Specification. Questions and suggested improvement from collaboration partners.

Figure 4 - Overview of interviews and informal conversations

4.1 Case-study

This thesis is based on a case-study concerning VELUX roof windows and the network that it is a part of. A case study is a qualitative method to test hypotheses in a certain bounded system (Flyvbjerg, 2006; Stake, 1978), which the researchers find beneficial as it narrows the focus area and helps make the researched phenomena more concrete. The limitations of a case study include that the empirical data may only be valid for a limited number of actors. Further tests may be necessary to determine if the findings from the case study are representative of the entire sector.

4.2 Data Collection and Reviewing

Different methods for gathering data have been applied in this thesis. In the following sections, the relevance and applicability of these methods are discussed.

4.2.1 Interview Approach

When interviews were facilitated during the thesis, the semi-structured interview method was applied, which is a mix of the structured and unstructured interview method (Galletta, 2013). By preparing themes with questions before the interviews, the researchers combined an open-minded approach to navigate the interview in directions that showed to be relevant. The semi-structured interview method was considered successful because it allowed for asking alternative questions during the interviews, leading to the discovery of unexpected new information. In combination with the semi-structured interviews, the "fly-on-the-wall" observation method (LUMA Institute, n.d.) was used. This method was applied specifically to study how second-hand windows are sorted and treated in the BaU. It was chosen for its ability to collect data with minimal disruption to the observed activities.

4.2.2 Desk Research

Desk research (Travis, n.d.) was used to gather secondary research material from articles, documents, books, and websites. This method provided insights and findings from relevant legislation and inspirational cases in the researched area.

4.3 Structuring the Data

In analysing and interpreting data, the affinity diagram method was used to organise large volumes of user data into clusters of categories, framing the design problem inductively (Holtzblatt & Beyer, 2017). This method handles data without predefined categories, allowing categories to emerge from the unstructured collected data. The affinity diagram facilitated collaborative data analysis among the researchers, enhancing their understanding of the project and identifying problem areas.

Data collected during the research process was categorised into different levels: institutional, technological, and behavioural drivers and challenges.

This data addressed both the evident linear lock-ins within the building industry and the drivers for transitioning to a CE (See appendix B). Categorising the data provided a structured method for organising it, making it more suitable for analysis

4.4 Design Methods

The design methods are primarily applied during the third analysis, focusing on conceptualising new concepts for VELUX roof windows.

4.4.1 Brainstorming

Brainstorming is a collaborative idea-generating process crucial for fostering creativity and exploring multiple concepts, with the goal to identify promising solutions (Cross, 2008). In this thesis, brainstorming is crucial during the conceptualisation phase, particularly for generating circular innovations for windows that tackle complex linearity barriers in the sector.

4.4.2 Product Specification

A product specification outlines the necessary requirements and preferences for an ideal solution to fulfil a specific purpose (Cross, 2008). It facilitates collaboration across professions by defining criteria and demands. Essential during the conceptualisation phase, it enables iterative improvement of concepts and evaluation to identify the most suitable solutions.

4.4.3 The Morphological Chart Method

The morphological chart method is a way of generating and systemically combining ideas into concepts. The researchers structured the criteria from the product specification and sorted the brainstormed ideas into these individual parameters. Combining ideas in multiple ways, it facilitated a creative conceptualisation process, for finding radical new innovations. By examining how well these combinations were answering the product specification, the best solutions could be identified (Cross, 2008).

4.5 Assessing the Environmental Burdens

While certain aspects of LCA may be theoretical, particularly when interpreting results in a specific manner, it is primarily employed in the thesis as a method. When addressing the fourth sub-question, the researchers utilise the LCA method to quantify environmental burdens.

4.5.1 Life Cycle Assessment

LCA was chosen for this thesis due to the availability of reliable data, and given that it is a recognised environmental assessment method in the building industry. A LCA allows for the evaluation of the full life cycle of a product or system by quantifying its environmental impact across various impact categories (Hauschild et al., 2018). A LCA consists of four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The primary reason for performing an LCA and adopting a life cycle-oriented approach is to identify and prevent burden shifting between life cycle stages (Hauschild et al., 2018).

Within the LCA world, the Environmental Product Declaration (EPD) is becoming the standard framework to model building components (Konradsen et al., 2023). Regarding EPD frameworks the EN15804+A2 framework that builds on the general ISO 14040/14044 LCA framework is chosen for this thesis. The researchers have chosen to model with the use of attributional unit processes, as it is the most common modelling approach for EPDs. The chosen system model is allocation cut-off, which determines that the environmental burdens connected to the waste scenario are allocated to the producer of the waste, which hereby follows the "polluter pays" principle (Ecoinvent, 2024). This leads to the total modelling approach of EN15804+A2, Attributional, Cut-off.

The applied simulation software is SimaPro 9.6.0.1 and Google Sheets with the use of the Ecoinvent 3.10 database combined with results from other EPDs. The processes are mainly Danish (DK) or European (RER), but Global (GLO) processes are applied when no location specific processes are better suited. The life cycle inventory data is based on data from EPDs, literature and interviews, to make the simulation more accurate according to the modelled scenarios of roof windows placed in Denmark.

5. Theoretical Framework

In the following, the applied theories used in the thesis will be presented, along with the reasoning behind their selection and their analytical purpose in answering the research question.

5.1 Business Model Canvas

To understand how companies operate, a BMC can be utilised to describe a company's business model. It illustrates the rationale of how an organisation creates, proposes, delivers, and captures value (Osterwalder & Pigneur, 2013). In this thesis, BMC served as a valuable tool for examining current capabilities and identifying potential concepts that can be integrated into VELUX's existing business model. It was furthermore used to highlight differences in the proposed concepts for VELUX, enhancing their tangibility by building on the current business model. Additionally, inspiration has been taken from sustainable business models, where the value proposition has been broadened to include environmental and social propositions (Bocken, 2023), highlighting the business models' sustainable efforts.

5.2 Circular Economy

In opposition to the linear economic system that currently dominates the window sector, principles from CE are being applied to analyse the system. Additionally, elements from CE are used as a framework in this thesis for designing and describing circular concepts. This framework also identifies the barriers and drivers for greater CE adoption, aligning with the goal of sustainable development.

CE can be defined as *"a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops."* - (Geissdoerfer et al., 2016, p. 759). The overall aim of CE is to reach an absolute decoupling of the consumption of Earth's finite resources from economic growth (Ellen MacArthur Foundation, 2015). CE is widely acknowledged as a solution to tackle numerous sustainability challenges, primarily aimed at mitigating environmental impacts such as global warming potential and resource scarcity (Bocken, 2023; Bocken et al., 2016; Geissdoerfer et al., 2016).

The focus is on keeping products and materials in use for as long as possible, retaining their value best possible when circulated (Kirchherr et al., 2017). Complementary to the CE is the Waste Hierarchy, which serves as the priority order for waste management in European legislation and policy (European Parliament, 2008).

Figure 5 - The Waste Hierarchy (European Commission, n.d.).

This waste hierarchy helps prioritise different circularity options placing the best in the top of figure 5, based on the value they retain. The waste hierarchy provides a straightforward way to determine which approach is preferable and is further considered as a set of initiatives aimed at achieving absolute decoupling (Geissdoerfer et al., 2016). Moreover, certain business models contribute to transitioning towards a CE.

5.2.1 Circular Business Models

The CE can be made more tangible for companies through the adoption of circular business models. Being a subset of sustainable business models, these models are based on the core principles of the CE, specifically focusing on strategies related to slowing, closing, and narrowing resource loops (Bocken et al., 2016; Bocken, 2023; Buchard &

Christensen, 2024; Geissdoerfer et al., 2016). Product-Service Systems are a type of CE model that yields potential for absolute decoupling, with an emphasis on service-oriented solutions over traditional product ownership, leading to more efficient use of resources (Kjær et al., 2019; Tukker, 2015). While services for windows are possible, service-oriented solutions for windows are generally not feasible because they are considered fixtures, which legally prevents them from being sold as a service (Ploeger et al., 2019). Additionally, as the case study focuses on AISL management, CE strategies based on the waste hierarchy have been chosen as the primary strategic fundament. Potting et al. (2017) has combined nine CE R-strategies with principles from the Waste Hierarchy, as shown in Figure 6.

The R-strategies are prioritised on a scale from linear to CE practices. This prioritisation helps to distinguish between different types of circular strategies and the level of value retention they provide. The model additionally introduces extended terminology to clarify the distinctions between the various circular approaches (figure 6).

In this thesis, circular business models are developed and evaluated based on the principles of circular strategies, and their level of value retention. Furthermore, an environmental assessment is conducted to quantify the environmental impact of the concepts.

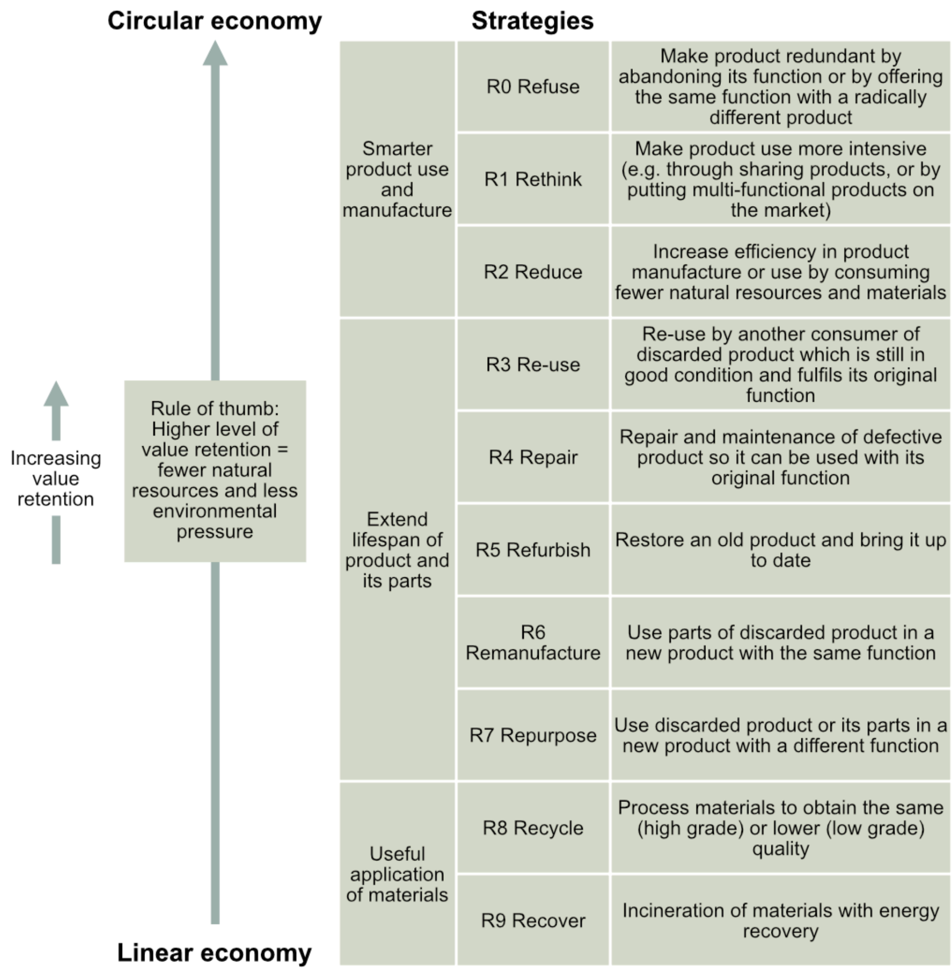

Figure 6 - R-strategies in aiming for CE, inspired by Potting et al. (2017).

5.2.2 Life Cycle Management

Life Cycle Management (LCM) refers to the strategic approach of having a life cycle perspective when considering both up- and downstream processes in a product chain in aiming for sustainable development of a certain product, service or system (Itskos et al., 2016; Sanchez et al., 2004). LCM can be defined as *“Management of the company decisions that have environmental consequences at any point of the product’s life-cycle.”* - (Sanchez et al., 2004, p. 13). The researchers interpret LCM as a management approach for decision-making with both environmental, social and economic aspects in focus. It is crucial to consider potential *rebound effects* (Kjær et al., 2019) when making decisions, especially when choosing one option over another. LCM highlights the importance of understanding a company's *decision space*, encompassing the range of choices and autonomy in altering a product's lifecycle (Sanchez et al., 2004). Another key term is *improvement potential*, focusing on opportunities to enhance environmental performance (Sanchez et al., 2004). Assessing VELUX's influence and capabilities within its decision space, and identifying improvement potentials, is essential. As LCM provides a life cycle perspective in a corporate setting, it directs efforts towards designing concepts feasible within VELUX's decision space, ensuring optimal environmental performance and avoiding burden shifting across life cycle stages.

5.3 Carbon Lock-in

In evaluating the current challenges that circular innovations and the overall shift towards a CE face, *lock-in theory* as defined by Unruh (2002) and Seto et al. (2016) helps explain how existing systems hinder the transition to a more sustainable, CE-based building sector.
The theory highlights the rooted systems currently operating in our society, through significant investments over time have become standardised ways of operating. It stresses moving from a linear economy to a circular one requires *systemic change* beyond sheer technical feasibility. The inertia of these incumbent systems is limiting the possibility of such a transformation, due to a *path-dependent* process known as *carbon lock-in* (Unruh, 2002).

While lock-in theory has an emphasis on the challenging act of changing the current systems, it also addresses how these incumbent lock-ins can be *disrupted* and *plasticity* can be made, allowing for shifts away from them (Seto et al., 2016). Governments and policy decision-makers possess the ability to influence and change the dynamics of existing systems, thus determining which systems are favoured (Seto et al., 2016). This is particularly evident in the study’s context with the implementation of the EU Green Deal and subsequent legislation (European Commission, 2019). These actions compel market mechanisms to incorporate environmental externalities and prompt national policies to prioritise transitioning towards more sustainable practices. Consequently, a step towards disrupting unsustainable lock-ins, and favouring those opting for sustainable transitions.

While *Multi-Level Perspective theory*, as defined by Geels and Schot (2007), could have been an alternative to lock-in theory for understanding the dynamics of socio-technical transitions and how *regime* shifts occur, it has a more systemic view and lacks the ability to differentiate between challenges within the incumbent regime. In contrast, lock-in theory offers better capabilities for describing the multifaceted nature of lock-ins within incumbent systems, particularly with Seto et al.'s (2016) categorisation of lock-ins. The categorisation separates the lock-ins into three levels: (1) institutional lock-ins involving legislation and governance; (2) technological lock-ins involving technologies and infrastructural elements; and (3) behavioural lock-ins related to values, habits, and norms (figure 7). The categorisation offers a clearer overview and distinguishing between different types of lock-ins, while emphasising their *intertwinedness* across the various levels.

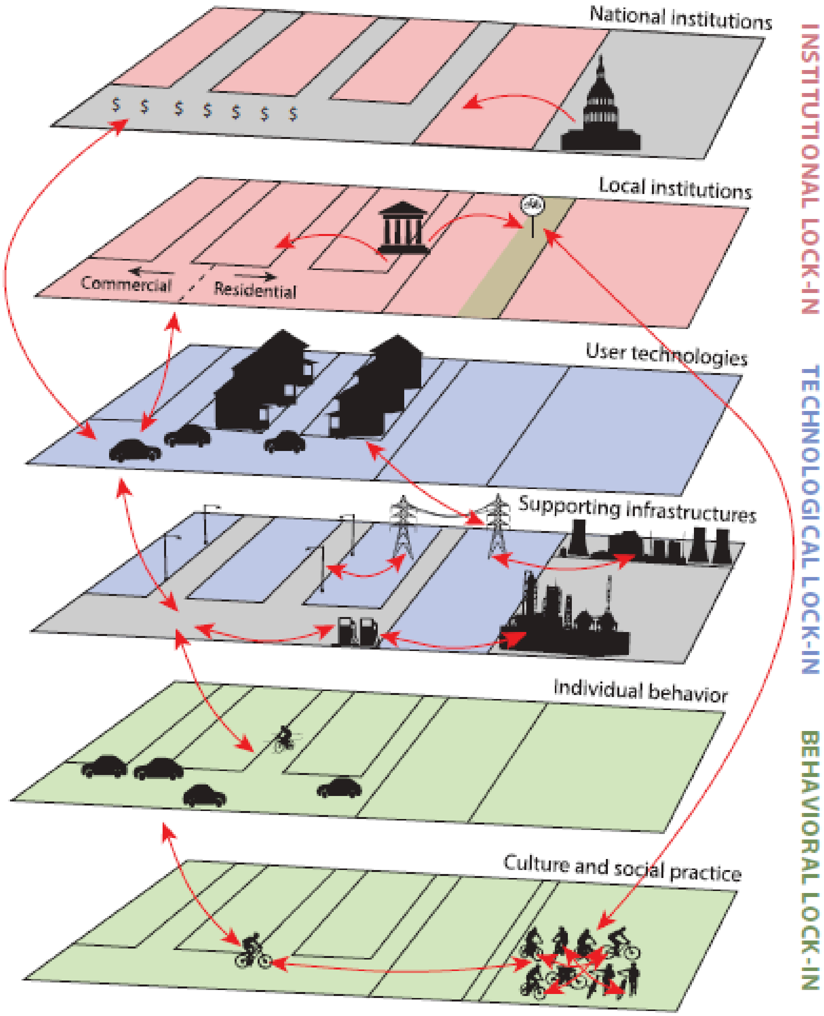

Figure 7 - Lock ins by Seto et al. (2016)

While carbon lock-ins in the literature typically focus on energy systems and carbon emissions, they can also be identified as *linear lock-ins* that inhibit the building sector's transformation to a CE. Emphasising linear lock-ins at institutional, technological, and behavioural levels provides a comprehensive framework for investigating challenges and drivers for circular innovation in the field.

Lock-in theory's capability to explain how society got to be what it is and why CE innovation has challenges, has the downside that the theory has a static nature and limitation of explaining how to facilitate transformation away from the current. Translation theory has been chosen in addition to the thesis, to fill out this gap, which will be further elaborated in the following section.

5.4 Translation Theory

To describe the actors, objects, and relations in the networks associated with VELUX roof windows, and how these can undergo change, the translation theory (Callon, 1986), a part of actor-network theory (ANT), is applied. ANT focuses on the relations among *actors*, both human and non-human, and understands an actor's *agency* through their roles and their capacity to influence the networks they are part of (Callon, 1986). Networks are formed when actors come together to express ideas or agendas, which within the framework of ANT can be seen as instances of innovation or acts of change. Consequently, the success of change and innovation can be attributed to the ability to establish stable networks by engaging and involving specific actors while potentially excluding those who oppose the network's agenda. The act of forming and stabilising networks can be defined as *translation*, consisting of processes of negotiation, transformation, and alignment of interests between actors that did not exist before (Latour, 1994). Callon's (1986) conceptual framework breaks down the processes of translation into four key moments: *problematisation*, *interessement*, *enrolment*, *mobilisation*. These moments provide insight into how actors and their interests are transformed and stabilised through negotiation and interaction processes, which is a crucial step in securing collaborative objectives that can be reached.

In the case study, translation theory within ANT is essential for understanding how to drive transformation towards a CE within the building industry. ANT allows for the analysis of diverse actors and power dynamics within networks, while translation theory ensures that relevant aspects for the transformation are addressed. This enables developed concepts to resonate with stakeholders, become actionable strategies, and effectively facilitate meaningful change.

5.4.1 Micro and Macro Actors

The concept of *micro* and *macro actors* in ANT is valuable for analysing actors within networks and their translation agency. While theoretically, all actors are considered micro actors, the distinction arises from their relational agency towards each other. An actor can be perceived as a macro actor if they can translate their ideas and interests to other micro actors. This implies that macro actors hold significant influence within networks, shaping the actions and decisions of other actors through their ability to mobilise resources, enact roles, and align interests (Czarniawska & Joerges, 1996).

5.4.2 Obligatory Passage Point

Another concept defined by Callon (1986) is *Obligatory Passage Points (OPP)*. The purpose of the OPP concept is to offer alternative passage points for micro actors, enabling them to achieve their goals. This disrupts the BaU and bypasses old passage points filled with obstacles. If the proposed OPP is adopted by the actors within the network, it signifies a successful translation initiated by the proposing actor. This can elevate the actor to the status of a macro actor, granting them greater agency to influence micro actors and drive change (Rottenburg, 1996).

5.4.3 Summarising Translation Theory

Understanding how networks are translated is essential for initiating the systemic change necessary to transition towards a CE. By employing this theory, researchers can explore how VELUX, as a company, can leverage its size and decision space to influence the building sector and form partnerships. Utilising OPPs, this influence can engage and motivate stakeholders toward a common goal of transitioning the building industry to a more CE. The theory also highlights that decisions are not solely the products of rational consideration of where the greatest environmental outreach can be gained, but are influenced by various interests that may converge or conflict (Akrich et al., 2002). Accommodating these diverse interests is crucial for driving meaningful change.

6. Analysis 1 - Lock-ins in the Current System

This analysis attempts to map out the current AISL processes for managing roof windows, as well as the linear lock-ins that reinforce the existing system:

Sub-question 1: What are the current barriers to implementing circular economy practices in the lifecycle management of VELUX roof windows?

To begin understanding the current barriers for implementing CE practices, the researchers have investigated VELUX to gain insights into the company's business and capabilities.

6.1 The Case of VELUX Roof Windows

VELUX is a Danish window manufacturer known for its extensive range of roof windows and accessories. To enhance the comprehension of VELUX's business model, a BMC was completed, concentrating on operations concerning roof windows and their decision space regarding AISL (figure 8). This focus was chosen due to its relevance to the thesis' research question. The BMC for VELUX has been developed from the collected empirical data, and partly in collaboration with VELUX collaboration partners, Gylling and Terkelsen (2024).

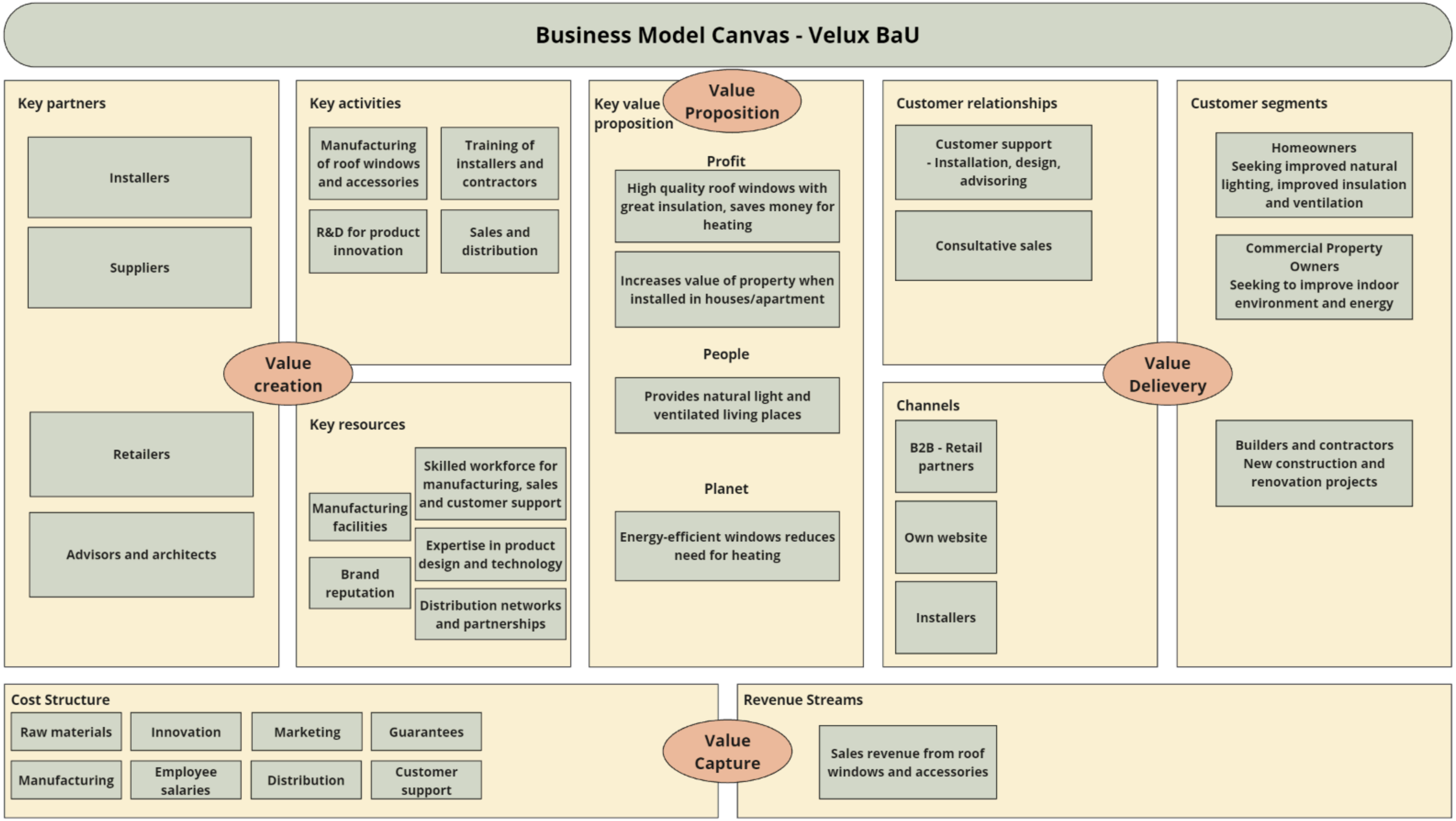

Figure 8 - BMC of VELUX's business as usual operations

Some of the key value propositions related to VELUX's business model are high-quality roof windows that provide natural light and ventilated places. When looking at VELUX's business model (figure 8), some of the key partners are suppliers of raw materials and components (*VELUX*, n.d.-a). As VELUX primarily distributes their windows through business-to-business retailers, these key partnerships hinder their ability to assess the windows' post-sale outcomes due to limited contact with final customers (Gylling & Terkelsen, 2024). VELUX's web page serves as a key channel for customers, offering extensive information about their roof windows. Additionally, installers play a crucial role as key partners, responsible for the installation and dismantling of windows at the customer's site. VELUX offers education for installers, qualifying them better for installing the products (*VELUX*, n.d.-b). The cost related to the roof windows is related to the supply of raw materials, manufacturing, employee salaries, innovation, marketing, distribution and customer support. VELUX's primary revenue comes from selling virgin roof windows.

The BMC for VELUX reveals how their business inherently adheres to a linear economy, primarily focused on manufacturing and selling new roof windows. However, gaining a deeper understanding of their operations provides valuable insights into VELUX's business model and their capabilities within their current decision space to adopt circular business models.

The following text will focus on identifying the apparent linear lock-ins in the building sector, categorising them as institutional, technological, and behavioural (Seto et al., 2016) to provide a clearer overview and emphasise the multifaceted nature of these lock-ins in the building sector.

6.2 After Initial Service Life Management of Roof Windows

In collaboration with VELUX, a case study was defined to investigate the AISL management of VELUX roof windows, an area where VELUX currently has limited insight (Gylling & Terkelsen, 2024). This case was chosen to focus on existing roof windows in the market and their role in transitioning to a more sustainable future. The researchers examined this topic by reviewing reports, conducting field research, and performing interviews to understand AISL handling and waste management systems. Based on the collected empirical data, the identified AISL treatment of roof windows in the BaU scenario is illustrated in figure 9.

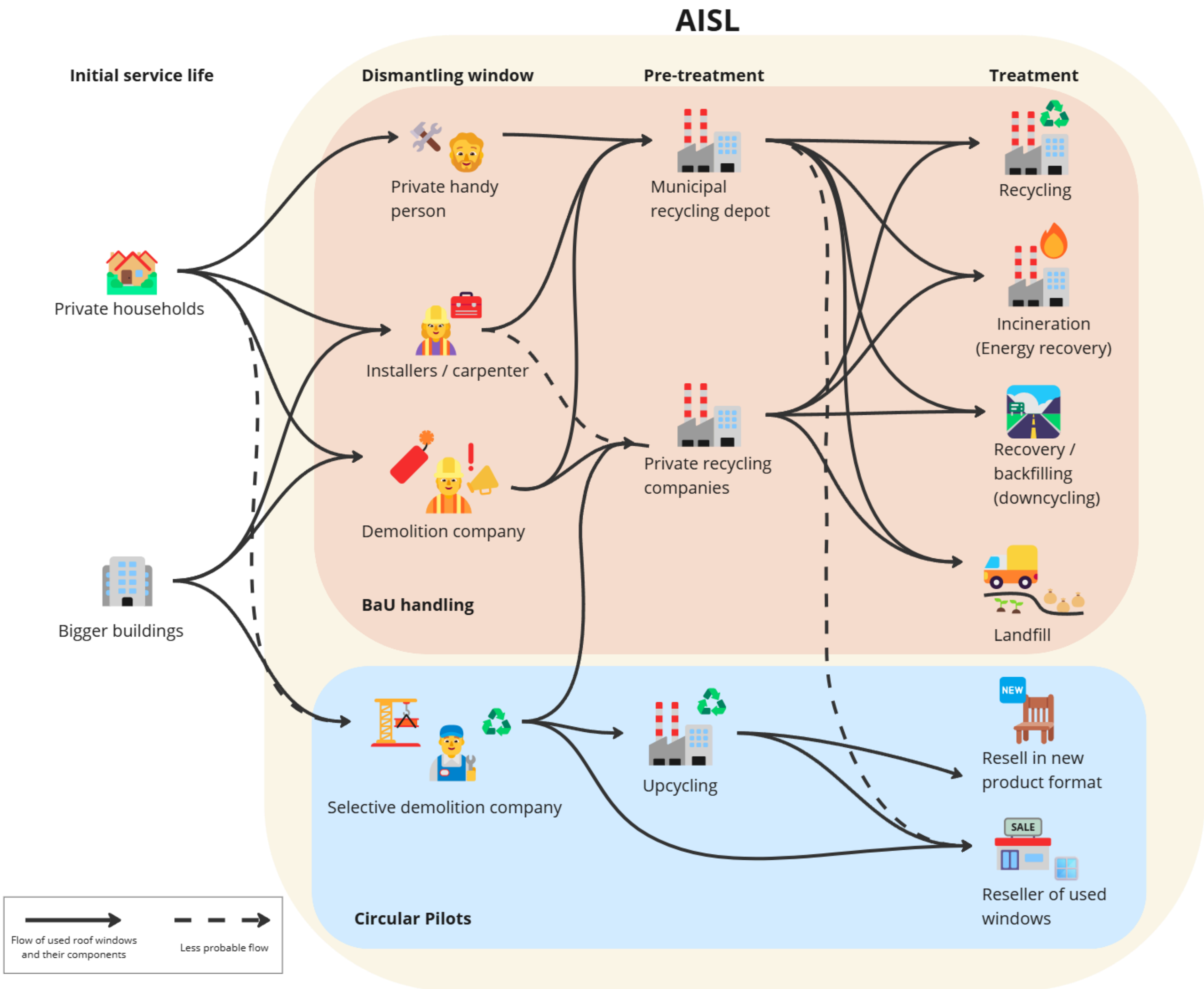

Figure 9 - Mapping of the current AISL flow of roof windows

As pictured in figure 9, the used windows can be categorised into coming from private households or larger scale buildings. The quantity of roof windows being disposed of will impact their EoL treatment and flow (Resource worker, 2024). According to a resource worker (2024) at Sydhavn Recycling Centre, it is primarily private citizens who provide used windows to the municipal recycling centre. For larger quantities of roof windows, professional installers and demolition companies typically stack them in large containers and transport them directly to private recycling companies (Møgelvang, 2024; Resource worker, 2024).

According to an assessment by Rambøll (2024), based on interviews with relevant stakeholders, the majority of windows, including roof windows in Denmark, are used for relatively linear purposes. Window frames are mainly incinerated for energy recovery, glass is crushed and used in backfilling for road construction, and aluminium and metal are recycled. Non-metal parts from blinds, awnings, and shutters, made of fabric and plastic, are mostly sent to landfill or incineration. According to a Resource Worker (2024), unpainted window frames are recycled into chipboard. A consultant from Amager Resourcecenter (Glottrup, 2024) has indicated that there is a screening procedure of windows when they are collected at municipal recycling centres. This regards age, thermal insulation, materials and production methods, which sets a guideline of how the windows should be treated (Glottrup, 2024).

Overall, the researchers identify an environmental problem in the current AISL handling of windows due to linear lock-ins. The high degree of linearity and downcycling leads to low value retention of the used roof windows, emphasising the improvement potential. While the overall system is dominated by linear practices, some pilot initiatives striving for more sustainable handling of used windows have been identified. The drivers and opportunities for these solutions will be discussed in analysis 2.

6.3 Technical Obsolescence

When examining the possibilities for prolonging the service life of the roof windows, there are some barriers related to technical obsolescence. According to a technical advisor at VELUX, Jesper Nielsen (2024), VELUX roof windows on average get outdated and obsolescent after 25 years of installation. This deterioration occurs mainly due to a lack of maintenance. Maintenance involves keeping the flashing clean for proper water flow, tightening window frame screws, inspecting and lubricating fittings, treating timber surfaces as required, and ensuring daily ventilation to prevent moisture accumulation and mould growth. Consequently, continuous maintenance is essential for prolonging the lifespan of roof windows, emphasising that user behaviour plays a critical role in preventing deterioration (Nielsen, 2024). See the construction of a typical window in figure 10.

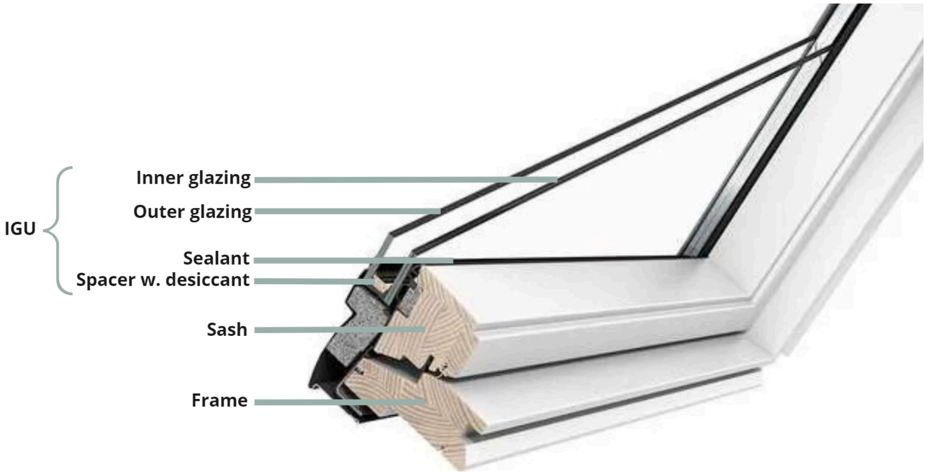

Figure 10 - Cross section of a VELUX roof window (Roofgiant, n.d.)

Another issue in the construction of the roof windows is the sealant between the IGU and the sash (Nielsen, 2024). Over time, the filling, commonly Argon, in the IGU will leak. As this gas evaporates, air enters the cavity. The moisture in this air is absorbed by the desiccant, typically located in the spacer known as molecular sieves (Nielsen, 2024). When the desiccant reaches its maximum capacity and can no longer absorb moisture, the humidity becomes visible within the glass cavity. This indicates that the IGU has reached the end of its service life, which has an estimated lifespan of 15 years (Nielsen, 2024). How this affects the lifespan of the window is uncertain, but it may reduce the service life of the whole roof window.

According to a Product and Regulation Specialist at VELUX, Karsten Duer (2024), VELUX roof windows have gas in the pane and a low-emission coating. *"When applying a low-emission coating, radiation exchange decreases, and heat loss is roughly halved. If you also replace the air with an inactive gas like argon, you suddenly get a very effective pane".* - (Duer, 2024). One challenge in considering the reuse potential of roof windows is the difficulty in determining the presence of gas in the IGU and the effect of low-emission coating on emissivity, if any (Duer, 2024).

One important consideration regarding used windows is the presence of any concerning substances. PCB, for instance, was commonly used in window construction until 1977, when it was classified as a poisonous substance (Halvarsson, 2024; Miljøstyrelsen, n.d.; Resource worker, 2024). Additionally, it is crucial to ascertain whether the windows have been contaminated with asbestos, a substance found in various building materials that can pose a risk during demolition. Asbestos was commonly used in building materials until 1988, often close to windows, and is also known to be hazardous to health (Resource worker, 2024; Sode & Galán, 2024).

6.4 Institutional Obsolescence

At an institutional level, there are some regulatory challenges that need to be considered when creating window solutions based on circular strategies.

6.4.1 The Danish Building Regulations - BR18

The revised Danish Building Regulations (BR18) sets requirements for the insulating properties and thereby the energy balance of roof windows (Social og Boligstyrelsen, 2024). When installing windows in new year-round housing, the roof windows' energy balance must not be less than: 10 kWh/m2/year. This can be calculated by the formula presented in figure 11.

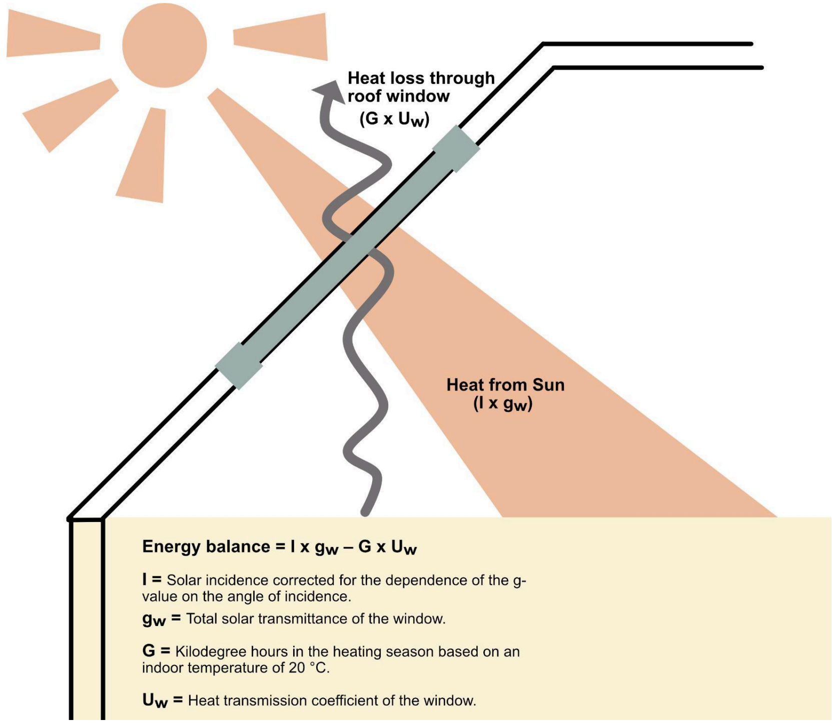

Figure 11 - Energy balance of a window (Social og Boligstyrelsen, 2024).

The I and G values are predetermined in Denmark, giving this equation:

$$\textbf{Energy balance} = 196{,}4 \times g_w - 90{,}36 \times U_w$$

The solar transmittance (g_w) and heat transmission coefficient of the window (U_w) are tested and provided by the manufacturers of windows. This is done as part of the mandatory CE-marking of the products by the manufacturer (Duer, 2024). CE-marking has become a standard for all new windows at VELUX since 2008. However, assessing the heat transmission for a used roof window can be difficult and expensive (Duer, 2024). Furthermore, the majority of the windows currently being disposed of are double-glazed, which does not meet current energy balance standards. Current requirements in Denmark necessitate triple glazing windows for optimal energy balance (Gylling & Terkelsen, 2024; Hansen, 2024; Møgelvang, 2024).

Although this regulation aims to improve housing insulation and reduce the need for heating, it makes reusing roof windows in new buildings difficult, creating an institutional linear lock-in. Furthermore, the applicability of the potential circular concept relies on its ability to match the energy balance provided by newer windows. VELUX roof windows ability to utilise solar transmittance to produce heating, provide an environmentally sustainable heat source, when it is able to substitute other heat sources in residential buildings. Consequently, environmental assessments attribute carbon emission savings to their use.

In a VELUX LCA comparing a roof window providing heat to a scenario without a roof window, an expected energy saving over 30 years is projected, resulting in a net negative impact of -180 kg CO2e considering all processes (The VELUX Group, 2023). Despite it can be criticised for assuming a direct energy correlation and lacking detailed insight on the reference scenario, it underscores the importance of energy balance in conceptualising alternative solutions.

6.4.2 Waste Framework Directive and End-Of-Waste Criteria

In the BaU scenario, when removing used roof windows, they will be categorised as waste according to the definition outlined in the Danish Waste Regulation (Affaldsbekendtgørelse, 2021), which aligns with the Waste Framework Directive set forth by the European Parliament (2008): *"'Waste' means any substance or object which the holder discards or intends or is required to discard"* - (European Parliament, 2008, p. 3).

An expert in the field states there are problems related to the current Waste Framework Directive as it opposes the feasibility of reusing building components (Buchard, 2024). The Waste Framework Directive (2008) has set up some end-of-waste definitions for when waste can be transformed and used for non-waste purposes:

- *"the substance or object is to be used for specific purposes;*
- *a market or demand exists for such a substance or object;*
- *the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and*
- *the use of the substance or object will not lead to overall adverse environmental or human health impacts"* - (European Parliament, 2008, p. 8).

When it comes to reusing roof windows, they must meet specific requirements, which can be challenging. Innovating new uses for C&DW requires an existing market or demand for that particular substance or object (Buchard, 2024). Another challenge is that the "waste" shall comply with the *Construction Products Regulation* to be used in new buildings when sold as a good (Buchard, 2024). If one intends to reuse the component in an existing building, it does not have to comply with the Construction Products Regulation, but it must meet technical and health criteria. When goods are given away for free, it does not have to adhere to it (Buchard, 2024), providing a legal opportunity to reuse more second-hand building materials.

6.4.3 Waste Management Tax

According to a private waste management company and selective demolition company, the low incineration and landfilling tax in Denmark creates a competitive disadvantage for them against stakeholders who opt to incinerate roof windows. This situation poses a significant challenge to efforts aimed at reusing or recycling windows (Halvarsson, 2024; Hansen, 2024). Furthermore, selective demolition is often more costly than traditional demolition, primarily due to its time-consuming nature. This can be considered as an institutional lock-in which opposes a more sustainable transition towards waste treatment with better sorting and recycling.

6.5 Behavioural Lock-ins

Regarding behavioural lock-ins, it is relevant to study how people perceive the used windows. Some actors experience a low demand for used VELUX roof windows, possibly influenced by the absence of warranties, as reused materials cannot be guaranteed, which may impact customer demand (Hansen, 2024; Jørgensen, 2024; Møgelvang, 2024). In contrast, a resource worker from Sydhavn Recycling Centre (2024) has pointed out that there is a high demand for used roof windows at their municipal sharing area, especially if they are handed over still attached to the frame. Meanwhile it is a standard procedure for Kingo Karlsen, a demolition company, to cut over the frame of the window, to disinstal the window fast at buildings sites and private homes (Møgelvang, 2024). According to an installer who has worked with both facade and roof windows, it is relatively easy to remove roof windows along with their frame (Zethner, 2024). This is also confirmed from the second hand store, Genbyg, *"Windows are mounted with screws and are fairly easy to take down again."* - (Jørgensen, 2024, p. 3).

Newer windows, with triple glazing, have become heavier to handle. This is a factor J. Jensen Genbrug considers when screening used windows, emphasising the importance of safety and ease of handling for installers (Hansen, 2024). According to the installer, Zethner (2024), the used roof windows are generally in decent condition when removed, but installers typically would not choose to install them in their own homes. Genbyg does not undertake any upcycling activities such as painting, as there is currently no demand for it, despite its potential positive impact on window quality and lifespan extension (Jørgensen, 2024).

6.6 Summarising the Lock-ins

To summarise the above mentioned lock-ins related to VELUX roof windows, they can be placed in a model separated by the type of lock-in (figure 12). Applying lock-in theory helps illustrate how deeply embedded linear lock-ins are in the building sector and how they are interrelated. This highlights the significant challenges that circular innovations will inevitably face in working towards a sustainable transformation.

It further allows for the analysis of lock-ins in connection with each other, reducing the system into a more tangible subject of study. This enables an understanding of the mechanisms and structures that constitute it.

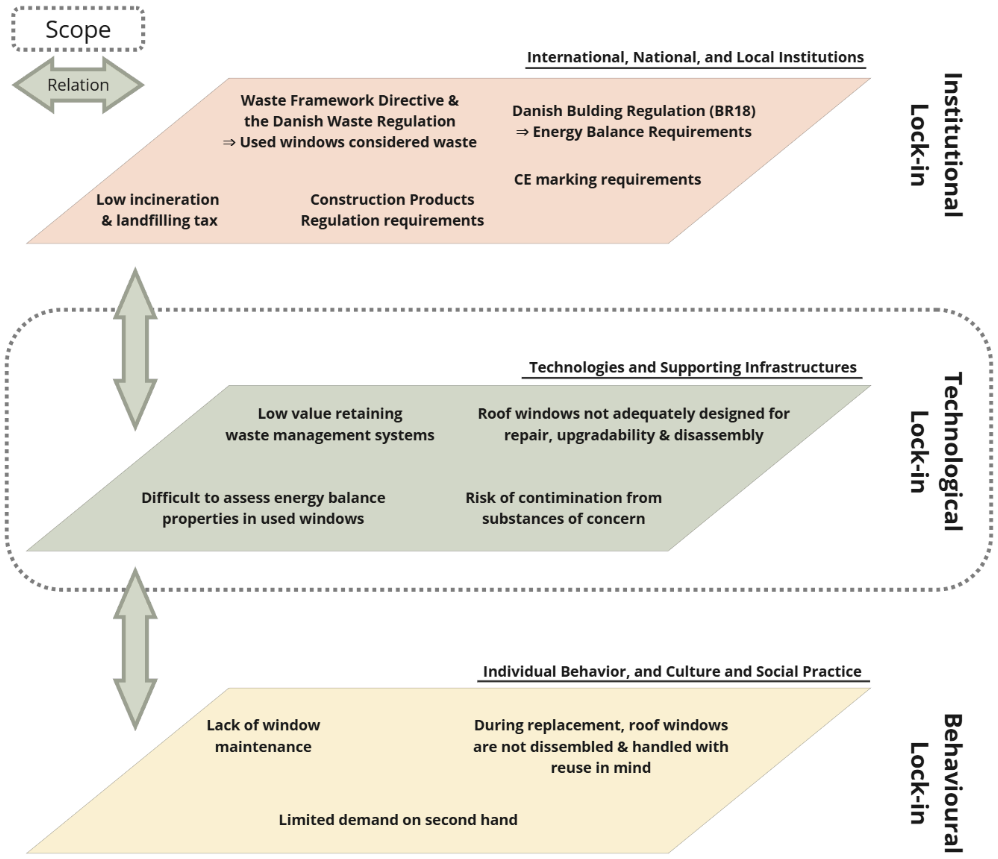

Figure 12 - Lock-ins in the BaU inspired by Seto et al. (2016).

As illustrated in figure 12, this thesis primarily focuses on the technological domain, particularly on technologies and supporting infrastructures. This focus is chosen because it represents a decision space where VELUX can disrupt linear lock-ins and realise improvement potentials. In the technological dimension, linear lock-ins are viewed as product/system design challenges, where suitable solutions can be explored. Elements of behavioural and institutional aspects are also included in this thesis to provide a comprehensive understanding of the system context affecting roof windows, as indicated by the arrows in figure 12.

At the institutional level, reinforcing lock-ins exist due to international EU regulations such as the Waste Framework Directive and the national Danish Waste Regulation, which define building and construction waste and complicate the reuse of building components in new constructions. The Construction Products Regulation and BR18 contribute to defining the performance and condition criteria that second-hand roof windows must meet.

Technological lock-ins in the design of roof windows make repairs difficult and hinder the development of circular concepts due to the energy balance requirements they must comply with. Additionally, assessing the quality of used roof windows demands significant human resources, and current infrastructures favour a linear life cycle for roof windows as it is often the quickest and easiest disposal method.

Behavioural lock-ins show the conflicting views on handling of roof windows and their demands highlight the multifaceted behavioural nature surrounding window usage. This complexity must be considered when designing AISL management solutions, aiming for options that fit various contexts. Furthermore, this underscores the importance of examining the behavioural aspects related to usage context to investigate the underlying factors driving demand.

In summary, there is significant potential for improving circularity in the current practices for VELUX roof windows. Drivers and opportunities for more CE will be further elaborated in Analysis 2.

7. Analysis 2 - Drivers and Opportunities for Circular Business Models

To facilitate the transition of companies in the building industry towards a CE, it is essential to adopt CE strategies and corresponding business models (IPCC, 2022). These models serve as practical tools for companies to translate the abstract concept of a CE into tangible actions within their operations. They offer significant environmental improvements, under the condition that the value proposition includes a high level of value retention (Lindahl et al., 2014).

Sub-question 2: What opportunities and drivers exist for adopting circular business models for VELUX roof windows after their initial service life?

Through research, various pilot projects and business models related to roof windows have been identified. These projects and models, to some extent, address linear lock-ins and advocate for a CE. Stakeholders associated with these initiatives have been interviewed to indicate the potential of their solutions in addressing linear lock-ins and promoting CE principles, as well as to identify the challenges they face.

7.1 Circular Pilots for Windows

The following section will review findings and insights into existing initiatives that can be further developed.

7.1.1 Take Back Pilot in the Netherlands

As part of the Dutch government's efforts to promote circularity in the building industry, VELUX Netherlands has initiated several circular projects. One successful pilot involved a collaboration with PreZero, a waste management company, to implement an open-loop take back system for roof windows (figure 13). The objective was to retain the window components by repurposing materials for reuse. This process disassembles windows to separate the wood from the other components, planning it down to remove any toxic elements. The repurposed wood is then used for applications like furniture, instead of being incinerated (Vreeken, 2024).

Figure 13 - Tables made out of wood from roof windows (Vreeken, 2024).

Repurposing the wood is preferable to its typical fate of being sent to incineration. However, it is important to note that wood generally has a relatively low carbon footprint, comprising only 4% of a generic VELUX window (The VELUX Group, 2023). The system falls short in terms of cost-effectiveness, as the final products are more expensive than alternatives made from virgin materials. This issue may stem from the business model's need for maturity and scaling, as of the prevailing linear lock-in system that favours cheaper virgin production.

Despite these challenges, the solution encompasses improvement potentials for inspiration. Exploring methods to utilise window components and extend their service life, could result in more efficient use of these materials. Although the project could be improved from an environmental perspective, it serves as an example of how building materials can be managed at the end of their life cycle in a manner that retains value and aligns with CE principles.

7.1.2 Repurpose to Indoor Wall Panels

A:gain is a company dedicated to upcycling building materials from urban mining, and has also had a focus on repurposing components from windows. In one of their projects, they concentrated on repurposing IGUs from windows, transforming them into indoor wall panels to substitute the conventional thicker tempered glass panels (A:gain, n.d.). This is made possible through collaboration with selective demolition companies that also resell reused building materials. The demolition companies supply A:gain with IGUs separated from used windows. These IGUs are then incorporated into wood panels by A:gain (see figure 14). Designed for disassembly, the panels are produced without glue or joint filler, facilitating easier separation and recycling when the wall panels reach the end of their lifecycle (Risom, 2024).

Figure 14 - Indoor wall panels made from repurposed IGUs (A:gain, n.d.)

A:gain currently faces challenges from limited demand, primarily because their upcycled products are often more expensive than conventional alternatives. This is due to price being a determining factor in the current linear system.

While the repurposed IGUs may not offer the same level of soundproofing and hardness as conventional tempered glass panels (Risom, 2024), this solution presents a more sustainable approach to handling glass while avoiding virgin glass for panels. Glass contributes significantly to the carbon footprint of a generic window, accounting for 26% of the total footprint (The VELUX Group, 2024). By extending the life cycle of the glass through repurposing instead of the typical practice of downgrading it significantly in an energy-demanding process, A:gain's solution proves to be a step in the right direction for a CE.

7.1.3 Refurbishment for Better Energy Balance

A window company, Optoglas, specialises in refurbishing windows by installing inner secondary glazing directly on the sash (figure 15). This process serves to preserve historically protected buildings with vintage single-glazed windows, as well as residential buildings where energy balance demands are not obeyed with current windows and replacement is deemed too expensive (Optoglas, n.d.-a). While initially developed without environmental sustainability in mind, this approach effectively extends the service life of windows, allowing them to remain in place when they would otherwise need replacement due to poor energy balance. Furthermore, Optoglas has started further prototyping their solution for roof windows (figure 16), having previously only been working with facade windows (Nordahl, 2024).

Figure 15 - Windows refurbished with a secondary glazing (Optoglas, n.d.-b)

Figure 16 - Optoglas concept on a roof window (Nordahl, 2024).

These solutions are only viable if the window is not removed due to general demolition or significant wear. However, when applicable, this method offers a sufficient means of prolonging the window's service life without the need for extensive steps, as the windows can be refurbished without removal (Nordahl, 2024).

7.1.4 Reuse of Windows

As selective demolition gains traction among demolition companies, the market supply of second-hand building materials has increased (Hansen, 2024; Jørgensen, 2024; Møgelvang, 2024). This includes used windows in good enough condition for reuse, effectively extending the service life of windows that would otherwise have been disposed (See figure 17).

Figure 17 - Second-hand windows from selective demolition

Reusing windows is potentially one of the most environmentally sustainable ways to manage them AISL, as it ranks high according to the Waste Hierarchy. Implementing procedures for refurbishment and quality control could bring used windows up to a standard close to that of new ones. Moreover, creating a platform for reuse remains valuable, especially for newer windows that are removed and still suitable for use in new residential buildings. Even double glazing windows that fail to meet energy balance demands could find use in buildings without such requirements, such as non-heated rooms, vacation homes, and allotment huts (Buchard, 2024; Hansen, 2024).

7.2 Legislative Drivers

Looking at existing business models based on CE principles, it becomes clear that they are struggling against a system that favours linear economic solutions as they are often the cheapest opportunity. Although linear lock-ins currently dominate and are deeply embedded in the building industry, increasing awareness and action regarding planetary boundaries in the government bodies on the institutional levels presents an opportunity for change. The European Parliament's announcement of the EU Green Deal in November 2019 marked a pivotal moment, outlining a plan for sustainable approaches and legislation to achieve climate neutrality by 2050, decoupling economic growth from resource use, while leaving no people or place behind (European Commission, 2019). With the initiatives from the Green Deal, the EU aims at destabilising the linear lock-ins and their conditions, while pushing for CE incentives, acknowledging it as an approach to translate the actors who are a part of the network into a sustainable transition. The European Parliament can be interpreted as a macro actor who through the Green Deal has created an OPP for the member countries and their companies, agreeing to legislation that must be complied to, thereby translating the network to collectively work towards a sustainable transition.

7.2.1 Corporate Sustainability Reporting Directive

The Corporate Sustainability Reporting Directive (CSRD), which has been in effect since January 2024, requires larger publicly traded companies to adhere to sustainability reporting standards. This reporting provides companies with valuable information for informed decision-making and holds them accountable for their sustainability impacts. It also promotes transparency for investors and stakeholders, incentivizing sustainable practices (European Parliament, 2022). Sustainability reporting is considered a crucial step for selective demolition as companies are being put further accountable for the waste generated during the demolition of their buildings (Hansen, 2024). This can be considered as a driver to let companies utilise their windows longer, and favouring CE initiatives that have lower environmental impact than the virgin based alternatives.

7.2.2 Ecodesign for Sustainable Products Regulation

The Ecodesign for Sustainable Products Regulation (ESPR) mandates companies to adhere to Eco-design rules for their products, to push for more CE initiatives. These rules encompass CE information and performance requirements, among these considerations for embedded CO_2e (European Commission, 2022). Having concrete CE based requirements, further disrupts linear lock-ins and pushes for CE.

7.2.3 The Danish Building Regulations

As part of the Danish National Strategy for Sustainable Construction, since January 2023, there have been requirements for LCAs on all new buildings. Additionally, there are carbon emission limits for buildings larger than 1000 square metres, which will be progressively tightened with specific values set for 2025, 2027, and 2029 (figure 18) (Social og Boligstyrelsen, 2024).

Requirements for buildings (kg. CO_2e / m^2 / year)	2025	2027	2029
Vacation homes under 150 m^2	4,0	3,6	3,2
Family houses, terraced houses, tiny houses, vacation homes above 150 m^2	6,7	6,0	5,4
Apartment buildings	7,5	6,8	6,1
Office buildings	7,5	6,8	6,1
Institutions	8,0	7,2	6,4
Other new construction	8,0	7,2	6,4

Figure 18 - Climate demands for different types of housing (Social, Bolig og Ældreministeriet, 2024).

Moreover, the BR18 from January 2024 has begun to credit reused building materials as having zero emissions, further incentivising circular practices (Social og Boligstyrelsen, 2024; Svensson, 2024). This initiative means second-hand windows will be considered as having zero emissions when building or renovating. The same applies to A:gain's indoor wall panels, due to the use of repurposed IGUs and discarded wood used for the panels. Risom (2024) at A:gain anticipates that this legislation, along with the reuse credit initiative and the carbon emission limits on buildings, will benefit and significantly drive their concept, as well translate the industry towards circularity.

7.3 Mobilisation of Circular Business Models for Roof Windows

Investigating the field, it becomes apparent concepts and business models are out there and drivers for them are present. The prevailing linear lock-ins that however exist on institutional, technological and behavioural levels showcase multiple aspects that are to be addressed, in order for the CE agenda to succeed. Challenges of economic feasibility, lacking demand, supporting infrastructures, and technical challenges necessitate a transformation that can not be achieved by single companies alone but requires the translation of heterogeneous actors to succeed. An illustration of how the researchers aim at translating the current network around VELUX roof windows is illustrated in figure 19.

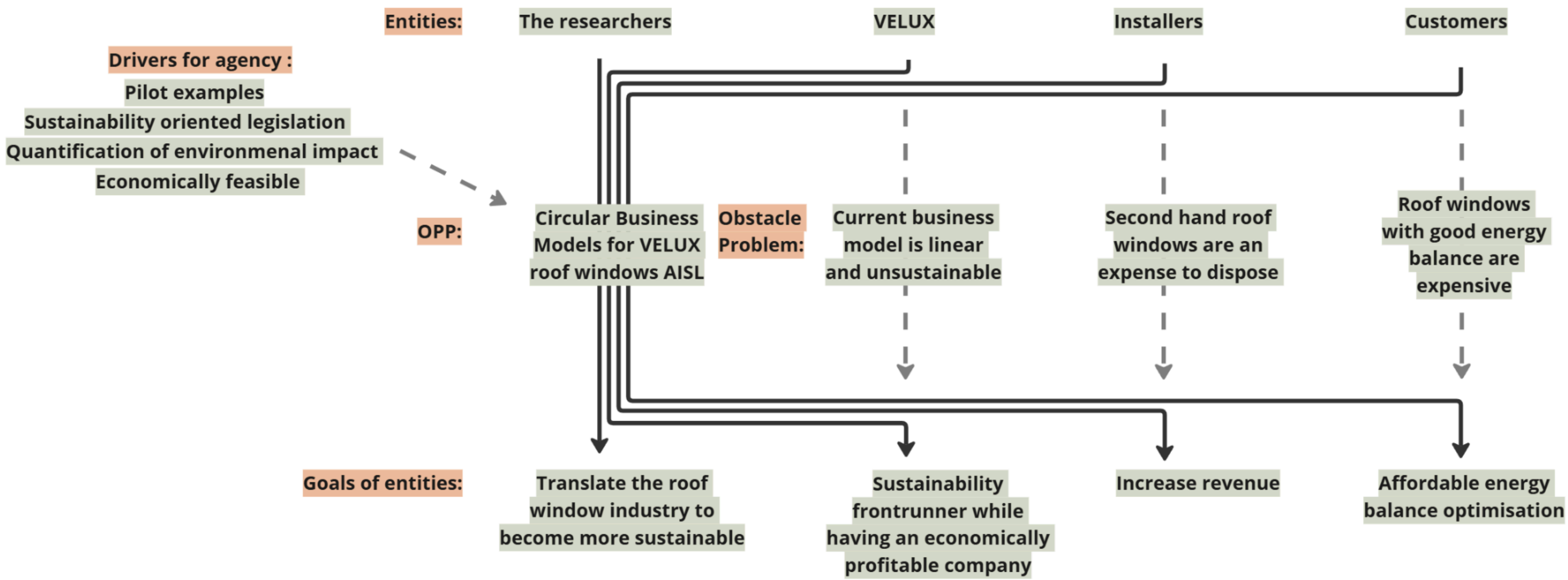

Figure 19 - OPP setup by the researchers in the network of VELUX roof window

Analysing the network of relevant actors with the use of the OPP model, provides a way to visualise relevant actors' problematisations and interests, and highlight what an OPP in terms of a circular business model should contain in order to have the ability to translate the network and mobilise circular design concepts.

As illustrated in figure 19, the researchers aim at translating the roof window industry to become more sustainable than the BaU. VELUX aims to lead in sustainability while maintaining a profitable business model. However, a significant obstacle, as outlined in analysis 1, is that their current revenue stream relies heavily on selling virgin roof windows that are neither circular or sustainable in itself. While installers currently view second-hand windows as an expense due to disposal costs, adopting a circular business model could shift their perspective, seeing these windows as a business opportunity and a way to increase revenue (Zethner, 2024). Lastly, since price is a determining factor for the demand for roof windows, customers seeking windows in good condition with a favorable energy balance may face an economic barrier. To translate this network of heterogeneous actors with different problematisations and goals, the researchers propose an OPP based on circular business models for VELUX roof windows AISL.

The circular business models should offer a solution where all the constituted actors can reach their goals. These circular design concepts can be considered as being supported by multiple driving factors, as highlighted in this analysis, which provides more agency for the solution to interest and engage the actors in the proposed network. If this enactment of interest succeeds, one can talk about a successful translation among the actors in the network.

7.4 Summarising the Drivers and Opportunities

The presented pilot concepts, each with their strategies and contexts of use, offer opportunities for circular-oriented projects in the face of a system dominated by linear lock-ins. The pilots demonstrate the potential and the means for a gradual but growing transformation towards a building sector based on a CE. The delay in implementing these pilot initiatives in the markets can be attributed to barriers outlined in analysis 1, such as lock-ins, which hinder their progress as they are still in the early stages of translation. Legislative initiatives are establishing standards and requirements to guide the future of the building industry towards more CE based solutions and inhibiting BaU. This shift is fostering plasticity within the entrenched linear lock-ins, facilitating space and improved conditions for the adoption of CE approaches.

While the prevailing system remains entrenched in linear lock-ins and their associated assets, researchers see a path for VELUX to drive a sustainable transition by leveraging opportunities and lessons from pilots and capitalising on forthcoming legislation promoting circular business models.

8. Analysis 3 - Conceptualisation of Circular Business Models

This analysis aims to conceptualise design concepts for the AISL management of VELUX roof windows, and investigate how these can address the linear located lock-ins.

Sub-question 3: How can design concepts for VELUX roof windows be developed to address identified barriers and reduce the environmental impacts throughout their life cycle?

Five design concepts were developed by the researchers, following the approach presented in figure 20.

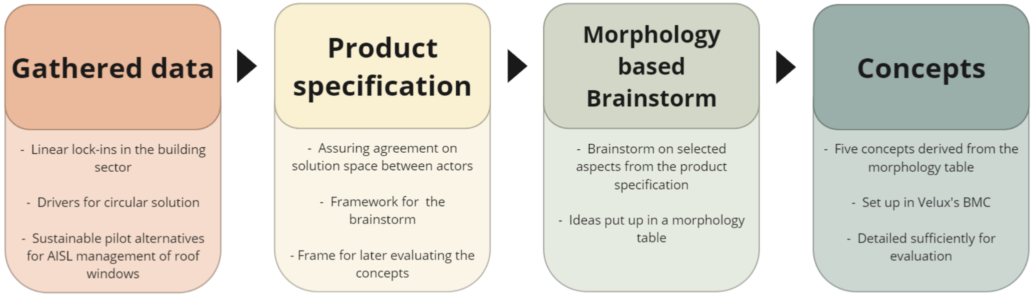

Figure 20 - Steps in the conceptualisation process.

The researchers developed a product specification from the gathered data outlining demands and criteria for the concepts. This specification aimed to create an optimal sustainable concept, contrasting conventional practices. Using the specification as a brainstorming framework, various ideas were conceptualised, drawing inspiration from pilot cases and CE strategies. The researchers then structured these brainstorming elements into a morphology table, combining elements into new concepts. The five final concepts were placed in a BMC to visualise their relationship to current operations and identify new elements needed for implementation.

8.1 The Conceptualisation Scenario

In the context of managing a roof window AISL, it is crucial to elaborate the foundational scenario driving this conceptualisation. This scenario occurs when a roof window within the current system needs replacement due to wear and tear, non-compliance with energy balance requirements, or a general desire to enhance thermal insulation. At this juncture, the researchers recognise a pivotal *moment of consideration* where various decisions can be made regarding the used roof window to meet the demands at hand (see figure 21). This marks the starting point of the conceptualisation process.

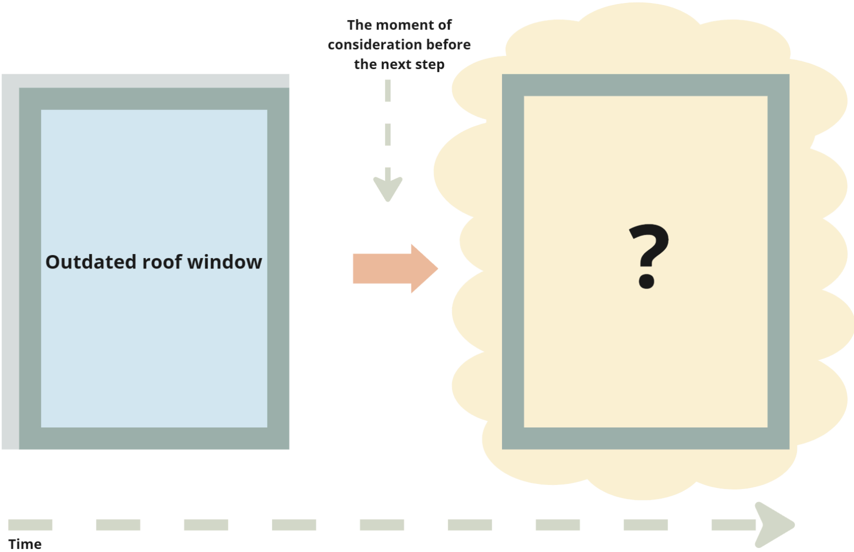

Figure 21 - Moment of consideration (own model)

In the conventional approach, known as BaU, it appears the resources already available are not considered, when aiming to meet energy balance demands. This typically involves disposing of existing windows and replacing them with triple glazing roof windows, neglecting to account for the embedded CO_2e associated with producing new windows. In contrast, this conceptualisation process begins by assessing the existing resources and considering what can be achieved with them. This involves exploring new solutions that can fulfil the function with the lowest possible environmental impact, while adhering to other relevant demands and criteria.

8.2 Developing the Product Specification

A product specification has been developed in order to set up demands and criteria for the design concepts to later evaluate them. Each criteria is assigned a Key Performance Indicator (KPI) to offer a clearer understanding of the specific aspect being evaluated for the given concept. The product specification can be seen on figure 22. In the following, the different categories and associated parameters will be assessed.

Category	Parameter	Demand	Criteria	KPI	Note
Environmental Sustainability	Closing		The concept should have the highest ratio of materials recycled when disposed	Ratio of recovered ressources to total ressources used	CE principle
			The concept should have the highest ressource recovery when disposed	Quality of ressource recovered compared to initial ressources used	CE principle
	Slowing		The concept should have the highest possible life span	Average Product Lifespan Before Disposal	CE principle
	Narrowing		The concept's material and energy consumption should be as low as possible	Mass of materials and energy used in life time	CE principle
	Global Warming Potential (GWP)	The concept must have a lower global warming potiential than the business as usual	The concept should have the lowest possible GWP from craddle to grave	GWP craddle to grave	CE principle
Economic feasibility	Labour hours		Minimum amount of labour hours needed for the concept	Labour hours pr. functional unit	Cost Structures / Revenue
	Price	The cost-to-benefit ratio needs to make sense for both manufacture and consumers.	The concept should generate the greatest financial profit for the manufacturer	Manufacturing cost pr. functional unit	Cost Structures / Revenue
Business Model Feasibility	Implementation		The concept should be easy to be implemented as a business model for the manufacture	Degree of readiness for the implementation of the concept	Translation of VELUX
	Market Flexibility		The concept should be adaptable to various customer segments	Ratio of applyability for existing windows	Translation of VELUX
Legislation	Thermal Insulation	The energy balance (Eref) for the window must not be less than 10 kWh/m2 per year	The concept should have the highest possible Eref value	Eref	Ref: BR18
	Hazardous substances	The concept must meet the requirements from the Danish Building Regulations regarding hazardous substances	The risk of the concept containing hazardous substances should be as low as possible	Risk of hazardous substance contimination	Ref: The Danish Building regulation
Customer appeal	Asthetic		The concept should be visual adaptive to its environment	Deviation from convetional product	Customer interessement
	Easy in use		The concept should be easy to operate by the user	Time spend to use	Customer interessement

Figure 22 - The product specification

Environmental sustainability is a crucial category, encompassing parameters related to key strategies for the CE: Closing, Slowing, and Narrowing (Bocken et al., 2016), along with considerations for global warming potential. The global warming potential will be the parameter used in the assessment of the concepts environmental performance.

Economic feasibility encompasses an additional key parameter, because it is obliged to be economically beneficial for VELUX in the long term (Gylling & Terkelsen, 2024). This includes the manufacturing and labour hours.

Related to the economic dimension, the business model feasibility examines how well the concept can integrate into VELUX's existing business model, as it may be easier to implement a concept that suits the existing business model. Additionally, the parameter of market versatility covers the adaptability of the concept across various customer segments. Both parameters address aspects that enhance VELUX's likelihood of adopting the given concept.

Legislation encompasses energy balance requirements that the windows must meet, with higher efficiency being preferred. Additionally, it demands that the concept does not contain any hazardous substances and poses a low risk of containing them. Both energy balance demands and regulations regarding hazardous substances stem from the BR18 (Social og Boligstyrelsen, 2024).

Finally, customer appeal considers the aesthetics of the window, its adaptability to the surrounding environment, and ease of use. It is important to note that the field research did not specifically target users of roof windows to gather insights into their preferences and values. Additionally, this category is subjective, as it relies on assumptions derived from statements made by relevant actors. It is however relevant because a low demand for a new concept is found to be one of the linear lock-ins located in analysis 1. These assumptions should be taken into consideration when evaluating the customer appeal, as they may not necessarily be representative for every user of roof windows.

Ideally, all proposed concepts should be evaluated against all demands and criteria. However, this study prioritises environmental performance as it is a key parameter to address the research question. The remaining parameters will be considered during the concept evaluation process.

8.3 Brainstorm and Morphology

To initiate concept development, a brainstorming session was conducted based on selected parameters or categories outlined in the product specification, deemed relevant for brainstorming. These categories included: Circularity, Slowing, Narrowing, Energy Balance, Economic Feasibility, Implementation, and Market Viability. The researchers engaged in brainstorming rounds lasting 5-7 minutes, focusing on aspects that could enhance a concept's performance within each category.

Following the brainstorming phase, a design morphology process was engaged. The researchers combined ideas to explore potential solutions derived from the aspects identified in the morphology chart (see figure 23).

Parameters	1	2	3	4	5	6	7	8
Circularity	Mono materials 1 2	DESIGN SASH CAN BE CLICKED OFF PARTS CAN BE REPLACED IF DAMAGED 3 5	IGU removed, use for other purposes Use for other purposes to replace production of other products → wood → metal 3	Takeback system Buy back system 3 4 5	Everything is screwed together 1 2 4	Incentives for clients and installers to return windows 3 4 5		
Slowing	SERVICE PACKAGE TO KEEP WINDOW ALIVE 1 2	Existing window Upcycling - Add-ons - Repair (oil, paint..) 1 2	Spareparts library 3 5	Quality control of second hand windows - Inspection process to assess the windows condition 1 2 3 4 5	Online catalogue with used windows Guides for maintenance / upcycling window 1 4 5	Reuse 3 4 5		
Narrowing	Windows with less raw materials	windows not able to be opened, to have fewer parts	Use of recycled materials 3	Less energy-heavy materials than glass and aluminium - Material substitution 2 3	Cover window for less heat loss 2			
Energy balance	Add sealant to weak connection between glazing and sash --> Avoid heat coming through 1 2	Add additional window sash on existing window 1	Wrap film on window	Extra glazing on the outside, that sits on the frame 2	Insulating shutters during night will compensate for the lower U-value of the window during the day 2	Smart unit with heat transmission and still fresh air		
Economic Feasibility	Avoid taking out the window, and work with the existing --> Make modifications to ensure it can live longer (cheaper) 1 2	Make modifications / repair / service. Taking down the window, putting it back in 1 2	Service deal (subscription) Modification / service / repair -> Sold as an offer when initally purchased, service is then »free« if something happens (ensure longer life time) 1 2	Re-sell windows 3 4	Deposit system for windows 3 4 5	Sell components for repair 3 5	Customer library for specific sizes and types of windows - Get notifications when available - Ensure that it will not be on stock forever 3 4 5	Online tracking with passports to indicate what is out there, that potentially will return soon. 3 4 5
Implementation and market viability	Mosaic roof window concept (use of mixed window sizes) --> Used windows can be used in larger buldings 3	Solutions that can be done by service, when one wants to avoid a window being replaced. 1 2 5	Installers education in upcycling windows - Certified upcycling experts 1 2	Special tools to make the handling more safe - Dismantling, transport, lifts - Heatgun to remove sealant 3 4 5	QR / ID code put on multiple parts, not just one place on the window 4 5	Adjustable frame 3	Add-ons fit existing windows 1 2	

Figure 23 - Design Morphology chart

As marked in figure 23, each of the concepts takes inspiration from certain ideas in the morphology chart. The numbers on the ideas indicate which concept is inspired by them. This iterative process yielded five design concepts, each offering environmentally sustainable alternatives for AISL management of windows.

8.4 The Proposed Concepts

The conceptualisation process resulted in five distinct design concepts aimed at transitioning the AISL management of roof windows to a more sustainable practice. In the following section, each concept will be elaborated in detail, outlining its fundamental premise, practical applications, key drivers, challenges, and potential solutions to overcome those challenges.

8.4.1 Concept 1 - Upcycling by Secondary Glazing

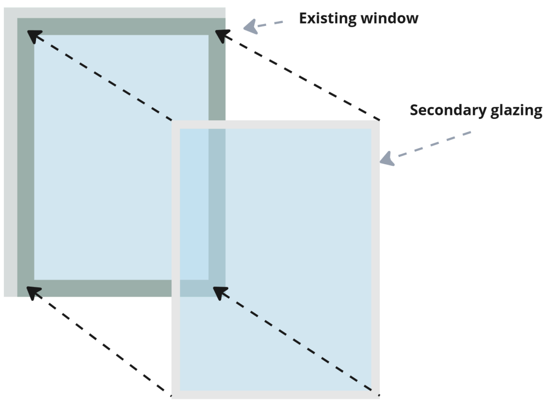

Figure 24 - Visualisation of upcycling by secondary glazing

Based on inspiration from the Optoglas solution, the following concept is applicable in cases where windows need replacement either because they no longer meet current energy balance standards, or when there is a desire for more energy-efficient windows in general.

Through a refurbishment process performed by an installer, the old windows are assessed and repaired if necessary. Then they are fitted with an inner secondary thermal glazing on the existing window sash, which enables an energy balance comparable to one of a triple glazing window (figure 24) (Optoglas, n.d.-a). This prolongs the service life of the windows.

This concept offers high-value retention with minimal installation procedures, primarily requiring the addition of a secondary thermal glazing. However, market flexibility is a challenge, as it relies on durable windows to offset the refurbishment's environmental impacts. The environmental performance of the concept depends on the window's condition, requiring an installer's quality assessment to estimate its suitability for customers in terms of both environmental and economic feasibility.

8.4.2 Concept 2 - Upcycling by Shutter

In contrast to concept 1, which involves an element on the inner side of the window, this concept is positioned on the outer side of the window and incorporates an insulating shutter (figure 25). This shutter closes at night, helping to prevent heat from escaping through the window.

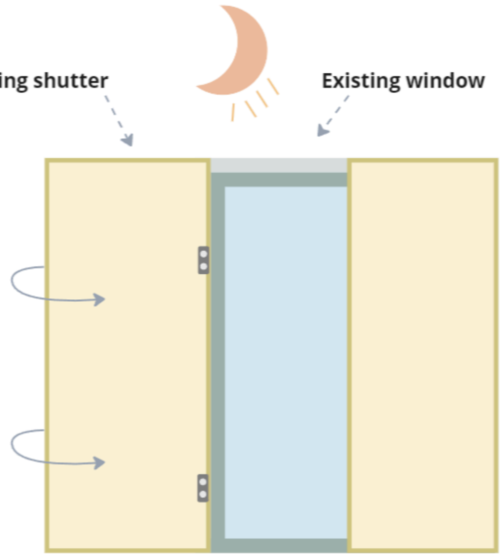

Figure 25 - Visualisation of Upcycling by shutter

Since roof windows primarily produce heat through solar transmission, a net heat loss is only applicable when the Sun is not present. The shutter insulates the windows, reducing heat transmission, which could potentially enable the window's energy balance to comply with energy balance standards. The energy balance is defined over a specified period of time, giving an average U-value that complies with the legislation from the BR18.

8.4.3 Concept 3 - IGU Repurpose

Based on inspiration from the A:gain solution, this concept focuses on the disposal of windows. When a window eventually is disposed of, it can be dropped off at a designated location or possibly picked up through a take back program. From here, the window is dismantled to access the IGU. The IGU is then repurposed for use in indoor wall panels, which are subject to less stringent regulations compared to windows (Risom, 2024). By utilising the IGU in this manner, it serves as a substitute for the thick hardened glass panes typically used in indoor wall panels (figure 26).

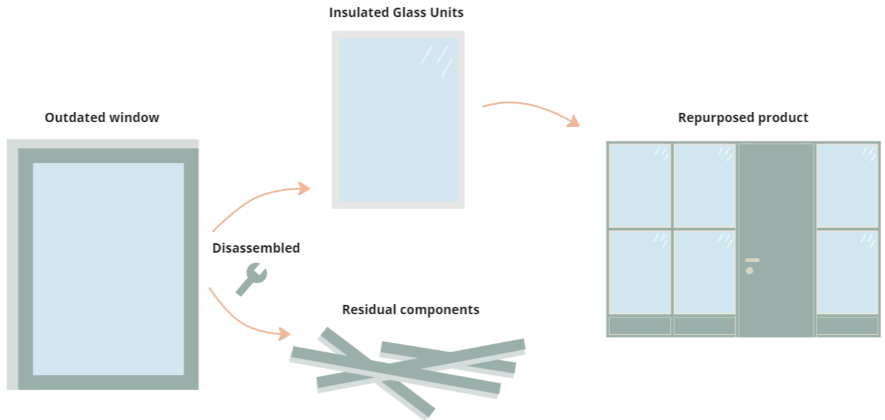

Figure 26 - Visualisation of IGU repurpose

The remaining components from the dismantling process can be sorted and recycled to achieve higher material recovery rates. While this concept prioritises lower value retention compared to the others, its market flexibility encompasses all second-hand roof windows in decent condition (Risom, 2024). However, considering that reusing the IGU may not always be profitable (Rota et al., 2023), it is crucial to assess market demand for this solution

8.4.4 Concept 4 - Take Back for Reuse of Windows

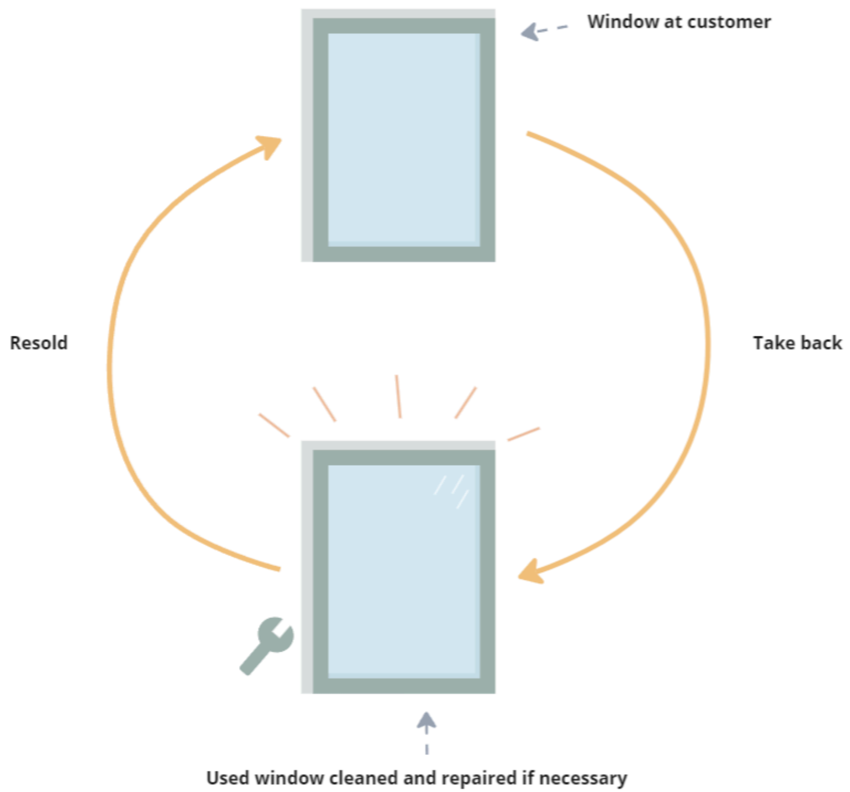

Figure 27 - Take back for reuse of windows

Similar to concept 3, this design concept operates through a take back system. Here, windows still in good condition undergo quality assessment and may be repaired or refurbished if necessary (figure 27). Possible mould growth can be cleaned, new paint added to the frame, and joint filler can be added to the window seal. These refurbished windows can be sold through a website, providing alternatives to virgin windows. While many of the windows currently taken back are double-glazed, they can still be utilised for applications where less stringent energy balance requirements are present.

However, it is important to note that triple glazing windows that are disposed of will have better flexibility for reuse, as they can comply with energy balance requirements. While this concept excels in terms of value retention, it can potentially be one of the more challenging solutions, as it involves multiple steps including a comprehensive quality assessment to ensure the second hand windows can comply with the same regulations and standards newer windows must meet.

8.4.5 Concept 5 - Take Back for Spare Parts

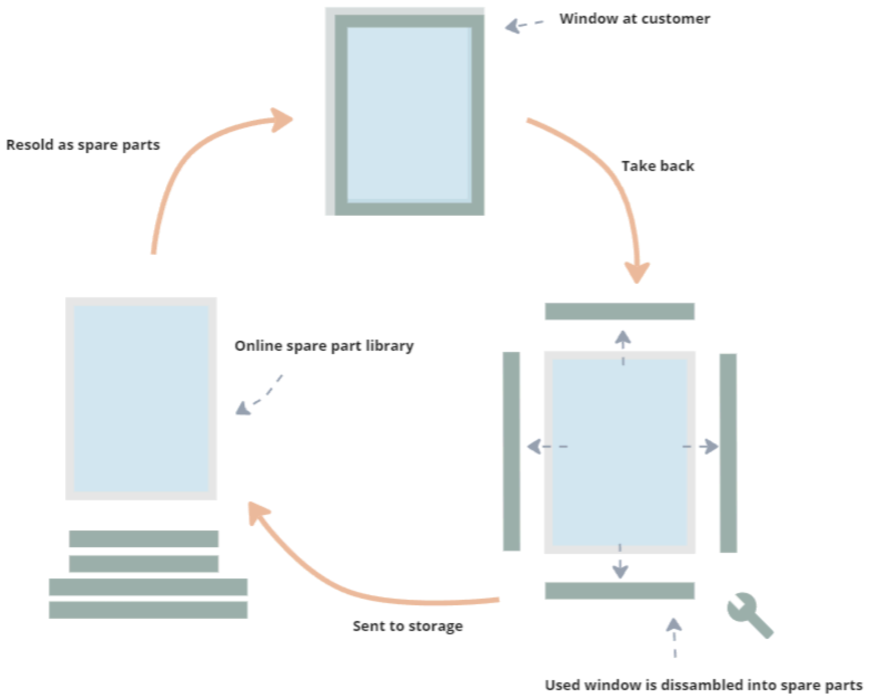

Figure 28 - Take back for spare parts

This concept revolves around a take back program, where windows are collected and disassembled with the aim of remanufacturing them for spare parts (figure 28). This approach allows VELUX to store parts from older generation windows, facilitating window repairs by ensuring a sufficient supply of spare parts for various components of VELUX roof windows. This can address one of VELUX's challenges, which involves storing older machines and having to produce multiple tests of certain spare parts if requested by customers (Nielsen, 2024).

While this is a lower circularity approach that requires some effort in the disassembly process, it encompasses high market flexibility that can cover all disposed-of windows. Even worn-out windows still have the potential to contain parts in decent condition. The challenging part of this concept may be to ensure a safe working environment for the employees disassembling the windows, and to ensure that the spare parts do not contain any substances of concern.

8.5 Adapting VELUX's Business Model Canvas

To illustrate how the concepts relate to and differ from the current business model for VELUX, additional elements have been added to the BMC presented in analysis 1. The purpose of integrating the various concepts into a BMC is twofold. Firstly, it aims to provide a clearer understanding of the new concepts. Secondly, presenting the concepts within a business model framework enhances their comprehensiveness and makes them more relatable to VELUX's current business model.

The model presents VELUX's BaU as "transparent" processes, while the numbers indicate the additional contributions or involvement of the concept beyond the original business operations (figure 29).

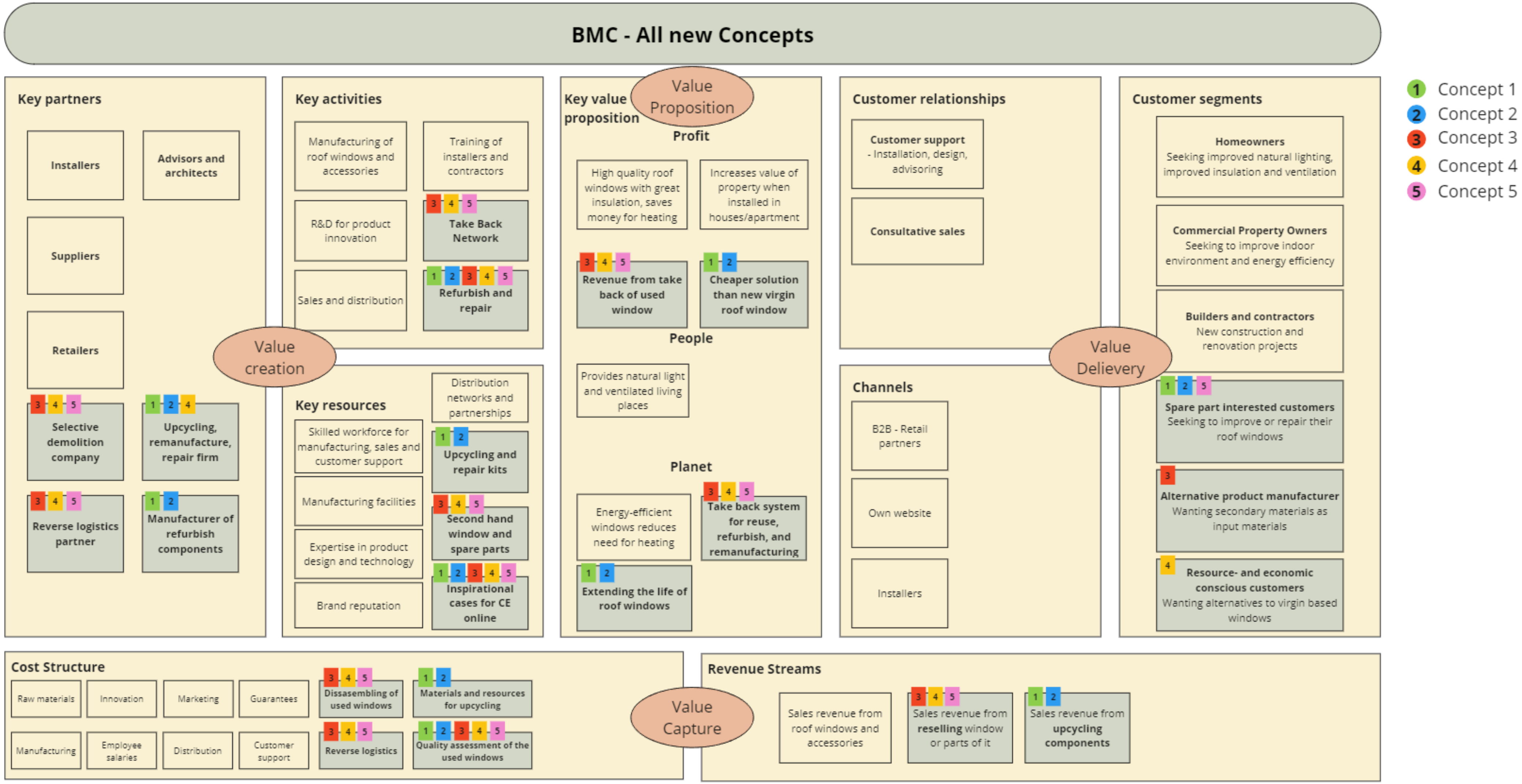

Figure 29 - BMC with new concepts

The five proposed concepts stem from two different CE approaches. Concepts 1 and 2 focus on refurbishing used roof windows to extend their service life by modernising them. Collaborating with an upcycling firm and a component refurbishment manufacturer may be crucial in these new business model approaches. Concepts 3-5 revolve around a take back system, where windows or their components will replace virgin-based alternatives. Key partners for these concepts may include a selective demolition company and a firm specialising in reverse logistics.

Customers for concept 3-5 will receive money for their used windows, rather than paying for disposal or giving them away for free. Concepts 1 and 2 offer a cost-effective solution, as customers only need to pay for add-ons to existing roof windows, making them cheaper than new roof windows. Environmentally, extending the life cycle of roof windows reduces the demand for new ones. The take back system avoids the production of new components, further reducing environmental impact.

The new business models for VELUX will include costs for reverse logistics, disassembly, quality assessment, and upcycling materials. However, additional revenue can be generated from selling used windows, parts, and spare parts for upcycling, potentially increasing sales. Determining the best business model for VELUX depends on market demands and costs, which are not detailed in this thesis.

8.6 Summarising the Conceptualisation

To summarise this analysis, five design concepts have been developed, which aims for a lower environmental impact than the BaU. The design concepts can be categorised according to the waste hierarchy from the Waste Framework Directive (2008), which is done in combination with the nine R-strategies from Potting et al. (2017) (see figure 30).

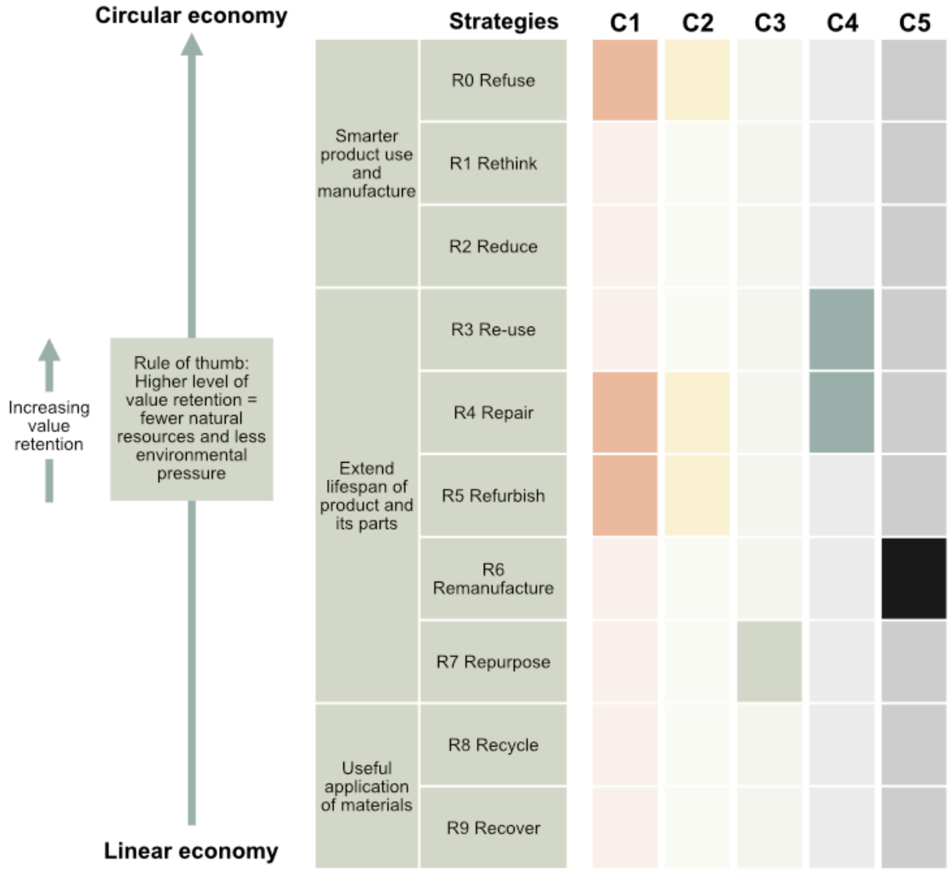

Figure 30 - Overview of solutions in the hierarchy of value retention

As depicted in figure 30, concepts 1 and 2 rank highest in the visualisation by avoiding the necessity for virgin triple glazing roof windows through repair and refurbishment of existing ones. Concept 4 also shows potential for relatively high scores as of the reuse strategy. Following the order of the R-strategies, concepts 3 and 5 are expected to have the largest environmental impact when evaluated. This hypothesis will be assessed by the researchers in the subsequent analysis.

9. Analysis 4 - Evaluating the concepts by environmental performance

The following analysis concerns the evaluation of the proposed concepts in terms of their environmental performance.

Sub-question 4: How can circular design concepts be evaluated in terms of environmental performance?

A comparable LCA is conducted to evaluate the environmental performance of the different concepts, chosen for its recognition in the building industry as a comprehensive and credible method for environmental assessment. This facilitates a tangible comparison between the proposed solutions, which can provide VELUX with insights into their environmental performance.

The LCA will be elaborated in the following sections, structured according to its phases.

9.1 Goal and Scope

As described in analysis 3, the context of these scenarios takes place in the “moment of consideration” where various decisions can be made regarding the used outdated roof window to meet the demands at hand (figure 21).

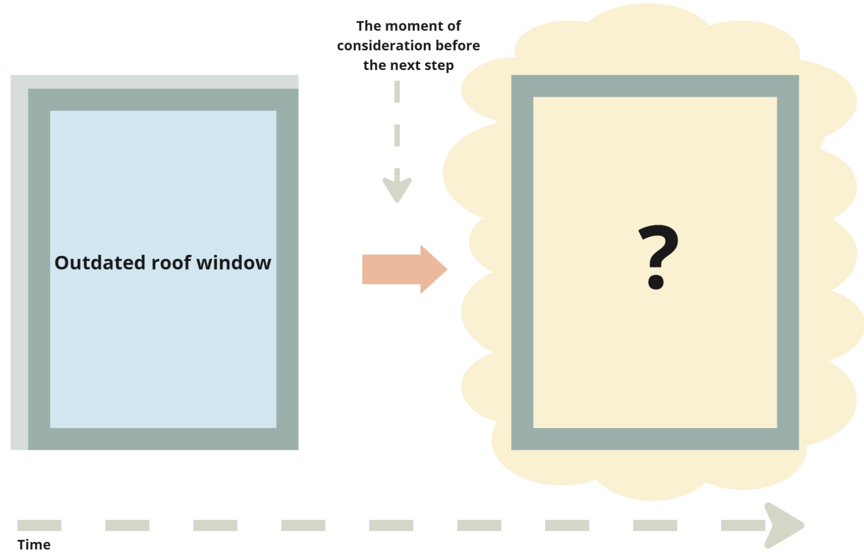

Figure 21 - Moment of consideration (own model)

9.2 Defining the Function

Based on the product specification in analysis 3 the researchers have defined the function for an energy and health compliant roof window as:

A product that provides year-round protection against moisture in indoor environments, while allowing daylight and fresh air to pass through temporarily. Additionally, it should enable solar transmittance while delivering an energy balance of at least 10 kWh/m²/year.

9.3 Functional Unit

The functional unit (FU) is made to have a common standard to compare the different concepts against each other. In continuation of the function, the functional unit for the LCA is:

FU: 25 years of fulfilling the purpose of an energy and health compliant roof window for year-round living of 1 m^2.

25 years is chosen as it is considered as the technical life cycle of a virgin VELUX Roof window (Nielsen, 2024).

9.4 System Boundary

The system boundary of the LCA simulation is displayed in figure 31. It is configured to comprehensively include all relevant processes and inputs, particularly focusing on the avoided products that the concepts substitute, as they would occur in real life. Since the existing window remains unchanged across all concepts, it can be excluded from the LCA comparison. Therefore, only the add-ons and the avoided products will need to be modelled.

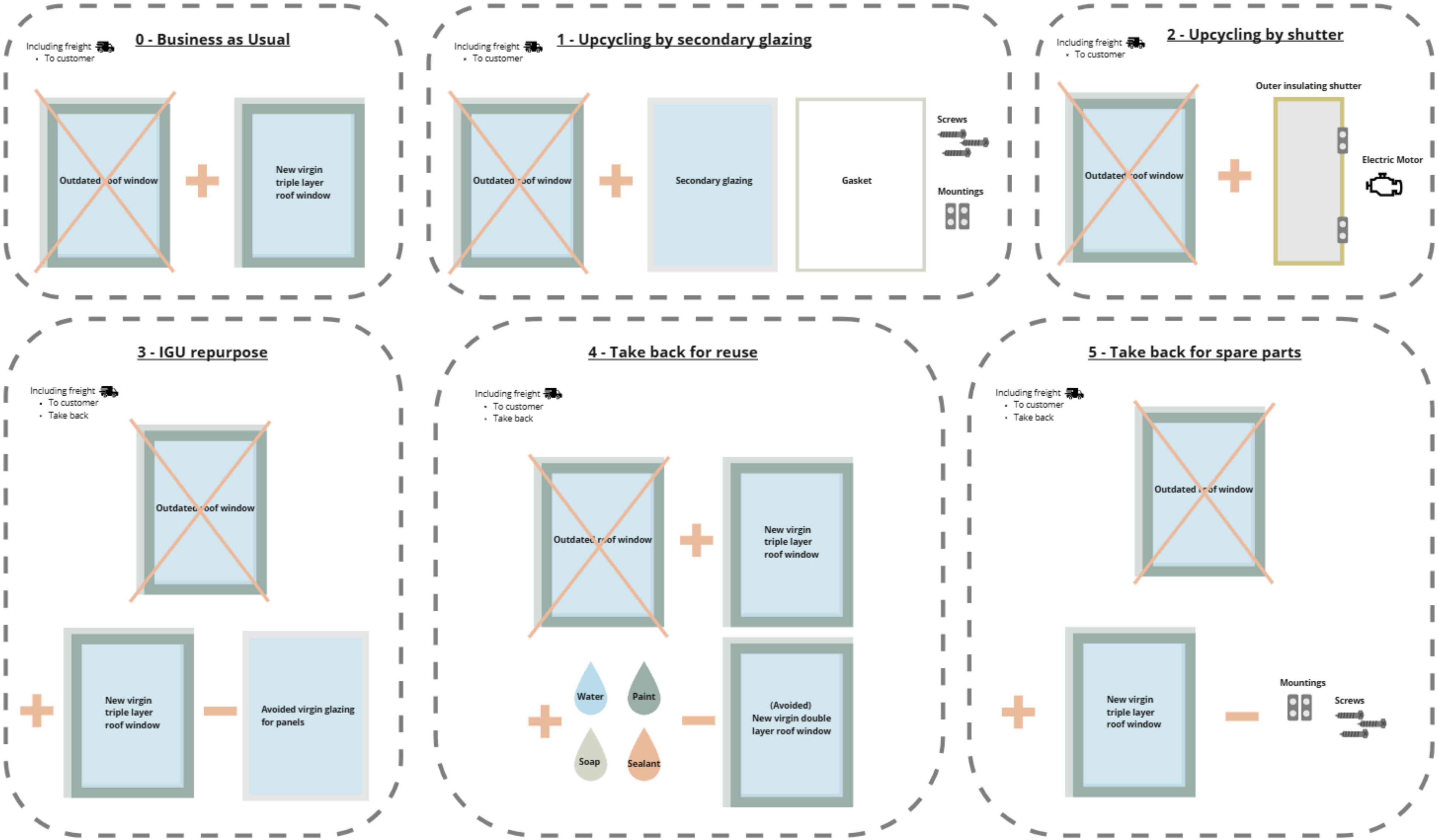

Figure 31 - System boundary of the LCA of the concepts

9.5 Life Cycle Inventory

The input data used in the life cycle inventory for the different concepts are pictured in the following tables (1 - 6). The details concerning the sources and calculations can be found in appendix C.

LCI - BaU Components	Process / Material	Quantity	Unit
Virgin VELUX triple glazing roof window	Roof Window	1	m2
Transport Van	Transport to customer by van from VELUX DK	5	metric ton * km

Table 1 - LCI BaU

LCI - Concept 1 Components	Process / Material	Quantity	Unit
Tempered energy glazing	Flat glass	9,16	kg
Mountings for glazing	Stainless steel	0,015	kg
	Metal working of mountings	0,015	kg
Screws	Stainless steel	0,06	kg
	Metal working of screws	0,06	kg
Gasket	Rubber gasket	0,33	kg
	Forming the gasket	0,33	kg
Transport Van	Transport to customer by van from VELUX DK	1,1	metric ton * km

Table 2 - LCI Concept 1

LCI - Concept 2 Components	Process / Material	Quantity	Unit
Virgin VELUX shutter	Rolling Shutter	1	m2
Mountings	Stainless steel	0,02	kg
	Metal working of mountings	0,02	kg
Screws	Stainless steel	0,026	kg
	Metal working of screws	0,026	kg
Transport Van	Transport to customer by van from VELUX DK	1,18	metric ton * km

Table 3 - LCI Concept 2

LCI - Concept 3 Components	Process / Material	Quantity	Unit
Virgin VELUX roof window	Triple glazing roof window	1	m2
Virgin glazing (avoided)	Glazing production	-1	m2
Use of power tool for disassembling	Electricity	0,0183	kWh
Transport of triple glazing roof window to customer	Transport to customer by van from VELUX DK	2,5	metric ton * km
Transport from take back of used roof window	Transport	2,21	metric ton * km
Transport of IGU from VELUX to remanufacturer	Transport	1,95	metric ton * km

Table 4 - LCI Concept 3

LCI - Concept 4 Components	Process / Material	Quantity	Unit
Virgin VELUX roof window	Triple glazing roof window	1	m2
(Avoided) Double glazing Virgin VELUX roof window	Double glazing roof window	- 1	m2
Prepare for reuse	Cleaning	0,2	kg
	Painting	0,1	kg
	New Sealant	0,1	kg
	Water	1	kg
Transport of new triple glazing VELUX-customer	Transport to customer by van from VELUX DK	2,5	metric ton * km
Transport from take back of used roof window	Transport	2,21	metric ton * km
Transport of used double glazing window to new customer	Transport	2,21	metric ton * km

Table 5 - LCI Concept 4

LCI - Concept 5 Components	Process / Material	Quantity	Unit
Virgin VELUX roof window	Triple glazing roof window	1	m2
Reuse of spare parts aluminium (avoided)	Aluminium	-3,08	kg
	Metal working of aluminium	-3,08	kg
Reuse of spare parts other metals (avoided)	Metal	-4,47	kg
	Metal working	-4,47	kg
Transport of new triple glazing VELUX-customer	Transport	2,5	metric ton * km
Transport from take back of used roof window	Transport	2,21	metric ton * km
Transport of spare parts	Transport	0,3775	metric ton * km

Table 6 - LCI Concept 5

9.6 Life Cycle Impact Assessment

By using the LCA software, SimaPro, to model the various scenarios, the comparative results between the concepts are visualised in figure 32. The EN15804+A2, recognised as one of the most widely used EPD impact assessment methods, is employed for the analysis (Konradsen et al., 2023).

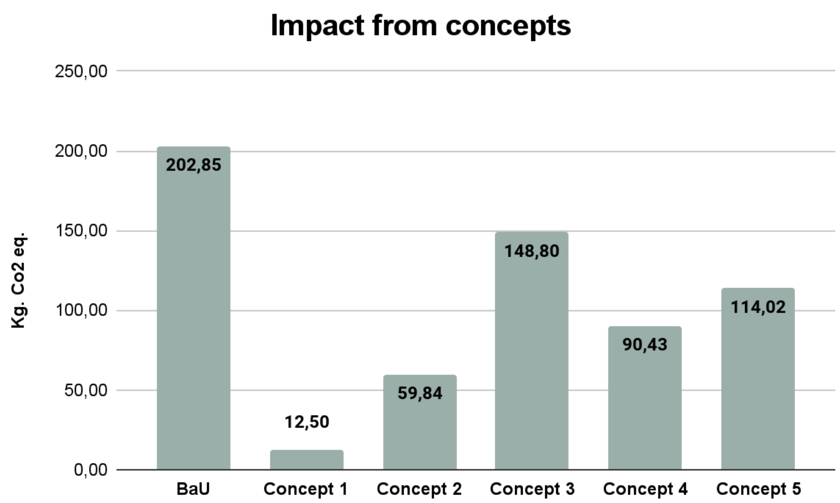

Figure 32 - Results from LCA

As illustrated in figure 32, the BaU scenario emits 202,85 kg. CO2e per functional unit, giving it the highest impact in the climate change category. This indicates that all conceptualised concepts outperform it, signifying a general improvement potential in environmental sustainability for the BaU approach.

Concept 1 demonstrates the lowest environmental impact, emitting 12,5 kg. CO2e. This can be attributed to its strategy of prolonging the used window, refurbishing it with relatively few materials and processes, thereby avoiding the need for a new triple glazing roof window.

Concept 2 follows closely, with a total impact of 59,84 kg. CO2e., also prolonging used windows like Concept 1 but involving more elements in the refurbishment process, resulting in a higher footprint.

Concept 3 ranks fifth in impact, emitting 148,80 kg. CO2 eq. The relatively high impact can be attributed to the difference between Concept 3 and the BaU, which lies in repurposing the used roof window's IGU into glass panels, thus avoiding the need for virgin glass.

Concept 4 ranks third in impact, emitting 90,43 kg. CO2e. Its reuse approach results in half the environmental impact of the BaU concept, but its inability to fully substitute virgin triple glazed VELUX roof windows due to energy balance standards limits its ranking.

Concept 5 has the fourth largest environmental impact, emitting 114,02 kg CO2e. It builds on the current system, necessitating a virgin triple glazing roof window. However, the remanufacturing of spare parts from used windows can be utilised in repairing other windows, thereby avoiding the production of these spare parts.

A contribution analysis is conducted and visualised in Appendix D, providing a more detailed overview of the environmental contributions to the concepts' environmental impact.

9.7 Assumptions and Limitations

The LCA was conducted using currently available data and an understanding of the anticipated use context for the solutions. This data is based on scope assumptions, generic database processes, a scientific article on a given roof window, and interviews. As the LCA is a method of quantification and reductionism it is essential, the claims made from it are only applicable under the circumstances of the given data and scenarios used. The results are not fully representative of a specific VELUX roof window, but the modelling can still be considered a reliable comparison of scenarios for decision-making purposes.

9.8 Summarising the Evaluation

It can be concluded that all the proposed concepts are better environmentally in terms of total emitted CO2e compared to the BaU scenario, validating CE based concept superiority of the BaU, when it comes to environmental performance. A correlation is evident between the results of the environmental assessment of the concepts and the prioritised order of the R-strategies (figure 33).

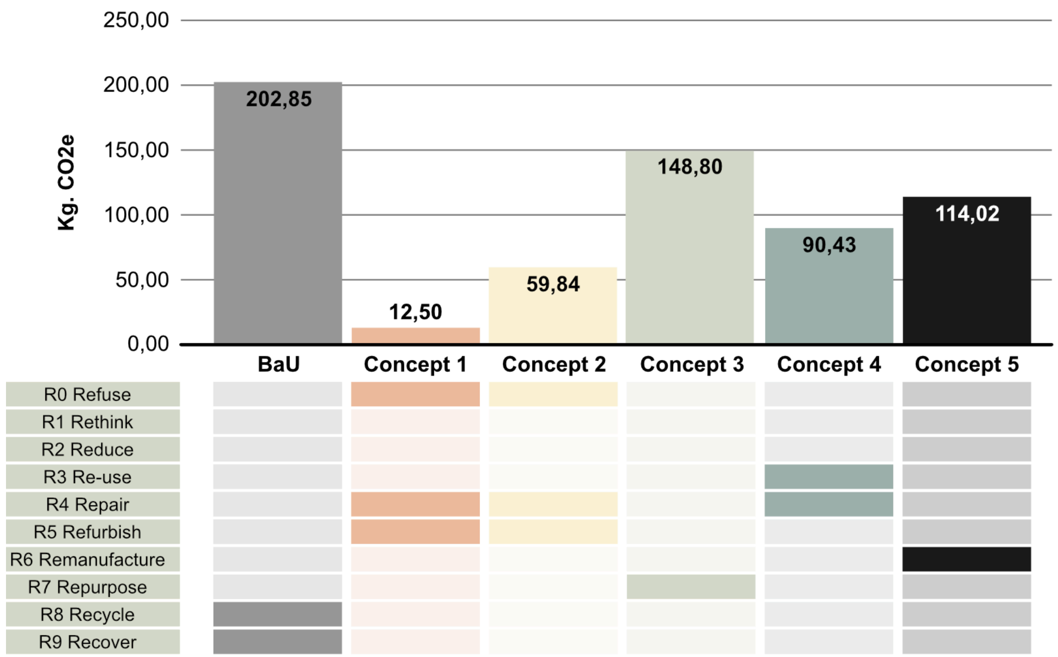

Figure 33 - Comparison between R-strategies and LCA results

Through the analysis, it becomes apparent that the prioritisation of R-strategies reflects the level of value retention and consequently, the reduction in environmental footprint. This serves as a preliminary tool for initial evaluation of the environmental performance of certain concepts. However, given its quantitative nature, LCA is recommended for a more accurate environmental assessment. LCA offers a clear understanding of which solutions have the lowest impact, under the given assumption the modelling is performed. The results of the LCA can be interpreted as a form of interessement for the suggested concepts, giving them agency, further supporting the translation of the building sector towards a CE.

10. Discussion

The findings from the thesis will be discussed in the following section. This includes the evaluation of the applied literature, theory, methods, research results, and contribution to the academic area with the skills from SDE.

10.1 Summary of Findings

Four analyses were conducted to address their respective sub-questions, ultimately enabling the researchers to address the main research question:

How can roof windows be managed and utilised after their initial service life to enhance environmental sustainability?

After investigating the field and uncovering the linear lock-ins within the building industry, particularly AISL management of roof windows, requirements for environmentally improved design concepts were identified. As highlighted in analysis 1, the current business model of VELUX is primarily linear. With a system that reinforces the linear lock-ins in terms of customers' limited demand for second-hand windows and technical implications for extending the service life of the roof windows, as well as institutional legislation necessitating compliance with energy balance requirements, the transition to a CE is hindered.
Similarly, drivers for transformation towards a CE were examined, assessing their transformative potential and how they could be further built upon from VELUX's perspective. Pilot initiatives exemplifying circular business models have been identified, which with the introduction of relevant legislation could serve as a catalyst for advancing the CE agenda.
Five design concepts were developed to provide tangible, understandable, and integrable opportunities for VELUX to outperform the BaU practices. Consequently, the thesis conducted an environmental assessment of these proposed design concepts to substantiate the sustainability claims made by the researchers. These processes provide VELUX with qualified design concepts to effectively manage and utilise roof windows AISL in a more sustainable manner than BaU.

10.2 Evaluation of Literature

Existing literature highlights the importance of finding alternatives to the current unsustainable practices in the building sector (Eberhardt et al., 2020; Fregonara et al., 2017; Geboes et al., 2023). Retaining the windows' environmental value is currently not the focus in the EoL treatment of the windows, as they end up in landfills, incineration or low-quality recycling (Eberhardt et al., 2020; Rota et al., 2023), which was confirmed in Analysis 1.
Geboes et al. (2023) suggest that one of the primary challenges hindering the more sustainable use of windows is the construction of the IGU. Both the literature review and the interviews conducted for this thesis, underscore the challenges associated with maintaining IGUs. These

challenges include issues with retaining insulating properties and the complexity of disassembly, which were parameters to be aware of during the conceptualisation process.

The thesis conceptualised concepts for roof windows with high levels of value retention. While strategies and examples of circular business models for windows were present in the literature (Arora et al., 2020; Forslund & Björklund, 2022; Geboes et al., 2023; Nußholz et al., 2020; Ploeger et al., 2019; Rota et al., 2023; Tazi et al., 2021), these mainly concerned lower levels of value retention.

A reason why there may have been limited literature in this topic could be as the words “value retention”, “repair”, “prevent”, or “extending” were not a part of the search string in the literature review. However, the terms “upcycl*” or “circular economy” were used and might have covered these areas. Therefore, the researchers highlight this thesis as contributing to a relatively unexplored academic area, with findings based on a case study involving VELUX.

10.3 Evaluation of Findings

In the following section, the validity of the results along with their respective limitations will be discussed. The research question set out to explore more environmentally sustainable concepts for the AISL management of roof windows. Therefore, the value of these concepts is closely tied to their actual environmental performance, which requires a comprehensive evaluation.

10.3.1 Modelling Scenario Assumptions

The applicability and usefulness of the design concepts depend heavily on the circumstances under which the windows are treated AISL. The base scenario used for conceptualisation and environmental assessment assumes a window replacement cycle of 25 years, based on expected replacement timelines (Nielsen, 2024). However, there is a lack of customer insight into the reasons for window replacement. It is unclear whether windows are replaced due to wear and tear, lack of energy balance, or simply in continuation of other planned renovations. Additionally, there will be variations in replacement periods, with some windows being replaced sooner or later. Change of setting for the scenarios changes the conditions for which solutions are feasible and which perform best.

The modelling scenario for the case study assumes that windows are replaced due to energy inefficiency, aiming to address challenges related to energy balance that could otherwise inhibit the concept from being applicable. However, whether the proposed design concepts are able to comply with energy balance requirements is a critical assumption that would need further assessment. A comprehensive method to assess the quality of second hand windows and how to treat them, would be a topic of major relevance for future research.

10.3.2 Energy Balance of Roof Windows

The researchers question the assessment of a net positive impact due to a positive energy balance in roof windows, as calculated in the sustainability report from Velux (2023) highlights, presented in analysis 1. This assessment underscores the importance of the energy balance offered by roof windows, emphasising the need for energy balance standards for optimal environmental performance. However, it should be emphasised that the environmental benefit depends on the scenario being compared, specifically the heating source used and the location's temperature. Suppose heating sources are to transition from fossil fuels to low-carbon energy sources, relying more on renewable energy over time, as proposed in the Green Deal (European Commission, 2019). In that case, the environmental benefit from the roof windows' heating may diminish. Additionally, it is relevant to recognise there is a threshold for energy balance beyond which further enhancement does not yield significant energy savings. Excessive heating might lead users to open windows for ventilation, which not only nullifies additional heating benefits, but also results in the wastage of excess materials used for further improving the thermal insulation capabilities of the roof window.

Future research could be beneficial in exploring the energy balance threshold of roof windows and its relationship to energy savings, to find the sweet spot of energy balance for roof windows compared to extending the service life.

10.3.3 Decoupling Capabilities

After conducting a LCA of the proposed concepts and concluding that they result in a lower carbon footprint compared to the BaU scenario, these solutions have the potential for an absolute decoupling of economic growth from resource consumption, if the concepts appear to be economically feasible. In a future study, it would be beneficial to do an economic assessment of the business models, and do a market analysis. However, there is still a risk that rebound effects may influence the actual reduction in resource usage, as improvements could be offset or even negated by behavioural or systemic responses (Kjær et al., 2019).

Studying how customers use roof windows during the use phase would add valuable insights. Potential rebound effects could arise from concepts, where existing window elements are credited with avoiding virgin material production. As an example with concept 3, IGU panels might replace virgin hardened glass, but there is a possibility they would be preferred over other types of wall panels that have a lower environmental impact than hardened glass. Alternatively, they might be chosen simply because customers are drawn to the idea of having the concept, where they would not otherwise have had it. Being aware of this is crucial for validating environmental performance and absolute decoupling claims.

10.4 Evaluation of Approach

In the following section, elements for the approach of the thesis will be evaluated, regarding its strengths and limitations. The researchers choose the problem-oriented approach, operationalised by use of the abductive approach.

10.4.1 Limited Participatory Design

To enhance the resilience of the developed concepts, effectively addressing required linear lock-ins and adhering to set requirements, greater involvement and a more participatory design approach could have been applied during the conceptualisation process. Involvement of intended users would have made it possible to iterate the concepts to better address the problematisations of relevant actors, thereby further improving the concepts' agency and the chances of mobilisation towards transitioning the building industry to a CE. While not as beneficial as including VELUX in the conceptualisation process, the researchers see an opportunity to ensure a proper handover of the findings and concepts by facilitating a concluding webinar after submitting the thesis. This webinar would present the research results and solicit feedback and input for improving the concepts.

10.5 Evaluation of Methods

As this thesis is based on a case study, data collection methods have focused heavily on qualitative approaches, such as semi-structured interviews and observations. It is important to be aware that interview subjects may have specific agendas, leading to potential bias in their responses. It is the researcher's responsibility to distinguish between what is said and what is true. This challenge represents a limitation of these methods, as assessing the credibility of the information can be difficult, depending on the perspectives of individual actors. While the design and conceptualisation methods were productive, incorporating additional methods to evaluate the concepts beyond the LCA would be beneficial. Introducing relevant KPIs from the product specification would enhance the validity and applicability of the design concepts.

10.6 Evaluation of Theoretical Framework

Transforming the building sector towards a CE necessitates a thorough understanding of the inherent challenges that inhibit change. Recognising that these challenges are interconnected across various socio-technical dimensions is crucial. In this context, the utilisation of the lock-in theory by Seto et al. (2016), which encompasses mechanisms and connections at institutional, technological, and behavioural levels, provides a solid framework for identifying and addressing these challenges when designing and evaluating concepts for applicability and success.

While the lock-in theory excels at outlining a static description of existing conditions, it falls short in describing the process of facilitating transformation. The researchers have applied the lock-in theory to structure and find linear lock-ins in different socio-technical levels. Later in the process, the lock-ins have been central to explore drivers able to disrupt these lock-ins and translate relevant actors towards a CE. R-strategies and LCM were introduced as additional support for the drivers, serving as design guidelines when aiming for the sustainable development of the system. The case study contributes an additional layer to lock-in theory, specifically highlighting transformative dynamics.

Despite numerous promising innovations, the emphasis on transformation towards a CE should ideally be placed on the establishment and translation of networks. The translation theory by Callon (1986) complements the use of lock-in theory by providing additional elements to describe the process of facilitating transformation. It was applied to enlight how a network could be constituted and how it potentially would look after a translation through a OPP proposed by the researchers. The theory is considered contributive when analysing networks of actors, their interests, and how to mobilise design concepts to translate them into the network of VELUX roof windows. Also the agency term is useful to describe relations between micro and macro actors and how they influence each other. Given the thesis' focus on technological dimensions, the analysis of individual actors' concerns has been limited. Conducting a more behaviourally oriented study could involve applying aspects of ANT to address these considerations.

10.6.1 Behavioral and Institutional Research Advancement

Although the thesis to some extent addressed the institutional and behavioural dimensions, there is undoubtedly additional material worth exploring concerning the transition towards a CE in the building industry.

Despite the impending legislative drivers advocating for a shift towards a CE in the building sector, work still lies in addressing the challenges that will arise from the existing linear-oriented legislation rooted in the industry. This is evident in the criteria set for building materials to attain CE-marking, aimed at ensuring durability and safety. Meeting these standards without necessitating complex procedures presents obstacles to integrating second-hand and other circulated building materials into the market (Duer, 2024). Additionally, challenges persist in legislation aimed at promoting CE initiatives such as End-of-waste criteria, which is currently challenging to navigate due to its conditional application and lack of consistency across Danish municipalities (Buchard, 2024). Addressing the legislative barriers within the building industry is crucial for promoting a CE while upholding the quality and safety of building materials, without imposing extensive procedural requirements. Therefore, the researchers recommend further exploration of the linear legislative constraints and circular incentives to advance the CE in the building sector.

Furthermore, while the case study lightly touches upon the behavioural dimension, its significance should not be undermined, as it is necessary to ensure the design concepts fulfil customers' demands if they are to compete with the BaU. As emphasised by Forty (1986), "*No design works unless it embodies ideas that are held in common by the people for whom the object is intended*" (Forty, 1986, p. 245). Thus, involving roof window users is imperative to understand the values and meanings associated with roof windows and how more sustainable concepts can fulfil those demands.

Additional work on the case study's proposed concepts can lay the groundwork for addressing legislation and developing policy recommendations to enable circular concepts further. Moreover, presenting these concepts to roof window users, can assist in assessing their meanings and values they attribute to roof windows. This can be used in identifying the requirements for these new solutions to meet their concerns.

Thus, developing concepts oriented towards technological dimensions that can address the inherent linear lock-ins acts as an initial step towards tackling institutional and behavioural lock-ins.

10.7 Contribution to the SDE Field

The thesis was developed by Sustainable Design Engineers who, prior to initiating the project, had limited insight into the building industry. Despite this, they managed to produce a valuable output that could benefit a large company with a prominent role within the window industry. This showcases that Sustainable Design Engineers play a crucial role beyond mere specialisation in particular topics; they possess the capability to work interdisciplinary. Their unique skill set enables them to stage interventions with diverse stakeholders, forging connections, and collaborations to achieve collective goals that would otherwise be unattainable by individual entities alone. By facilitating cross-disciplinary dialogue and cooperation, sustainable design engineers drive innovation, foster holistic solutions, and contribute to the advancement of sustainable practices across various sectors and industries. Their ability to bridge gaps, integrate diverse perspectives, and navigate complex systems empowers them to lead transformative change towards a more sustainable future. Analysing the system with lock-in theory provides the opportunity to identify breakdowns that need to be addressed in order to destabilise the network and aim for translation. This approach can inspire other case studies aiming for a transition towards more circular business models. In summary, this thesis serves as an example of how two SDE students can contribute to the advancement of the SDE field.

11. Conclusion

This conclusion aims to address the research question:

How can roof windows be managed and utilised after their initial service life to enhance environmental sustainability?

Through a literature review, it was found that there is a scientific gap in investigating sustainable management practices for roof windows after their initial service life (AISL). The review furthermore highlights a need for a comprehensive overview combining barriers and drivers to sustainable transformation, particularly in managing windows AISL. Identified Circular business models for Construction and Demolition Waste (C&DW) exhibit low-value retention, partly due to a failure to differentiate between low- and high-quality recycling. Furthermore, limited research on assessment frameworks linked to tangible Circular Economy (CE) design concepts hinders the prioritisation of concepts with the lowest environmental footprint.

By investigating the field, the researchers of this thesis concluded that the current linear business model of VELUX roof windows and the building sector results in unsustainable treatment after use, reinforced by linear lock-ins in the BaU model. This poses challenges in transitioning to more circular business models.

Drivers for circular business models were identified through pilot examples in the window sector and relevant legislation. These findings, coupled with insights from lock-in and translation theories, guided the exploration of disruptive drivers and facilitated the understanding of actor networks for transitioning towards a CE. Five circular design concepts, rooted in CE R-strategies, were conceptualised and environmentally assessed using a Life Cycle Assessment (LCA). The concepts outperformed the BaU scenario regarding carbon footprint. Furthermore, a correlation between the concepts' carbon footprint and the prioritised order of R-strategies was found, recognising the application of the R-strategies to preliminarily evaluate circular concepts' environmental impact. Proposed concepts focusing on extending the service life by refurbishing existing windows showed the most promising environmental impact, followed by concepts consisting of take back systems, creating an opportunity to reuse the windows or parts of them.

A limitation of the environmental impact modelling is uncertainty regarding the correlation between roof windows' heat production and energy savings from heating. Future research should explore the energy balance threshold of roof windows and its impact on energy savings to identify the optimal balance related to extending the windows' service life.

Further studies should assess the economic feasibility and other relevant aspects that determine the solutions' suitability for implementation. It is also crucial that the modelling scenarios accurately represent real-life usage for achieving absolute resource decoupling and mitigating rebound effects.

Regarding the approach of the thesis, greater use of participatory design during conceptualisation could have enhanced the concepts resilience, addressing linear lock-ins more effectively.

Overall, this thesis demonstrates that transitioning to circular business models is not only feasible for VELUX but also essential for advancing sustainability in the building industry. By addressing embedded CO2e and enhancing value retention, the study paves the way for more comprehensive environmental impact solutions. The case study serves as a great example of how to navigate a complex industry with wicked problems and linear lock-ins, illustrating how translating the network of actors can foster meaningful change.

12. Bibliography

Aalborg University. (n.d.). *Sustainable Design, MSC in Engineering*. Aalborg University. https://www.en.aau.dk/education/master/sustainable-design-msc-in-engineering

A:gain. (n.d.). *Tystø | Wall System*. A:Gain.Dk. Retrieved 9 May 2024, from https://again.dk/product/tysto/

Akrich, M., Callon, M., Latour, B., & Monaghan, A. (2002). THE KEY TO SUCCESS IN INNOVATION PART I: THE ART OF INTERESSEMENT. *International Journal of Innovation Management*, *06*(02), 187–206. https://doi.org/10.1142/S1363919602000550

Alvesson, M., & Sköldberg, K. (2018). *Reflexive methodology: New vistas for qualitative research* (Third edition). SAGE.

Arora, M., Raspall, F., Cheah, L., & Silva, A. (2020). Buildings and the circular economy: Estimating urban mining, recovery and reuse potential of building components. *Resources, Conservation and Recycling*, *154*, 104581. https://doi.org/10.1016/j.resconrec.2019.104581

Bekendtgørelse Om Affald, BEK nr 2512 af 10/12/2021 (2021). https://www.retsinformation.dk/eli/lta/2021/2512

Bocken, N. (2023). *Business Models for Sustainability* (SSRN Scholarly Paper 4731205). https://doi.org/10.2139/ssrn.4731205

Bocken, N., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. Scopus. https://doi.org/10.1080/21681015.2016.1172124

Brundtland, G. H. (1987). *Report of the World Commission on Environment and Development: Our Common Future*. Springer Berlin Heidelberg. http://www.un-documents.net/our-common-future.pdf

Buchard, M. V. (2024). *Interview, RUC, [Appendix 1]*.

Buchard, M. V., & Christensen, T. B. (2024). Business models for the reuse of construction and demolition waste. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *42*(5), 359–371. https://doi.org/10.1177/0734242X231188023

Burrell, G., & Morgan, G. (1979). *Sociological paradigms and organisational analysis: Elements of the sociology of corporate life* (Reprinted). Ashgate.

Callon, M. (1986). Some Elements of a Sociology of Translation: Domestication of the Scallops and the Fishermen of St Brieuc Bay. *The Sociological Review*, *32*(1_suppl), 196–233. https://doi.org/10.1111/j.1467-954X.1984.tb00113.x

Ceschin, F. (2014). How the Design of Socio-Technical Experiments Can Enable Radical Changes for Sustainability. *International Journal of Design*, *8*(3), 1–21.

Cross, N. (2008). *Engineering design methods: Strategies for product design* (4. ed). Wiley.

Czarniawska, B., & Joerges, B. (1996). Travels of ideas. In *Translating organizational change*. Walter de Gruyter.

Duer, K. (2024). *Interview, Velux, [Appendix 3]*.

Eberhardt, L. C. M., Birgisdóttir, H., & Birkved, M. (2019). Life cycle assessment of a Danish office building designed for disassembly. *Building Research & Information*, *47*(6), 666–680. https://doi.org/10.1080/09613218.2018.1517458

Eberhardt, L. C. M., Van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a Life Cycle Assessment Allocation Approach for Circular Economy in the Built Environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

Ecoinvent. (2024). *System Models*. https://support.ecoinvent.org/system-models

Ellen MacArthur Foundation. (2015). *Circularity Indicators—An Approach to Measuring Circularity*. https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o

Ellen MacArthur Foundation. (2023). *Adaptive strategy for Circular Design*. https://emf-digital.shorthandstories.com/introduction/

European Commission. (2019). *COMMUNICATION FROM THE COMMISSION The European Green Deal* [Bill]. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

European Commission. (2022). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A0142%3AFIN

European Commission. (n.d.). *Waste Framework Directive—European Commission*.

https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

European Parliament. (2008). *DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives (Waste Framework Directive)*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705

European Parliament. (2022). *Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (Text with EEA relevance)* [Bill]. http://data.europa.eu/eli/dir/2022/2464/oj/eng

Flyvbjerg, B. (2006). Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, *12*(2), 219–245. https://doi.org/10.1177/1077800405284363

Forslund, H., & Björklund, M. (2022). Toward Circular Supply Chains for Flat Glass: Challenges of Transforming to More Energy-Efficient Solutions. *Energies*, *15*(19), 7282. https://doi.org/10.3390/en15197282

Forty, A. (1986). *Objects of desire*. Pantheon Books.

Fregonara, E., Giordano, R., Ferrando, D. G., & Pattono, S. (2017). Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage. *Buildings*, *7*(4), 65. https://doi.org/10.3390/buildings7030065

Galletta, A. (2013). *Mastering the semi-structured interview and beyond: From research design to analysis and publication*. New York Univ. Press.

Geboes, E., Galle, W., & De Temmerman, N. (2023). Make or break the loop: A cross-practitioners review of glass circularity. *Glass Structures & Engineering*, *8*(2), 193–210. https://doi.org/10.1007/s40940-022-00211-y

Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy*, *36*(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2016). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Glottrup, C. (2024). *Interview, ARC, [Appendix 4]*.

Gylling, A., & Terkelsen, A.-L. (2024). *Interview, Velux, [Appendix 5]*.

Halvarsson, S. (2024). *Interview, Solum, [Appendix 6]*.

Hansen, K. (2024). *Interview, J. Jensen Genbrug, [Appendix 7]*.

Hauschild, M. Z., Rosenbaum, R. K., & Olsen, S. I. (Eds.). (2018). *Life Cycle Assessment: Theory and Practice*. Springer International Publishing. https://doi.org/10.1007/978-3-319-56475-3

Holtzblatt, K., & Beyer, H. (2017). The Affinity Diagram. In *Contextual Design* (pp. 127–146). Elsevier. https://doi.org/10.1016/B978-0-12-800894-2.00006-5

IPCC. (2022). *Working Group III contribution to the WGIII Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* [Summary for Policymakers.]. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf

Itskos, G., Nikolopoulos, N., Kourkoumpas, D.-S., Koutsianos, A., Violidakis, I., Drosatos, P., & Grammelis, P. (2016). Energy and the Environment. In *Environment and Development* (pp. 363–452). Elsevier. https://doi.org/10.1016/B978-0-444-62733-9.00006-X

Jørgensen, T. (2024). *Interview, Genbyg, [Appendix 8]*.

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005

Kjær, L. L., Pigosso, D. C. A., Niero, M., Bech, N. M., & McAloone, T. C. (2019). Product/Service‐Systems for a Circular Economy: The Route to Decoupling Economic Growth from Resource Consumption? *Journal of Industrial Ecology*, *23*(1), 22–35. https://doi.org/10.1111/jiec.12747

Konradsen, F., Hansen, K. S. H., Ghose, A., & Pizzol, M. (2023). Same product, different score: How methodological differences affect EPD results. *The International Journal of Life Cycle Assessment*, *29*(2), 291–307. https://doi.org/10.1007/s11367-023-02246-x

Kosanović, S., Miletić, M., & Marković, L. (2021). Energy Refurbishment of Family Houses in Serbia in Line with the Principles of Circular Economy. *Sustainability*, *13*(10), 5463. https://doi.org/10.3390/su13105463

Latour, B. (1994). On Technical Mediation—Philosophy, Sociology, Genealogy. *Common Knowledge*.

Lindahl, M., Sundin, E., & Sakao, T. (2014). Environmental and economic benefits of Integrated Product Service Offerings quantified with real business cases. *Journal of Cleaner Production*, *64*, 288–296. https://doi.org/10.1016/j.jclepro.2013.07.047

LUMA Institute. (n.d.). *Fly-on-the-Wall Observation*. LUMA Institute. Retrieved 18 December 2023, from https://www.luma-institute.com/fly-on-the-wall-observation/

Miljøstyrelsen. (n.d.). *PCB*. Miljøstyrelsen. Retrieved 27 May 2024, from https://mst.dk/erhverv/groen-produktion-og-affald/affald-og-genanvendelse/affaldshaandtering/affaldsfraktioner/pcb

Møgelvang, K. (2024). *Interview, Kingo Karlsen, [Appendix 10]*.

Nielsen, J. K. (2024). *Interview, Velux, [Appendix 11]*.

Nordahl, T. (2024). *Interview, Optoglas, [Appendix 12]*.

Nußholz, J. L. K., Rasmussen, F. N., Whalen, K., & Plepys, A. (2020). Material reuse in buildings: Implications of a circular business model for sustainable value creation. *Journal of Cleaner Production*, *245*, 118546. https://doi.org/10.1016/j.jclepro.2019.118546

Optoglas. (n.d.-a). *Homepage—Optoglas.dk*. Retrieved 28 April 2024, from https://www.optoglas.dk/

Optoglas. (n.d.-b). *Om Optoglas®—Optoglas.dk*. Retrieved 28 April 2024, from https://www.optoglas.dk/da/hvad-er-optoglas/

Osterwalder, A., & Pigneur, Y. (2013). *Business model generation: A handbook for visionaries, game changers, and challengers*. Wiley&Sons.

Ploeger, H., Prins, M., Straub, A., & Van Den Brink, R. (2019). Circular economy and real estate: The legal (im)possibilities of operational lease. *Facilities*, *37*(9/10), 653–668. https://doi.org/10.1108/F-01-2018-0006

Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular Economy: Measuring innovation in the product chain*.

Rambøll. (2024). *Analysis of the organisation and handling of VELUX windows and accessories end-of-life [Confidential]*.

Resource worker. (2024). *Interview, Sydhavn Municipal Recycling Centre, [Appendix 9]*.

Risom, M. (2024). *Interview, A:gain, [Appendix 13]*.

Roofgiant. (n.d.). *VELUX Windows | VELUX Roof Windows*. https://www.roofgiant.com/velux-windows/

Rota, A., Zaccaria, M., & Fiorito, F. (2023). Towards a quality protocol for enabling the reuse of post-consumer flat glass. *Glass Structures & Engineering*, *8*(2), 235–254.

https://doi.org/10.1007/s40940-023-00233-0

Rottenburg, R. (Ed.). (1996). When Organization Travels: On Intercultural Translation. In *Translating Organizational Change* (pp. 191–240). DE GRUYTER. https://doi.org/10.1515/9783110879735.191

Saeed, F., Mostafa, K., Rausch, C., & Hegazy, T. (2023). Environmental Impact and Cost Assessment for Reusing Waste during End-of-Life Activities on Building Projects. *Journal of Construction Engineering and Management*, *149*(10), 04023099. https://doi.org/10.1061/JCEMD4.COENG-12943

Sanchez, I. G., Wenzel, H., & Jørgensen, M. S. (2004). Models for Defining LCM, Monitoring LCM Practice and Assessing its Feasibility. *Greener Management International*, *2004*(45), 9–25. https://doi.org/10.9774/GLEAF.3062.2004.sp.00003

Seto, K. C., Davis, S. J., Mitchell, R. B., Stokes, E. C., Unruh, G., & Ürge-Vorsatz, D. (2016). Carbon Lock-In: Types, Causes, and Policy Implications. *Annual Review of Environment and Resources*, *41*(1), 425–452. https://doi.org/10.1146/annurev-environ-110615-085934

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, *104*, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Social, Bolig og Ældreministeriet. (2024). *Ny aftale stiller ambitiøse klimakrav til nyt byggeri*. https://www.sm.dk/nyheder/nyhedsarkiv/2024/maj/ny-aftale-stiller-ambitioese-klimakrav-til-nyt-byggeri

Social og Boligstyrelsen. (2024). *Bygningsreglementets vejledning om bygningers klimapåvirkning* (Energiforbrug og klimapåvirkning (§ 250 - § 298)). https://bygningsreglementet.dk/Tekniske-bestemmelser/11/BRV/Version-2-Bygningers-klimapåvirkning/Kap-1_5#7f41e71a-b195-4e36-92af-fc0dc0af753e

Sode, T. R., & Galán, S. K. (2024, April 10). *Asbest i boliger*. Videncentret Bolius. https://www.bolius.dk/asbest-i-boliger-17967

Stake, R. E. (1978). The Case Study Method in Social Inquiry. *Educational Researcher*, *7*(2), 5–8. https://doi.org/10.3102/0013189X007002005

Svensson, P. C. (2024). *Interview, Velux, [Appendix 2]*.

Tazi, N., Idir, R., & Ben Fraj, A. (2021). Towards achieving circularity in residential building materials: Potential stock, locks and opportunities. *Journal of Cleaner Production*, *281*, 124489.

https://doi.org/10.1016/j.jclepro.2020.124489

The International Organization for Standardization. (2024). *ISO 59004:2024 Circular economy—Vocabulary, principles and guidance for implementation*. https://www.iso.org/standard/80648.html

The VELUX Group. (2023). *Sustainability Report 2022*.

The VELUX Group. (2024). *Sustainability Report 2023*.

Travis, D. (Director). (n.d.). *Desk research: The what, why and how*. https://www.userfocus.co.uk/articles/desk-research-the-what-why-and-how.html

Tukker, A. (2015). Product services for a resource-efficient and circular economy – a review. *Journal of Cleaner Production*, *97*, 76–91. https://doi.org/10.1016/j.jclepro.2013.11.049

Unruh, G. C. (2002). Escaping carbon lock-in. *Energy Policy*, *30*(4), 317–325. https://doi.org/10.1016/S0301-4215(01)00098-2

Velux. (n.d.-a). Retrieved 23 April 2024, from https://www.velux.dk/omos

Velux. (n.d.-b). Retrieved 23 April 2024, from https://ressourcer.velux.dk/find-en-toemrer

VELUX. (n.d.). *About us—VELUX Group*. https://www.velux.com/who-we-are/about-us

Vreeken, M. (2024). *Interview, Velux Netherlands, [Appendix 14]*.

Zethner, V. (2024). *Interview, Carpenter, [Appendix 15]*.