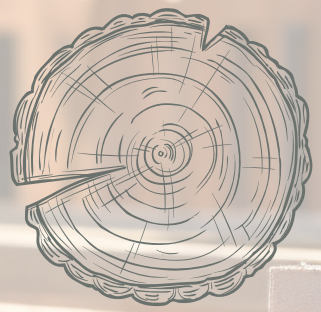
Accelerating change:
Bio-based materials addressing the combined crisis





Master Thesis for Sustainable Cities 2024

BREAKING NEW GROUND
AALBORG UNIVERSITY

“Look deep into nature, and then you will understand everything better.”

Albert Einstein

Accelerating Change: Bio-based Materials Addressing the Combined Crisis

Master Thesis for Sustainable Cities

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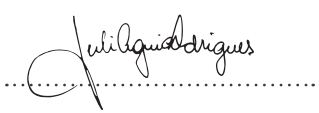

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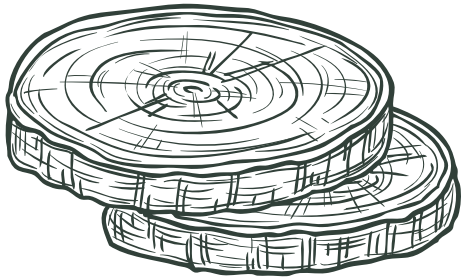
Abstract

Environmental concerns and warnings arising at the beginning of 1970 have evolved to become part of today's critical ecological reality, characterized by significant biodiversity loss, resource depletion, and increasing CO_2 emissions. This combined environmental crisis requires urgent and systemic changes, particularly within sectors like construction, which significantly contributes to global emissions and resource extraction. In Denmark, despite various efforts to promote sustainable building practices, the construction industry's reliance on conventional materials continues to pose challenges. This thesis investigates the potential acceleration of bio-based materials' adoption in the Danish construction industry as a means to mitigate these environmental impacts. Through a comprehensive review of literature and interviews with industry stakeholders, and supported by the theoretical framework of Multi-level Perspective (MLP) , this study revealed that the Danish building industry is resistant to change and incorporate new materials due to the complex interplay between social and technical factors , urging to act at different levels. Additionally, it was realized that bio-based materials are in an early stage of development, still having a long way to go to be part of the mainstream. Therefore, the research proposes necessary actions to accelerate their use so they are able to replace part of the conventional materials and become institutionalized and anchored in regulatory programs, user habits and professional standards. The study also highlights a critical research gap concerning the impact of bio-based materials in biodiversity, advocating for an integrated approach that encompasses CO_2 reduction, resource scarcity, and biodiversity preservation and restoration. The findings underscore the need for further research and incorporation of regenerative and circular practices to fully harness the potential of bio-based materials in addressing the combined environmental crisis.



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As we complete our master's thesis journey, we would like to extend our deepest gratitude to those who have supported us along this remarkable path.

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To all the interviewees of this research, who generously shared their time and empirical insights with us, enriching our research and contributing to the realization of this thesis.

Lastly, we want to thank each other for the past two wonderful academic years we shared. From the endless discussions and meetings to the shared laughter and friendship, our bond has been a source of strength and inspiration for our journey. We cherish the invaluable lessons learned by the mutual support and the joy of learning together. It's been an honor to share this transformative experience with such amazing companions.

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Content

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Definitions & key concepts

Combined crisis: The set of interconnected and complex environmental stresses The world encounters which influence and exacerbate each other, form essentially a combined crisis (Hoyer, et al. 2023). For this research, it is considered as the combination of resource scarcity, biodiversity loss, and climate change crisis.

Bio-based building materials: are materials composed of living organisms such as plants or animal biomass, excluding materials of fossil or geological origin, that have undergone processing to become functional products (Bourbia et al., 2023; Vangsbo et al., 2024).

Conventional materials: building materials composed of mined resources that are of fossil or geological origin, such as concrete and steel, refer to this report also as "mineral-based materials".

Symbiosis: "Physical exchange of materials, energy and water between two or more companies, turning what is normally seen as waste, into a resource. It is thereby part of the circular economy and allows industry to move away from the linear take-make-dispose system towards circular use of resources" (Kalundborg Symbiosis, 2023).

Planetary Boundaries: "The planetary boundaries concept presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come." (Stockholm Resilience Centre, n.d.)

Reading guide

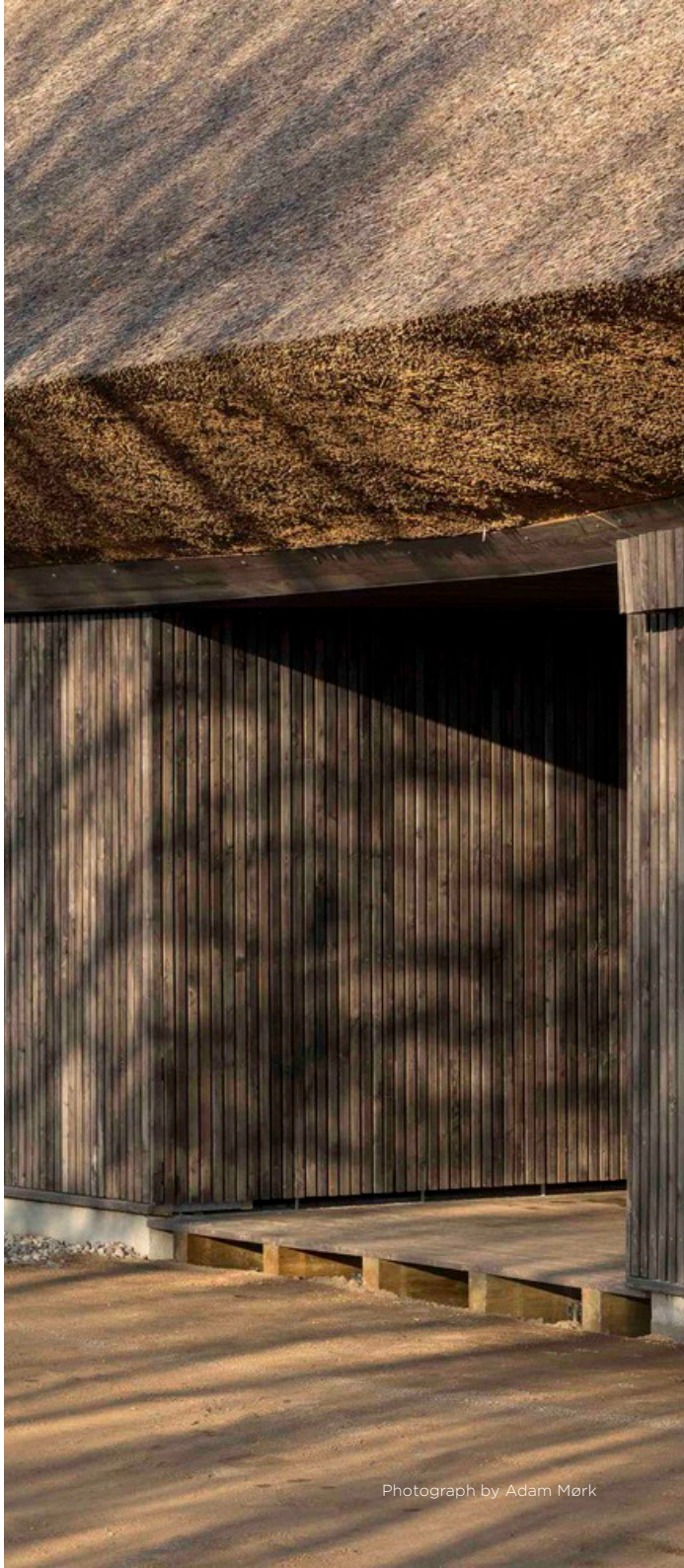
This report is organized in a way that an introduction is presented in chapter 1 to first outline the critical importance of transitioning to bio-based materials in the Danish construction industry, leading to the formulation of the research questions, the scope, and the purpose of the project. This is followed by chapters 2 and 3 focusing on the presentation of the methodological approach and the theories that assisted the research process and organization of the information.

The following chapter named "Analysis" is divided into three sections and aims to answer the 5 sub-research questions that guide this study. The information provided in this chapter is later discussed in section 5, where a reflection upon the main findings is presented.

Chapter 6 presents recommended actions to answer the main research questions. Finally, chapter 7 presents the conclusion remarks for this report, followed by the reflections regarding the work done, and decisions taken.

In this report, chapters and sections are labeled using the format X.Y.Z., where X refers to the chapter, Y signifies the section, and Z indicates the subsection. Figures and tables within these chapters are numbered consecutively, starting from 1.

A bibliography in APA style is provided at the end of the document.



Photograph by Adam Mørk

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1 Introduction

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1. Introduction and Problem Statement

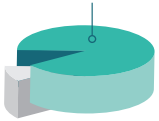
Already from the beginning of 1970, researchers began expressing concerns and warnings about environmental consequences stemming from the prioritization of economic growth over the balance of nature (Meadows and Club of Rome, 1972). Since that time these warnings have turned into today's reality. The global annual rate of material extraction has tripled, while in Denmark the extraction of minerals has increased by roughly 30% (UNEP, 2024a; UNEP, 2024b). At the same time, 69% of the world's monitored wild animal populations have disappeared, with roughly 90% of biodiversity depletion attributed to extraction activities and processing of natural resources (Ellen MacArthur Foundation, 2021; WWF, 2022). Lastly, the atmospheric concentration of CO2 emissions has risen by 22,3 billion tonnes – reflecting a 30% of increase (NOAA, 2024). The world encounters a set of interconnected and complex environmental stresses that influence and exacerbate each other, forming essentially a combined crisis (Hoyer, et al. 2023). This combined crisis, characterized by resource scarcity, biodiversity loss, and climate change, necessitates urgent and radical systemic changes (Lai et al., 2017).

Six out of nine planetary boundaries have been breached, posing severe risks of unpredictable and irreversible changes that threaten both planetary and human well-being (Richardson et al., 2023; Steffen et al., 2015). This alarming reality underscores the imperative to act now to mitigate the most severe impacts, as highlighted in the 6th IPCC report (IPCC, 2023) and emphasized by Johan Rockstrom in his statement: "What happens in the next 10 years will likely determine the state of the planet we hand over to future generations" (Rockstrom, 2022).

42% of global CO2 emissions comes from the construction industry

The global annual rate of material extraction has **Tripled**

90% of biodiversity loss stems from extraction & processing of natural sources



> *To accommodate the largest wave of building and infrastructure growth in human history, from 2020 to 2060, the world is expected to add about 241 billion m2 of new floor area to the global building stock, the equivalent of adding an entire New York City to the world, every month, for 40 years. Additionally, three-quarters of the infrastructure that will exist in 2050 has yet to be built.*
>
> *Why the built environment, Architecture 2030*

The construction industry accounts for 42% of global CO2 emissions, and materials alone represent over 70% of the environmental impact of buildings (Newell et al., 2019). Moreover, it contributes to 40% of all extracted materials, 40% of energy consumption, and generates 40% of annual waste at the European level (Sizirici et al., 2021). Considering this significant contribution of the construction industry to environmental degradation, decisive actions are imperative to transition towards more sustainable building practices.

In Denmark, recent political initiatives, such as the Climate Act of 2020, National strategy for sustainable construction (Den nationale strategi for bæredygtigt byggeri) from 2021 and mandatory LCA for new constructions starting in 2023, aim to support this transformation (BR18; Andersen, 2023). Despite legislative efforts in Denmark, the transition to sustainable building practices remains hindered by well-established

industry norms and infrastructures, which poses significant challenges to rapid change (Uusitalo & Lavikka, 2020; Andersen, 2023).

The transition to sustainable practices must occur at various levels, and from building to material is one of them. Considering all the impacts regarding the building industry, materials represent one of the biggest issues. Today the industry relies on conventional building materials and they have substantial environmental impacts, including high CO2 emissions, resource depletion, and biodiversity loss (Birgisdottir et al., 2023). One promising solution is the use of bio-based materials, which require less energy for production, are renewable, reduce waste and store carbon (Torben et al., 2023).

1.1 Scope of the project

Given the urgent need to address multiple environmental crises and acknowledging the role bio-based materials potentially play in the Danish building industry transition, this thesis aims to explore how the use of bio-based materials in the construction industry can be accelerated. It aims to recommend actions for the acceleration of their uptake, integrating ongoing discourses and strategies that contribute to the development of more sustainable practices within the Danish building industry.

The central research question and sub-research questions guiding this study is as follows:

RQ **How can the use of bio-based materials be accelerated while addressing the combined environmental crisis?**

1. Which elements of the environmental combined crisis are influencing the emergence of bio-based materials into the building industry?
2. What is the role of bio-based materials in addressing the combined crisis?
3. What is the current state of development of bio-based materials?
4. What hinders the transition towards the use of bio-based materials?
5. Which discourses for sustainable construction are supportive towards the use of bio-based materials?

The theoretical framework of multi-level perspective (MLP) will be applied to organize the gathered knowledge and facilitate the analysis of the elements that influence the transition towards the use of bio-based materials. It will also facilitate the identification and analysis of the social and technical factors that hinder or slow down the uptake of bio-based materials. Even though the focus is on materials, dynamics that occur in building and material level are going to be considered, as they are both deeply interconnected. Moreover, the Planetary Boundaries Theory developed by Stockholm Resilience Center will be utilized as lenses to understand the combined crisis and the urgency to expand the efforts beyond the reduction of CO2 emissions (Stockholm Resilience Centre, n.d.).

This study will strive to achieve a comprehensive understanding and overview of the current status of bio-based building materials in Denmark. This will be achieved by incorporating various perspectives based on discourses relevant to sustainable construction and by identifying the potentials and implications of bio-based materials, beyond their carbon storage capabilities. The theories and the discourses chosen in this study will help identify problem areas that were potentially overlooked. Finally, it aspires to provide insights for industry stakeholders, and researchers involved with bio-based materials.

1.2 Research design

> *Without a stable climate and healthy ecosystems, socio-economic goals cannot be achieved, as such we must redesign society (of which the economy is a part) through systems change.*
>
> *Bjørn et al., 2023*

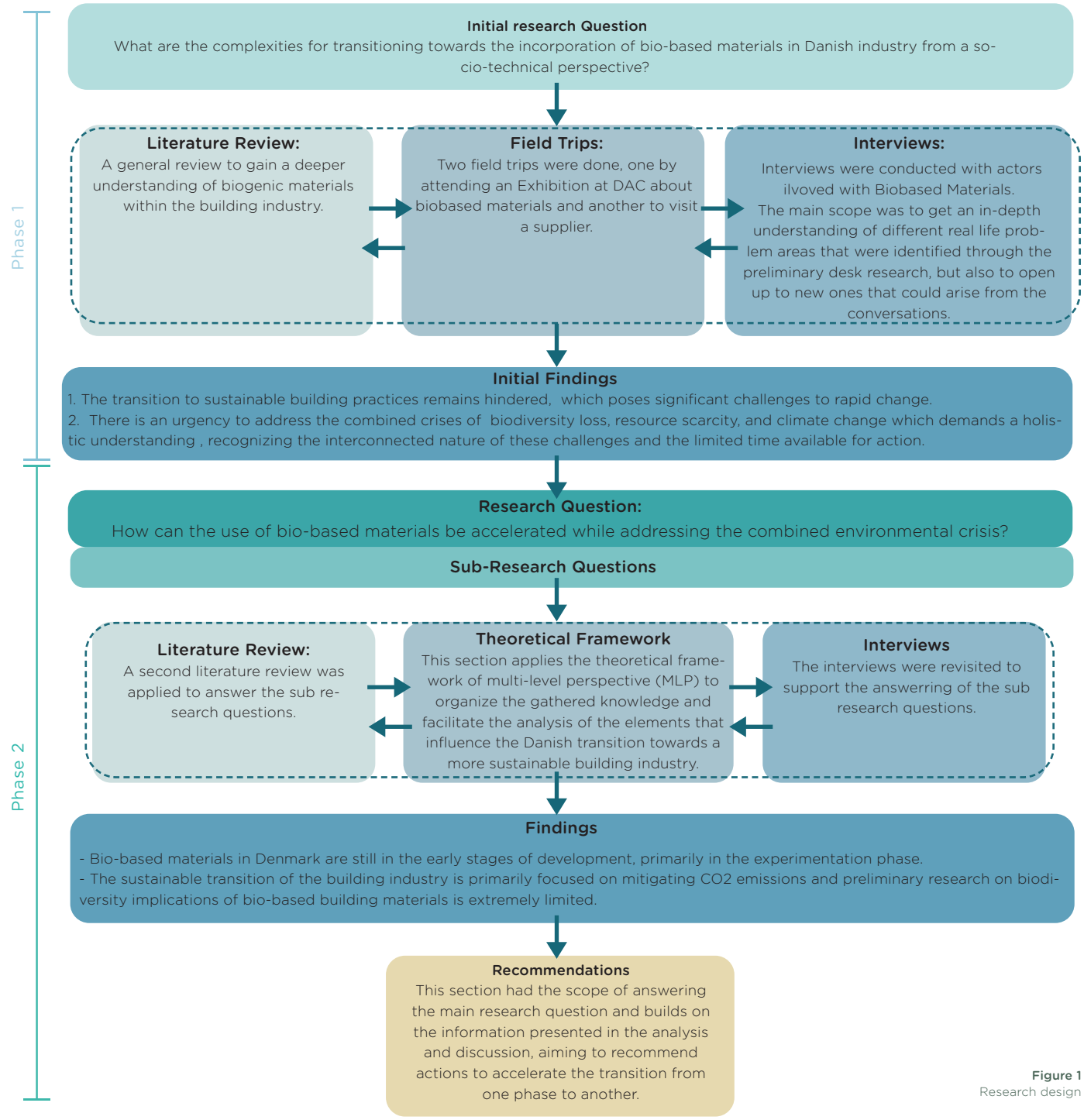


Figure 1
Research design

2 Methodological Approach

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2 Methodological approach

In this study, a combination of qualitative data collection methods was employed to ensure a comprehensive analysis. These methods included conducting literature reviews to gather existing information, carrying out semi-structured interviews to obtain empirical insights and experiences from relevant actors of the industry, and attending an exhibition on bio-based building materials to observe directly from relevant displays and presentations.

2.1 Literature review

The literature review was developed following a process of gradual accumulation of knowledge throughout the development of this study. The research was essentially conducted in three phases. The initial phase had a broad scope aimed at understanding and gaining more insights about the subject. This was followed by a second phase, which supported the analysis of the empirical insights from real-life problematizations gathered through interviews and site visits, helping to refine and direct the scope of the study. Lastly, the final phase facilitated the discussion and formulation of recommendations.

The literature review is based on academic articles, industry reports and articles, books, and technical documents. The authors primarily used the Primo search tool from Aalborg University, along with Google Scholar to find these resources. The Miro software was used as an online workspace and knowledge-sharing platform, where each read article was shared on a virtual board with post-its highlighting key content or areas of relevance, as can be seen in Figure 2.

Figure 2
Example of real-life Miro boards illustrating how the knowledge gathered from literature review was shared, organized and highlighted by the thesis group

2.2 Semi-structured interviews

After acquiring some fundamental knowledge about bio-based materials through the literature review, eleven interviews were conducted, eight of which were online and three in person with a diverse range of actors representing various sectors and areas of expertise in the value chain. Their empirical insights working within the building industry and with bio-based materials were gathered and analyzed, serving as a foundation for understanding what is happening within the field, identifying points of concern and areas for improvements.

The interviews were carried out in a semi-structured format, aiming to facilitate an open dialogue around the research topic and to ensure a certain degree of consistency across the interviews. However, they were also customized according to the interviewees' profile, the projects they were involved in and the ongoing knowledge acquired during each interview and literature review process. The majority of the interviews were conducted digitally on the Teams platform, where the audio was automatically transcribed. Transcriptions were edited to correct typographical errors. Notes were taken during the interviews to highlight key points and to formulate new questions if necessary. The transcription of the interviews can be seen in the Annex.

Finally, the empirical data from the interviews was visually summarized in Miro digital boards, which helped to organize the main findings, identify problem areas and relevant topics for further investigation (figure 3).

Figure 3
Example from Miro boards, illustrating key points that were identified in the interviews and clustered in themes according to the points of interest the thesis group defined. Colour coding was used as indication for differentiating each participant's insights.

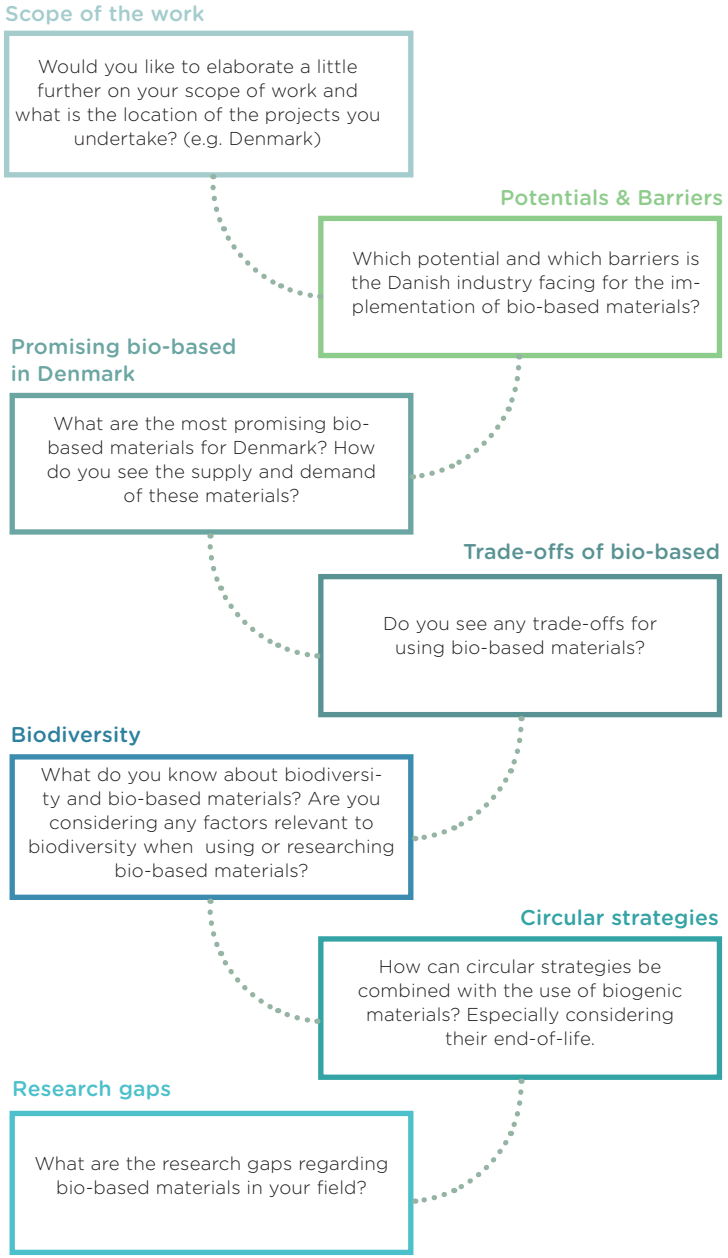

Figure 4
Core interview guide, customized for each interview according to the participants' professional background and knowledge gathered

Date	Participant's position	Area of expertise	Organization/company name	Represented sector	Citing in text
09/02/24	Architect and Sustainable design engineer	R&D Build Environment	Effekt	Architectural design and research studio	(Effekt, Sustainable Design Engineer)
09/02/24	Architect and Sustainable design engineer	R&D Build Environment	Effekt	Architectural design and research studio	(Effekt, Head of innovation)
01/03/24	Chief engineer	Civil engineer specialized in load-bearing structure of buildings, houses, offices, industrial buildings.	Rambøll	Global engineering and consulting company	(Rambøll, Civil engineer)
05/03/24	Chief project manager	Architect and project manager with a focus on development in the construction industry.	Realdania	Philanthropic association	(Realdania , Chief project manager)
07/03/24	Innovation consultant - Project Manager	Soft funding advisor and R&D services for Danish companies, mainly for the building industry.	DBI	The Danish Institute of Fire and Security Technology	(DBI, Innovation consultant)
07/03/24	Architect	Architect and industrial PhD fellow for Sustainable Building Transformations.	Henning Larsen	Architecture & landscape architecture studio.	(Henning Larsen, Architect)
08/03/24	Co-founder and Co-CEO	Craftsman	Havnens Hænder	Bio-based building supplier	(Havnens Hænder, Craftsman & CEO)
08/03/24	Senior researcher	Researcher specialized in the building environment sustainable transition, member of the research team in the 'BUILD' department of Aalborg university	Aalborg university	Academia	(AAU, Senior researcher)
12/03/24	LCA specialist	Architect & industrial PhD fellow about how the built environment affects the transgression of critical limits for biodiversity loss in a life cycle perspective.	Rambøll	Global engineering and consulting company	(Rambøll, LCA Specialist)
14/03/24	Advanced Product Development Consultant	Project manager working with innovation, research and development projects, focusing on enabling bio-based materials and circular products to enter the market.	DBI	The Danish Institute of Fire and Security Technology	(DBI, Development consultant)
22/03/24	Sustainable cities engineer	Building environmental certifications consultant	Nordic Swan Ecolabel	Environmental certification	(Nordic Swan,Engineer)

Figure 5
Description of interviewees' professional background and dates of interviews.

2.3 AI tools

As many key sources were available in Danish, the use of AI translation tools was necessary to facilitate the collection of knowledge. Documents were efficiently translated from Danish to English, giving access to a wealth of literature that was vital for this research. Essentially, the incorporation of AI tools into the research methodology amplified the literature reviewed and helped to overcome the language barriers, contributing significantly to the project's success. Generative AI, such as ChatGPT, was used to clarify concepts, get inspiration for new ideas and verify the clarity of the written.

2.4 Field trips

During the research process, two field visits were conducted. The first visit took place on the 9th of February 2024 in the Danish Architecture Center, to view the exhibition ''Changing Our Footprint'', where bio-based building materials were displayed giving the opportunity to explore different materials, their applications, and examples of completed, ongoing and future projects where those materials are being used.

The second visit was to a bio-based building materials supplier Havnens Hænder, located in Refshaleøen in Copenhagen, which houses an office, hardware store, showroom, and workshop department. The visit allowed the authors to have a firsthand visualization and contact with these materials.

3 Theoretical Framework

Source: Adobe stock

3. Theoretical framework

3.1 Multi-level Perspective Theory

3.1.1 Landscape, regime and the niches

Multi-level perspective theory (MLP) is a theoretical framework that aims to understand the dynamics of interaction between different systems to achieve the radical transformation needed to face increasing environmental problems such as climate change, biodiversity loss and resource scarcity. These systems are defined as "socio-technical" as they include technologies but also other elements needed to fulfill societal needs, such as markets, policies, culture, social values, among others. (Geels, 2004). Changes in those socio-technical systems are described by Geels as socio-technical transitions which follow non-linear trajectories and take decades to come about (Geels, 2012).

As represented in figure 6, these transitions are the result of interactions at three different analytical levels, defined as socio-technical landscape (exogenous context), socio-technical regime, and the niche-innovations level (Geels 2010, Geels 2012), as described below.

The Socio-technical landscape

The socio-technical landscape is defined as the broader context that exerts an influence on both niche and regime levels. It can be seen as the greatest level of structuration in the MLP context as it is outside the direct control of actors. Changes at landscape level still occur, but at a slow pace. In the context of this research, the lascaped encompasses the external pressures such as biodiversity loss, resource scarcity, and climate change.

Socio-technical regime

The set of deep-structure and rules that direct the practices and perceptions of actors are defined as socio-technical regimes. Established regimes are resistant to changes, being stabilized by the existence of lock-in mechanisms and path dependence, such as cognitive routines that make actors "blind" to consider different directions or formal rules such as binding contracts are examples of stabilizing forces in the regime (Geels, 2004). This leads to changes that occur gradually and follow predictable trajectories (Geels, 2004; Geels, 2012). For this study, the conventional Danish building industry is recognized as the socio-technical regime.

Niche-innovations

The third systematic level comprising the society as MLP indicates is the niches level. According to Geels (2011) niches can be described as 'protect-

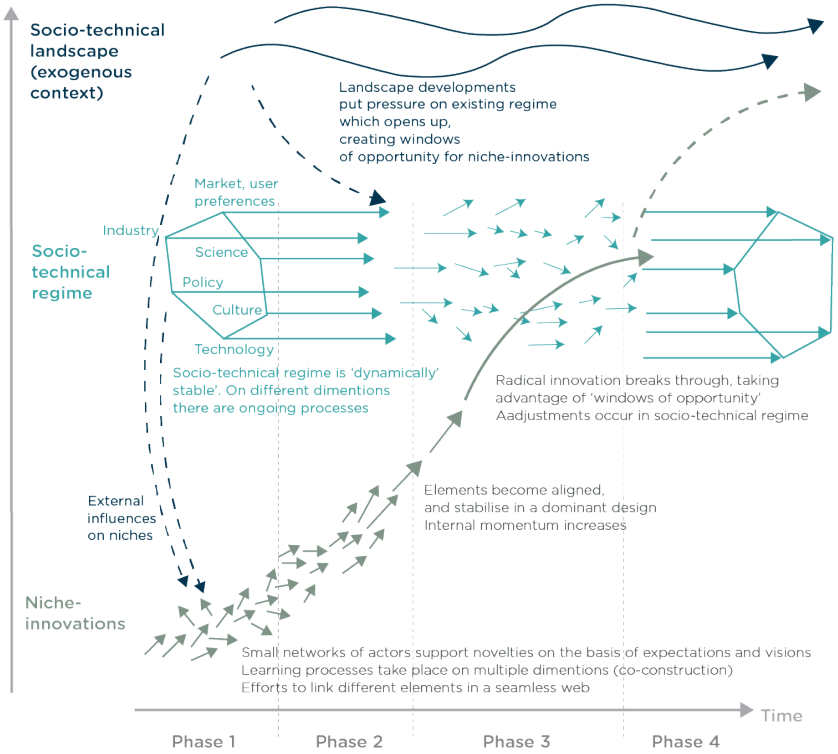

Figure 6
Multi-level Perspective on Socio-Technical Transitions and phases of transitions, Geels et al. 2017

ed spaces' where emerging and radical innovative ideas can be developed and nurtured. These innovations essentially seek to disrupt or challenge the established or conventional existing regime, which in this case is the building sector following the business-as-usual trajectory. Therefore, niches serve as the catalysts for systemic change as they contain the potential to reshape or replace the existing regime, paving the way for sustainable transitions (Geels, 2011). In this research, we identify bio-based materials as niche innovations that have the potential to disrupt the current regime of the building sector.

3.1.2 Transition phases

As showcased in figure 7 MLP divides the sustainable transition process in four phases, that according to Geels et al. (2017) and Geels (2019) are defined as follows:

Phase 1

In the first stage, radical innovations arise within niches on the periphery of existing regimes. The networks of innovators during this phase are characterized by instability, uncertainty, experimentality, and fragility, advancing various design options, many of which do not succeed.

Phase 2

In the second phase, niches infiltrate small markets that give resources for their further development. During this phase, the innovation follows its own trajectory, a dominant design starts to emerge, and expectations along with associated rules begin to stabilize.

Phase 3

In the third stage, the innovation becomes more widespread and starts to compete directly with the established regime. This process is driven by internal niche factors such as improvements in price and performance, economies of scale and learning, the development of complementary technologies and infrastructures, positive cultural narratives, and support from influential actors.

Phase 4

The fourth phase involves regime substitution, where innovations are widespread adopted, followed by significant adjustments in infrastructures, policies, industrial and markets, lifestyles, and perspectives.

As MLP is broadly used to understand complex sustainable transitions, it is considered as a suitable framework for this study to analyze the dynamics that influence the Danish transition towards a more sustainable building industry, focusing on the role of bio-based materials.

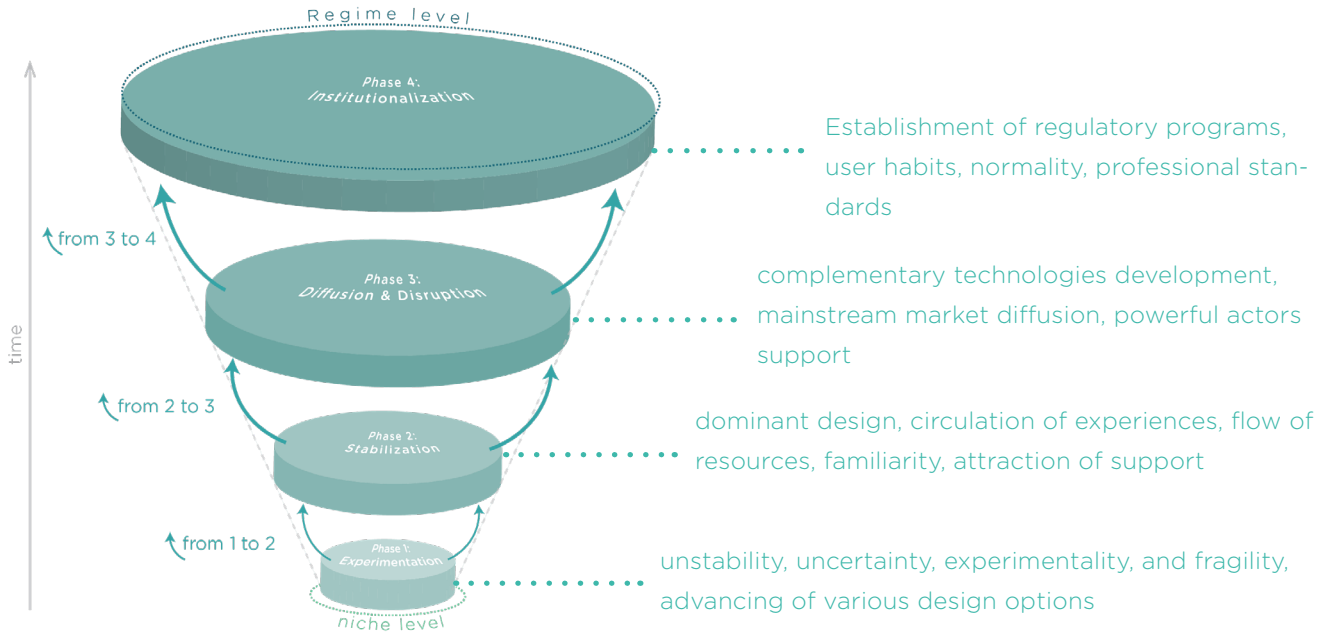

Figure 7
Transition phases and their characteristics, inspired by Geels et al., 2017 & Geels, 2019.

3.2 Planetary boundaries

Today, humanity confronts an environmental combined crisis, with six out of nine planetary boundaries already breached (Richardson et al., 2023). These nine planetary systems and their respective limits represent a safe operating space within which humanity can continue to develop and thrive for generations to come. Once these boundaries are surpassed, there is an elevated risk of unpredictable and irreversible environmental changes that adversely affect both planetary and human well-being (Steffen et al., 2015). This current state highlights the urgent need to expand the focus beyond solely reducing greenhouse gasses, as the planet faces a combined crisis with challenges across numerous other environmental parameters (Birgisdottir et al., 2023).

The use of bio-based building materials necessitates careful consideration within these boundaries , given that six out of nine planetary boundaries can be directly influenced by their use, such as CO2 levels, biodiversity, nitrate leaching into marine environments, land usage, pesticide consumption, pollution and freshwater consumption (VIA et al, 2024). Recent studies highlight that climate change and biodiversity loss are the two core boundaries. These are considered fundamental because significant violations in either of these areas alone can destabilize the Earth system, pushing it out of its stable and safe operating space. (Birgisdottir et al., 2023).

For this study, the concept of Planetary Boundaries will be utilized as lenses to understand the combined crisis and the urgency to expand the efforts beyond the reduction of CO2 emissions (Stockholm Resilience Centre, n.d.). Even though the authors acknowledge the importance of all six boundaries related to bio-based materials, this study will focus on the two most urgent and important ones: climate change and biodiversity loss.

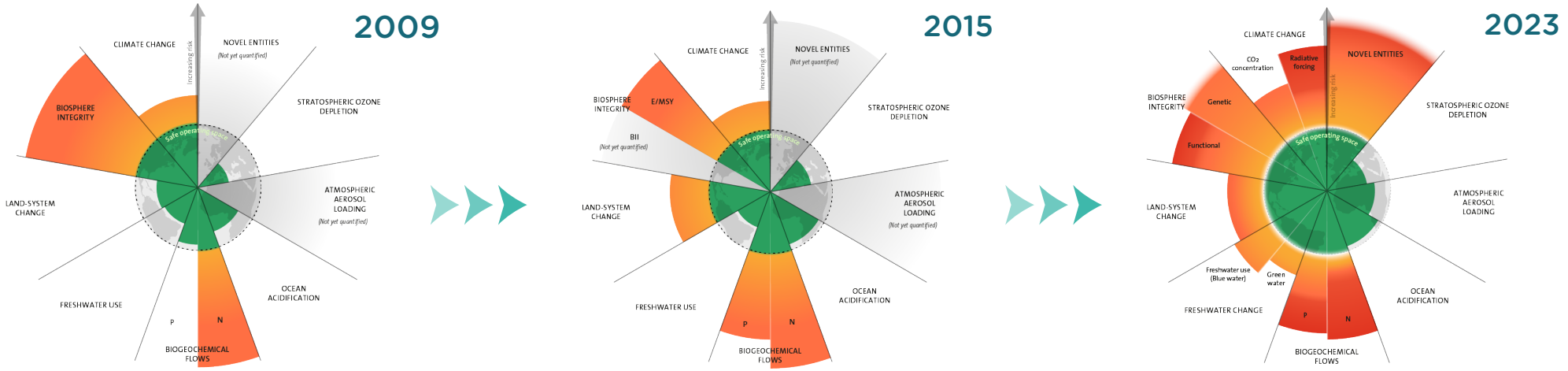

Figure 8
"The evolution of the planetary boundaries framework", Source: Stockholm University, 2023, 3rd update

4 Analysis

Source: Adobe stock
The Natural Pavilion, Almere, the Netherlands

4. Analysis

This section applies the theoretical framework of multi-level perspective (MLP) to organize the gathered knowledge and facilitate the analysis of the elements that influence the Danish transition towards a more sustainable building industry. Even though the focus will be on the material level, the analysis will address problem areas and influences that occur inherently both in building and material level as materials do not operate in isolation.

4.1. Landscape developments urging the change of the building industry

This section aims to answer the following research questions: Which elements of the environmental combined crisis are influencing the emergence of bio-based materials into the building industry?

In this research, the environmental combined crisis is identified as part of the landscape forces, hence external developments that put pressure both on the regime of the building industry and the niches of bio-based materials (Geels, 2011). Therefore, this section focuses on exploring how climate change, resource scarcity, biodiversity loss and other developments occurring at the landscape level can exert pressure on the current building industry. This leads to its destabilization and consequently creates potential windows of opportunity for bio-based materials to emerge.

Climate change

There is an urgent need for action when facing the likelihood of global warming exceeding 1.5°C. Europe is experiencing warming at about twice the global rate (EEA, 2024). In the 3°C world scenario, according to the IPCC report,, the annual hottest day in many parts of Europe is projected to be 7°C higher than it is now (IPCC, 2023). There is a growing risk of megadroughts spanning large regions and lasting multiple years, causing severe degradation of food and energy supply (EEA, 2024). Sea levels will rise by more than 2 meters, and permanently submerge many low-lying coastal cities, including Copenhagen. Political initiatives like CO2 emission limits and environmental restrictions will transform several sectors including the practices of agriculture and construction. These changes will potentially reveal vulnerabilities in the current building system that can serve as opportunities for the adoption of bio-based materials (Westermann, 2023; VIA University, 2024).

Resource scarcity

In addition to generating greenhouse gas (GHG) emissions, the building sector heavily depletes global resources. Construction and infrastructure account for 40% to 50% of the materials extracted worldwide, and this percentage is projected to rise as the demand for new housing and infrastructure grows to accommodate increasing population and economic development (Le et al., 2023).

Images source: Adobe stock
Icons: Own creation

After decades of building with predominantly carbon-intensive, mineral-based materials such as concrete and steel, the climate crisis and global resource scarcity of those are putting pressure on the existing building industry to explore low-carbon alternatives and innovative materials that do not rely on oil and minerals; thereby creating an opportunity to consider bio-based materials as viable and renewable alternatives (Westermann et al., 2023).

Biodiversity loss

Another crucial development defining the landscape is the loss of biodiversity. Research has indicated a notable decline in biodiversity over the past century which is primarily attributed to human activities. Since 1970, there has been a 68% decline in global biodiversity among mammals, birds, fish, reptiles, and amphibians (Manders, 2022). Out of this, 90% of biodiversity loss is linked to the extraction of raw materials (Kuittinen, 2023), exerting a pressure on the current building industry, leading to its destabilization and consequently creating potential windows of opportunity for bio-based materials to emerge.

> *"1 million of the world's estimated 8 million species of plants and animals are threatened with extinction."*
>
> *IPBES, 2019*

Other pressures identified in the landscape

In the broader context, there are also other developments that can be recognised as additional forces operating within the landscape, able to put pressure on the building industry regime. War, for instance, affects the industry's transition to sustainable materials in multiple ways. Military activities contribute significantly to greenhouse gas emissions through the use of fossil fuels and ecosystem destruction. Recent studies revealed that a total of CO2 emissions after 18 months of war in Ukraine was estimated at around 150 million tons (de Klerk et al., 2023). Moreover, the intense demand for natural resources during conflicts leads to overexploitation and ecosystem degradation, further straining the availability of raw materials (Vuong, 2024).

In addition, population growth and urbanization are projected to increase, with a substantial 40% of the global population requiring new housing (Akenji et al., 2015). This growth will intensify the demand for resources within the construction sector.

Nevertheless, while these forces are recognized, further exploration falls beyond the scope of the current research and they are not going to be regarded in the forthcoming analysis.

Images source: Adobe stock
Icons: Own creation

4.2 Bio-based materials as part of the building industry transition

Literature review, alongside the information gained from the interviews, made it possible to construct a comprehensive overview and understanding of the current status of bio-based materials within the building industry and thus answering the following to research questions: 1) What is the role of bio-based materials in addressing the combined crisis? and 2) What is the current state of development of bio-based materials?. To do so, the analysis explores the benefits of bio-based materials, their potential implications on the ecosystems, their availability in Denmark, their current status of development and the forces that support their use.

4.2.1 Bio-based materials and their benefits

The dialogue around embracing more sustainable building practices intensifies, reshaping architectural innovation by placing bio-architecture at the forefront of future building design (Sandak et al., 2018). Within this context, bio-based materials emerge as pivotal components, representing a departure from the solely use of conventional mineral-based building materials (Bauhaus Earth, 2023).

Bio-based building materials are materials composed of living organisms such as plants or animal biomass, excluding materials of fossil or geological origin, that have undergone processing to become functional products (Bourbia et al., 2023; Vangsbo et al., 2024). The radicality of using them in construction practices lies within their strong capability to address and mitigate climate change and resource depletion (Bauhaus Earth, 2023). One of their major benefits stems from their renewability. Unlike materials derived from minerals or fossil fuels, which are finite and non-renewable resources, bio-based materials can be renewed over time through natural processes. By utilizing bio-based materials instead of non-renewable ones in construction, it becomes possible to reduce resource scarcity and environmental impacts (Sandak et al., 2018; Bauhaus Earth, 2023).

Additionally, bio-based materials are characterized by low embodied energy and carbon emissions; they require lower amounts of energy for their production and they are able to actively store carbon while growing, effectively locking it away when the material is harvested and preventing its release into the atmosphere until their end of life (Vangsbo et al., 2024). This unique characteristic can significantly contribute to the climate change mitigation efforts (Sandak et al., 2018; Bourbia et al., 2023). Building with bio-based extends beyond environmental benefits, as it can also enhance wellbeing and health. Bio-based typically contain less toxins and contaminants compared to conventional materials, creating a healthier indoor environment. Moreover, they are 'breathable' materials, enabling them to effectively regulate moisture levels, humidity and air quality, assuming that proper design and installation procedures are followed (Ramboll, 2022; Vangsbo et al., 2024).

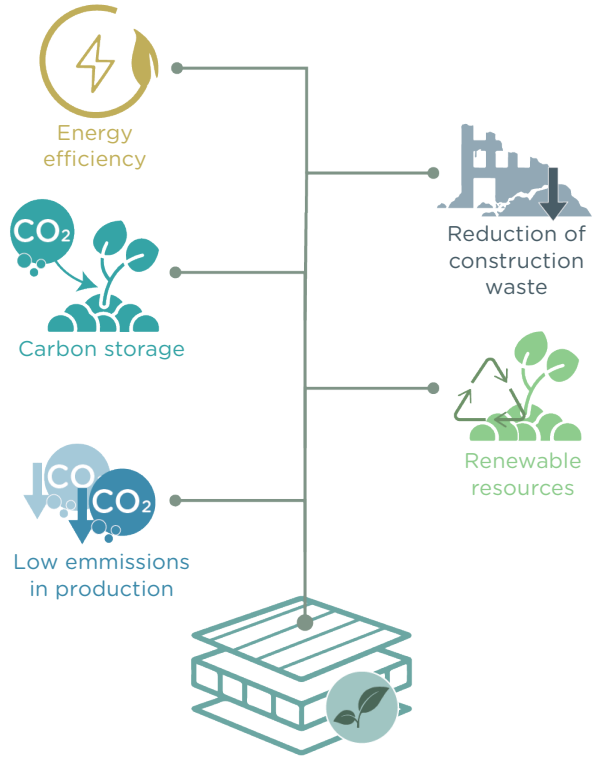

Figure 9
Main benefits of bio-based materials

Currently, the adoption of bio-based materials in constructions is significantly lower in comparison to the use of conventional building materials. In Europe, only 3% of the total mass of building

materials used corresponds to bio-based materials (Bauhaus Earth, 2023). However, substituting conventional building materials with bio-based materials provides the potential to significantly scale down CO2 emissions, with estimations suggesting reductions of up to 75% (Jaja Architects, 2023).

4.2.2 Exploring bio-based beyond their benefits

When it comes to mineral-based materials, research has documented their severe impacts on biodiversity loss, especially during the extraction phase (Opoku, 2019). However, literature review conducted for this report revealed a significant lack of studies on how bio-based materials might affect biodiversity. This gap highlights that the potential environmental consequences of bio-based materials are not yet widely regarded.

From bio-based material resources, wood is essentially the only one that presents a rather adequate knowledge database connecting it with biodiversity loss, due to its long history of use in many sectors (energy, products, construction). Extensive evidence indicates that logging and generally forestry operations can cause substantial harm to ecosystems and their services by disrupting or eradicating crucial microhabitats, leading to substantial species loss (Chaudhary, et al. 2017; Ritchie, 2021).

While research on other bio-based materials and their impact on biodiversity is extremely limited, there is a gradual growing interest in understanding the environmental consequences. Some of the interviews conducted as part of this research have revealed a shared acknowledgment and concern about the importance of considering biodiversity impacts. However, the challenge remains due to the lack of data and the early stage of development of tools for measuring biodiversity loss (e.g LCA for biodiversity) (Rambøll, LCA Specialist; Henning Larsen, Architect; Realdania , Chief project manager, Winter et al., 2017).

> *Due to the land use requirements for bio-based materials, it is expected that they will not perform very well in terms of biodiversity loss in comparison with mineral based materials.*
>
> *Rambøll, LCA Specialist*

> *We need to be very precise on with farmland, are we harvesting forests or are we mining minerals and each have their different drawbacks.*
>
> *Realdania, Chief project manager*

> *The impact on biodiversity depends on the plant you choose as bio-based material. Hemp, for instance, is very good at biodiversity. It makes a healthy soil because it's a deep root plant.*
>
> *Havnens Hænder, Craftsman & CEO*

Considering the resources that bio-based materials require for their production, an indirect connection with biodiversity can be formulated through agriculture. Since most bio-based materials originate from crop cultivation, they are inherently linked to agricultural practices. There is substantial existing knowledge exploring the connection between agriculture and biodiversity (Jameson et al., 2024). Currently, in Denmark, the agricultural sector is one of the most significant contributors to biodiversity depletion. In 2022, approximately 61% of Danish farmland was utilized primarily for conventional farming, which significantly compromises biodiversity (Statistics Denmark, 2024; Danmarks Naturfredningsforening, n.d.). The types of crops grown, the agricultural techniques employed, and the land management practices used, all influence the diversity of plant and animal species (Jameson et al., 2024). Therefore, by understanding and addressing biodiversity considerations in agriculture, makes possible to partially explore and un-

derstand the potential biodiversity implications that bio-based building materials may entail, given their connection to agricultural processes and their associated environmental impacts.that bio-based building materials may entail, given their connection to agricultural processes and their associated environmental impacts.

4.2.3 Bio-based resources availability in Denmark

Denmark possesses a significant amount of resources that remain underutilized and hold a great potential for supporting the sustainable transition of the construction industry. Realdania, in collaboration with the Department of Building, City, and Environment (BUILD) at Aalborg University, has conducted an analysis, titled 'Biogene materialers anvendelse i byggeriet', in which they identified and evaluated potential resources within Denmark that are deemed suitable for the future development of bio-based materials. Among these resources, wood, straw, grass, hemp, eelgrass, seaweed, and seashells were indicated as the most prominent options for the production of bio-based building materials (Rasmussen et al., 2022; Realdania,Chief project manager). However, there is a need for considering both the availability of these resources and their demand across other sectors, like energy, agriculture and food sector, in order to prevent shortages or imbalances in their operation (Rasmussen et al., 2022; VIA University College et al., 2024). Although the primary focus of this research is not to delve into the specifics of each material, a brief overview of the most prominent materials in Denmark will be provided to enrich the knowledge foundation.

When it comes to wood supply, Denmark heavily depends on imports to meet its domestic demands. A significant amount, roughly 87%, is used for energy production. However, even if wood resources were not allocated primarily to energy purposes, the domestic supply would still be insufficient to meet the country's wood demand for other uses in furniture production, construction or other wood products (Brownell et al., 2023).

In contrast to wood, other materials that can be produced locally are more abundant in supply. Danish agricultural land is predominantly cultivated with annual cereal and seed crops, which results in a significant amount of straw being available. Specifically, winter wheat is the most widespread crop, making wheat straw the largest resource, followed by spring barley, rapeseed, rye, and winter barley (Rasmussen et al., 2022). According to Mortensen and Jørgensen (2022), there is a substantial amount of straw that remains unutilized, but is often used as compost to enhance soil quality and carbon storage. However, an assessment showcased that extracting straw for construction purposes would not compromise soil quality in most soil types across the

Figure 10
Main resources available in Denmark for the åproduction of bio-based materials

country (Mortensen and Jørgensen, 2022).

Different types of grass and hemp are also increasingly regarded as promising crops for building materials due to their numerous benefits. Grass, for instance, can be harvested multiple times throughout the year, does not depend on pesticides, and exhibits overall resilience (Realdania , Chief project manager). On the other hand, hemp cultivation currently occupies a relatively small portion of land, approximately 350 hectares (Rasmussen et al., 2022). Despite this limited presence in the market, it is gaining more

recognition in the building industry as a fast-crop due to its ability to regenerate areas degraded by industrialization, without competing in land with existing crops (Bauhaus Earth, 2023; Vangsbo, et al. 2024; DBI, Innovation consultant; DBI, Development consultant; Havnens Hænder, Craftsman & CEO).

In addition to land crops, Denmark possesses a range of marine resources suitable for the production of building materials, including mussel shells, seaweed and eelgrass among others. However, while these resources naturally present, their availability for large-scale supply might be limited (Rasmussen et al., 2022).

4.2.4 Understanding the current state of development of bio-based materials

The range of development, applicability and availability differs across different bio-based materials. While there are numerous examples of successful cases showcasing the application of various bio-based materials in projects, demonstrating their effectiveness, there are also materials still at a conceptualization level, existing more as potentials rather than products. However, wood is by far one of the most advanced bio-based material in terms of applicability and development, as it is one of the oldest construction materials, with a history in buildings spanning thousands of years (Wimmers, 2017; Bauhaus Earth, 2023; Henning Larsen, Architect; Rambøll, Civil engineer).

Denmark, compared to other countries, falls behind in manufacturing bio-based materials, with most materials imported from countries like Belgium, France, Germany, and Sweden (Havnens Hænder, Craftsman & CEO, 2024). In addition, when compared to conventional materials, bio-based materials lack a comprehensive data catalogue, certification and testing showcasing their capabilities, applications and performance. While there are some significant demonstration projects showcasing the possibilities of some materials, the overall knowledge base for bio-based materials remains limited (Vangsbo, 2023; DBI, Development consultant; AAU, Senior researcher).

4.2.5 Forces that support the incorporation of bio-based: building up niche mo-

In the study of socio-technical transitions, the momentum of niches constitutes a critical factor for achieving systemic changes within the established Danish building system. As outlined by Geels (2012), niches' momentum is reinforced by several critical factors: when expectations become more precise and acknowledged on a wider scale, when different learning processes align and establish a 'dominant design' and lastly, when networks expand and the involvement of more influential actors increases, providing credibility and more resource investments to niche innovations (Geels, 2012). Niches can gain momentum both externally and internally. Externally, tensions within the existing regime create opportunities for niche innovations to flourish and potentially replace the established system, while internally niche innovations gain momentum by factors such as increasing substantial investments, public support, consumer demand, political support and so on (Geels, 2011).

Both the knowledge and empirical insights provided from literature review and the interviews showcased that bio-based materials gain increasing acknowledgment within the Danish building industry. As stated by Geels, 2012, "Niches gain momentum if social networks become bigger; especially the participation of powerful actors may add legitimacy and bring more resources into niches" (Geels, 2012). The formation of collaborative networks is expanding among diverse stakeholders, including architects, engineers, constructors, organizations, consultancies and academic institutes (Realdania , Chief project manager; AAU, Senior researcher). This is showcased by the increase of projects focusing on investigating different types of bio-based building materials, exploring their performance, application characteristics and potentials (such as suitability for structure, insulation, facades and so on).

These projects are the result of collaborations between significant Danish stakeholders, including funding associations like Realdania, and academic institutions such as Aalborg University, Aarhus University and the Royal Academy, architects firms like Effekt, Jaja and Henning Larsen, engineering consultancies like Artelia and Arup, and suppliers like Havnens Hæanders, among others. Examples such as 'Biogenene materialers anvendelse i byggeriet', 'City Handbook for Carbon Neutral Buildings,' 'Plant a Seed: Designing with Wood and Bio-based Materials,' 'The Urban Bio-loop,' and 'Veje til Biobaseret Byggeri' demonstrate these collaborative efforts among the stakeholders mentioned, alongside others and a growing engagement of more (Cara, et al. 2017; Realdania, 2023; Henning Larsen, 2023; VIA University College, 2024; Vansgbo, et al. 2024).

Projects like the Wood:UpHigh initiative, managed by DBI (Dansk Brand- og Sikringsteknisk Institut) in collaboration with Readania, Ramboll, Aalborg university and others, stands as a prime example of resource investments reinforcing the growth of bio-based materials. This project is strategically designed to support their use by exploring, testing, and analyzing the fire resistance of wooden structures in combination with other bio-based insulation, and eventually provide documentation that can support their implementation (DBI, Development consultant).

> *"Bio-based have become a super realistic part of the palette when we talk with clients."*
>
> *Henning Larsen, Architect*

Moreover, bio-based materials gain recognition and acceptance among other relevant stakeholders, like clients. The Feldballe School project, led by Henning Larsen, serves as another example that highlights the growing momentum of bio-based materials. What makes Feldballe School particularly noteworthy is the proactiveness they displayed as a client. They took the initiative to request the use of bio-based materials as they wanted to prioritize sustainability as well as inspire and educate their students. Feldballe embraced a higher level of risk by accepting construction materials that went beyond traditional practices, showcasing the growing trend of acknowledgement and public support towards bio-based (Henning Larsen, Architect).

Other key actors like Træ i byggeriet association, consists of a number of companies within the construction sector, and aims to increase the use of wood in construction. Træ i byggeriet is an example of a network that is becoming bigger with the participation of powerful actors such as Ramboll among others, which helps the niches, in this case wood, to gain momentum by adding

Eelgrass product for acoustic and thermal comfort
Source: Søuld.dk Source: Søuld.dk

Søuld is one of the few Danish bio-based material manufacturers. They specialize in the collection and processing of eelgrass, a resource that naturally exists and reproduced yearly in the Danish coasts. They create products that are used indoors for thermal and acoustic comfort that are used indoors, into interior walls and ceilings.

Image and information source: Søuld.dk

credibility and gathering resources (Træ i byggeriet, n.d.; Rambøll, Civil engineer). Additionally, Havnens Hænders, a key bio-based materials supplier in Copenhagen, reinforces credibility by supplying diverse options of materials (mostly imported) and serving as a bio-based material hardware store, workshop department and showroom. With a vision to inspire the construction industry to recognize the potential of bio-based materials and the urgency for changing the current building paradigm, Havnens Hænders provides guidance, education, and knowledge dissemination on bio-based materials, principles and solutions within construction. Together, these actors reinforce the momentum of bio-based materials into the Danish construction sector (Havnens Hænders, n.d.; Havnens Hænder, Craftsman & CEO).

> *“Things are changing fast for bio-based materials, now we have a place where you can visit and see the products. And that’s our success story actually.”*
>
> *Havnens Hænder, Craftsman & CEO*

4.3 Assessing the current regime

Supported by the theoretical framework of MLP, this section aims at answering the fourth sub-research question: What hinders the transition towards the use of bio-based materials?

The socio-technical regime of the building industry is composed of elements that have been around for many years and are reproduced by many actors, resulting in a stable and locked-in system that is resistant to change. However, for transitions to happen it is necessary to change the existing system and that requires changing many of the elements that constitute it (Geels, 2012).

4.3.1 Elements influencing material choices

Regulations, existing technologies, discourses, and artifacts, markets and user practices, among others, are some of the most relevant identified system elements that constitute the conventional regime of the Danish building industry. These elements are maintained and reproduced by diverse regime actors such as architects, engineers, contractors, material suppliers, and building owners, whose perceptions and actions are shaped by well-established structural rules (Geels, 2012). Figure 11 summarizes the most relevant elements, focusing on the ones that influence the choice of materials in the Danish building industry.

Figure 11
Elements of the Danish building industry, inspired by Geels et al. (2017).

Universities, educational institutes, and training programs educating the workforce and advancing knowledge in the field of materials & construction. They provide academic courses, hands-on training, and collaborative research opportunities to students and professionals dedicated to advancing the science and technology.

e.g. safety, quality, longevity, aesthetics, durability, resistance

Facilities used for extracting raw materials needed for the production of building materials

eg. iron, steel, sand, gravel, gypsum, limestone, etc

e.g. Design Processes, building owners preferences, contractor preferences

It includes everything from ports, highways, railroads, and airports to warehouses, distribution centers, transportation management systems, and electronic data interchange (EDI) software

Funding from government grants, private investors, and venture capital firms is crucial for supporting research, innovation, and infrastructure development.

Collaboration between countries facilitates knowledge sharing, technology transfer, and trade of building materials and products on a global scale. International agreements and partnerships promote standards harmonization, regulatory coherence, and mutual recognition of certifications.

e.g. fire requirements

e.g. BR18, Danish Climate Act, National Strategy for sustainable construction, The European Green Deal, Construction Products Regulation (CPR) etc.

4.3.2. Navigating the resistance to change

As defined by Geels (2012), changes are incremental and follow predictable trajectories, and radical change takes decades. The core challenge of sustainable transitions revolves around bringing change to a very stable system (Geels, 2012; Geels, 2019).

Identifying the factors or "forces" that stabilize the regime is crucial to understanding why the Danish building industry does not change radically but incrementally, and to determine what elements of the existing system need to change for sustainable transitions to happen (Transitions NEST, 2020). Therefore, this section explores the factors that prevent the mainstream use of bio-based materials, referred to as lock-in mechanisms that stabilize the current practices in the Danish building industry. Nine lock-ins were identified through the interviews analysis and literature review, which are divided into eight clusters: supply-chain, economic, risk and accountability, technological, socio-cultural, knowledge, and regulatory.

Supply-chain lock-ins

1) Energy, agriculture and construction sector: The strong reliance on bio-based resources for energy and food purposes compromises their use in the building industry , thus stabilizing the regime.

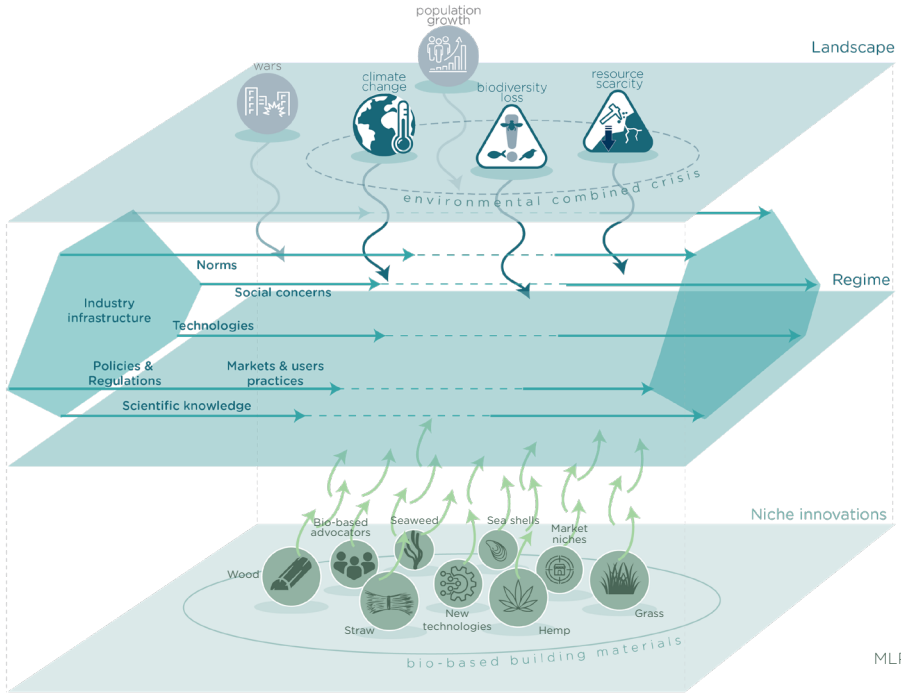

Figure 12
MLP framework for bio-based material niches, inspired by Geels et. al. (2012).

The amount of biomass resources dedicated to the Danish energy infrastructure, primarily wood and straw for burning, poses a challenge to the availability of the crops needed for the building industry (Realdania, Chief project manager; VIA University College, 2024)

Despite the majority of wood Denmark consumes being imported, it is a leading country regarding bioenergy production in Europe. Brownell et al. (2023) estimated that, in 2018, 87% of the wood used in Denmark was for energy production, indicating a relatively high amount when compared with 63% of total timber use for energy in Europe (Brownell et al., 2023).

When it comes to the use of straw, it has evolved into a robust tradition in Denmark, with small-scale straw boilers commonly utilized in agriculture and medium-scale boilers employed for district heating. The Danish agriculture sector stands out globally for having an advanced and well-established infrastructures and logistics for gathering, storing, and transporting straw to power facilities (State of Green, 2015). From the total amount of straw obtained from wheat, barley and other cere-

als, roughly 50% remains on the field, about a quarter is utilized for energy production, and the remaining portion is allocated for feeding and bedding purposes (Venturini et al., 2019).

At the same time, 61% of Denmark's land is covered by agriculture, with intensive cultivation practices that result in high crop yields. Consequently, significant biomass resources can be harvested from these lands. However, agricultural practices in Denmark are primarily optimized for food production rather than maximizing carbon sequestration or providing raw materials for construction purposes (VIA University College, 2024). Even if they are interested in growing crops for other sectors such as the building industry, farmers prioritize demand and profitability, which limits the availability of the fundamental resources to produce bio-based materials.

This reliance of the energy system on biomass, the primary focus of agricultural practices for food production, and the need of these resources for the building industry highlights a potential conflict between the major systems, involving big corporations and large investments.

> *"If I could get these materials from a Danish manufacturer, I would do that, but I cannot, so we get them from Europe (...). We need to talk to agriculture, they know how to do it (...)."*
>
> *Havnens Hænder, Craftsman & CEO*

Economic lock-ins

2) Conventional materials have been part of the standardized solutions for many years which makes them cheaper and easier to build

Conventional materials have been dominating the construction industry for many decades, since the 20th century when industrialization of construction brought them to the market as cheaper and standardized solutions (Niras, 2024). Their prolonged presence in the market, and their associated lower prices poses a significant challenge for their replacement with bio-based materials, which in contrast, yield higher project costs by roughly 10% to 25% (Dams, et al. 2023; Vangsbo, 2024; AAU, Senior researcher; Havnens Hænder, Craftsman & CEO; Rambøll, Civil engineer).

The adoption of new construction methods requires a significant amount of time (10 to 20 years) for their incorporation into the established practices of the Danish construction industry's "general technical knowledge" (alment teknisk fælleseje) (Bill-Jessen, 2023). Therefore, bio-based materials due to the early stage of development in the Danish industry, are naturally not part of the recognized and standard solutions for construction which represents one of the main obstacles for their use nowadays (Niras, 2024). As a consequence, when intending to incorporate bio-based materials into projects, practitioners are forced to deviate from established solutions, which creates economic burdens and diverse implementation complexities (Niras, 2024). The insufficient database of bio-based properties (e.g. fire resistance, durability and so on), and the lack of guidelines and procedures on how to build with them and how to create the necessary documentation to get the project approved, significantly increases the cost and complexity (Niras, 2024). This acts as a deterrent for the choice of bio-based materials over conventional bio-based ones.

For instance, when it comes to fire safety, the use of bio-based materials frequently entails deviations from pre-approved fire safety solutions in many projects. This elevates the project to a higher fire safety class (Class 4) and results in a greater documentation procedure. Moreover, it requires the involvement of certified fire advisors, which are limited in number, resulting in even higher construction costs (Niras, 2024; DBI, Development consultant). To maintain the same level of fire safety, extra measures like installing

technologies, such as sprinklers or automatic fire alarm systems, might also be necessary, further adding to the financial burden (DBI, Development consultant).

> *To be honest, it is frustrating from our side that we are trying to push these solutions and often when clients see that the prices are maybe 20% higher than a traditional concrete solution, it always ends up being the concrete solution. I mean we can only put our arguments forward, but we cannot make the client choose.*
>
> *Rambøll, Civil engineer*

Risk and accountability lock-ins

3) Responsibility and accountability regarding the use of conventional materials is clearer than in the case of bio-based materials.

Another lock-in mechanism that arose from the interview is risk distribution and accountability, which is associated with the certainty and perceived low risk linked with the use of mineral-based materials. When adopting new and non standardized materials such as bio-based alternatives, respondents express concerns regarding accountability in the event of material failure. As expressed, suppliers are responsible solely or contractors are accountable for their use in the construction of a building. Eventually, the building owner bears the ultimate responsibility for the project. Other struggles derived from the lack of established technical standards and common acceptance of bio-based materials is the hesitance of insurance companies to provide coverage, and the reluctance of banks to offer loans. (AAU, Senior researcher; Henning Larsen, Architect; Havnens Hænder, Craftsman & CEO). These uncertainties and derived complexities may act as deterrents for the increased use of bio-based materials and represent a driving factor that leads to a preference for conventional materials where responsibility is more clearly defined.

> *Any building material can go wrong if you don't know how to do it properly. But they know where to hang the hat if something goes wrong on conventional.*
>
> *Havnens Hænder, Craftsman & CEO*

Technological lock-ins

4) Major players within the building industry are heavily invested in conventional paradigms of materiality.

In Denmark, there is an established and well-developed infrastructure that meets the needs of conventional materials. The major players within the building industry, exemplified by large companies such as Aalborg Portland and Rockwool, are heavily invested in traditional paradigms of materiality and machinery. This presents a two-fold challenge for the production of bio-based alternatives. Firstly, the current infrastructure for producing building materials may lack the flexibility to incorporate bio-based materials into their production processes, as it is not inherently adaptive to other materials (Realdania, Chief project manager; Havnens Hænder, Craftsman & CEO).

Additionally, these companies profit from the production of conventional mineral-based materials and, therefore, show reluctance or lack of interest in adopting bio-based alternatives. Their financial incentives are tied to the existing, well-established industry, making them resistant to change (Realdania,Chief project manager; Havnens Hænder, Craftsman & CEO).

> *Some big players in Denmark don't see any interest in using bio-based building materials. If we want to implement bio-based in the mainstream, we need to talk (...) big coorporations.*
>
> *Havnens Hænder, Craftsman & CEO*

Socio-cultural lock-ins

5) Historical preferences for passive building materials favor mineral-based ones due to their perceived fire safety.

Denmark's sensitivity towards fire because of its history formulates a strong cultural dimension and preserves a tradition that favors the certainty and security of mineral-based materials and stabilizes the regime of the construction industry. Past fire incidents have significantly influenced its building regulations, where the rules are"based on traditions, which are 80 plus years old" (DBI, Innovation consultant). These regulations are quite strict and narrow regarding fire safety requirements, reflecting the country's sensitivity to fire risks. As a result, Denmark exhibits a tradition of building with more passive systems, focusing on fire security through materials that do not contribute to the fire, such as mineral wool, gypsum boards, concrete, and steel, instead of using more technological fire detection systems (DBI, Development consultant; Havnens Hænders, Craftsman & CEO; Effekt, Head of innovation).

> *"We have one of the largest companies producing mineral wool and that's because we have a large tradition using mineral wool and I think a lot of the building code reflects that tradition."*
>
> *DBI, Development consultant*

6) Perceptions regarding the better performance of conventional materials influences consumer choices and construction practices.

In the context of the selection between mineral-based or bio-based materials, a preference for mineral ones persists due to societal beliefs that they are more durable, more resistant and safer than bio-based alternatives, especially regarding fire safety (Havnens Hænder, Craftsman & CEO; Westermann et al, 2023). This perception of bio-based materials often leads them to be immediately disregarded as viable options without further investigation, leaning towards the use of "safer" conventional materials and thus stabilizing the Danish building industry regime (DBI, Innovation consultant).

> *"The myths actually feel quite a lot because it prevents people from investigating because one assumes that it's unsafe."*
>
> *DBI, Innovation consultant*

In addition to this, a long tradition of using mineral-based building materials for the load-bearing structure such as steel, concrete, and bricks exacerbates the struggles for bio-based to be implemented. As one respondent noted, the Danish industry is very conservative, and thus change is slow (Rambøll, Civil engineer).

7) The current design process when planning new buildings is based on knowledge and standards associated with the use of conventional materials.

Architects' design logic and material choices tend to reproduce the industry's practices, which results in overlooking the need for early consultation with other professionals when designing with bio-based materials, leading to more complexities in their final incorporation within the projects (Henning Larsen, Architect; DBI, Development consultant; Rambøll, LCA Specialist; Havnens Hænder, Craftsman & CEO; Gottlieb, 2023). Unlike the well-established practices for mineral-based materials, bio-based materials are part of an emerging field, and knowledge about them is still evolving. As suchAs such, the incorporation of bio-based materials demands early consideration of technical parameters such as fire safety, moisture, durability, resistance, and maintenance (DBI, Innovation consultant).

Knowledge lock- Ins

8) Building industry professionals typically withhold valuable information related to the use of innovative solutions.

There is a lack of sharing knowledge when it comes to building with bio-based materials between various practitioners. This tendency

usually stems from a culture where valuable knowledge about innovative construction methods and materials is considered confidential and provides an advantage in the market, therefore providing value to the company that has the knowledge (Gottlieb, et al. 2023; Henning Larsen, Architect; DBI, Development consultant; AAU, Senior researcher; Havnens Hænder, Craftsman & CEO). This perception of protecting knowledge, acts as a lock-in mechanism by limiting access to information and excluding other practitioners who may be interested in incorporating bio-based materials, but lack the necessary knowledge and resources to do so.

> *"It's really important that the market starts to share and because the architect or the engineer that are designing the construction, they don't have an idea on what's actually possible because at the moment it's like it seemed as a business secret."*
>
> *DBI, Development consultant*

Regulatory Lock-ins

9) The Danish Building Code - BR18 favors the use of conventional building materials

The most prominent regulatory lock-ins in the system stem from specific requirements regarding material characteristics, documentation processes, and CO2 emission limits enforced by the Danish building code (BR18) (Niras, 2024; Effekt, Sustainable Design Engineer; Effekt, Head of innovation; Rambøll, Civil engineer; DBI, Innovation consultant; DBI, Development consultant; Havnens Hænder, Craftsman & CEO).

Even though BR18 is intended to be material-neutral, prioritizing their functionality, it sets out requirements regarding material properties that are difficult to meet and document using non-conventional materials. This ultimately undermines the aforementioned neutrality, and essentially favors conventional materials over other alternatives (Niras, 2024; DBI, Innovation consultant; DBI, Development consultant; Rambøll, Civil engineer). Moreover, as expressed by Gottlieb (2023), this unrestriction of choice often results in prioritizing conventional solutions over bio-based ones (Rambøll, Civil engineer; Havnens Hænder, Craftsman & CEO).

As conventional materials have improved their properties through the years, such as strength, insulation, and fire resistance, the regulations have been updated to reflect these higher standards. This tightening of requirements makes it more difficult for bio-based materials to be used, as they struggle to meet them (Niras, 2024; DBI, Development consultant). For example, to comply with regulations, bio-based materials require the use of fire retardant treatments to reduce fire propagation and fire resistant coatings to improve fire performance, which affects their recyclability and biodegradability properties (Sandak et al., 2019). This challenge is further exacerbated by the lack of necessary documentation on bio-based materials (Gottlieb et al., 2023; Bauhaus Earth, 2023).

In addition, the current CO2 emission limits for the construction of new buildings specified in the building code is set at 12 kg CO2-eq/m2/year, which is relatively easy to to comply with by using conventional materials. This essentially supports the preference of using mineral-based over bio-based (Reduction Roadmap, n.d.; BR18, n.d.).

Finally, even though the Danish building legislation mandates Life Cycle Assessment (LCA) calculations for new constructions, it does not extend the same requirements or limits on CO2 emissions to renovation projects. This provides flexibility in material selection and further liberty for the use of mineral-based materials (BR18, n.d.; Rambøll, LCA Specialist).

4.3.3 Discourses and strategies supporting the emergence of bio-based materials in the building industry

There are some ongoing discourses and strategies that overlap and collectively contribute to the development of more sustainable practices within the building industry. This section aims to explore some of these key discourses and analyze their potential influence on the upscale of bio-based materials.

Reduction Roadmap I.

The Reduction Roadmap was published in the fall 2022 as a way for the Danish building industry to align the climate impact from new buildings with the Paris Agreement. It was based on the most updated knowledge and data and it revealed an urgent need for a fast transition towards sustainable building practices (Reduction Roadmap, n.d.). However, in 2023 updated data showed that despite international policies and ambitions to reduce climate impact, half of the remaining carbon budget was used in less than three years, making the need for change even more urgent (Foster et al, 2023).

The latest publication of the Reduction Roadmap illustrates that new constructions must emit less than 5.8 kg CO2-eq./m2/year on average by 2025 to comply with the Paris Agreement. Presently, the legislative emission requirement is 12 kg CO2-eq./m2/year, while the average building emits 9.5 kg CO2-eq./m2/year. These figures highlight a gap between legislation and climate science in Danish construction (Reduction Roadmap, n.d.).

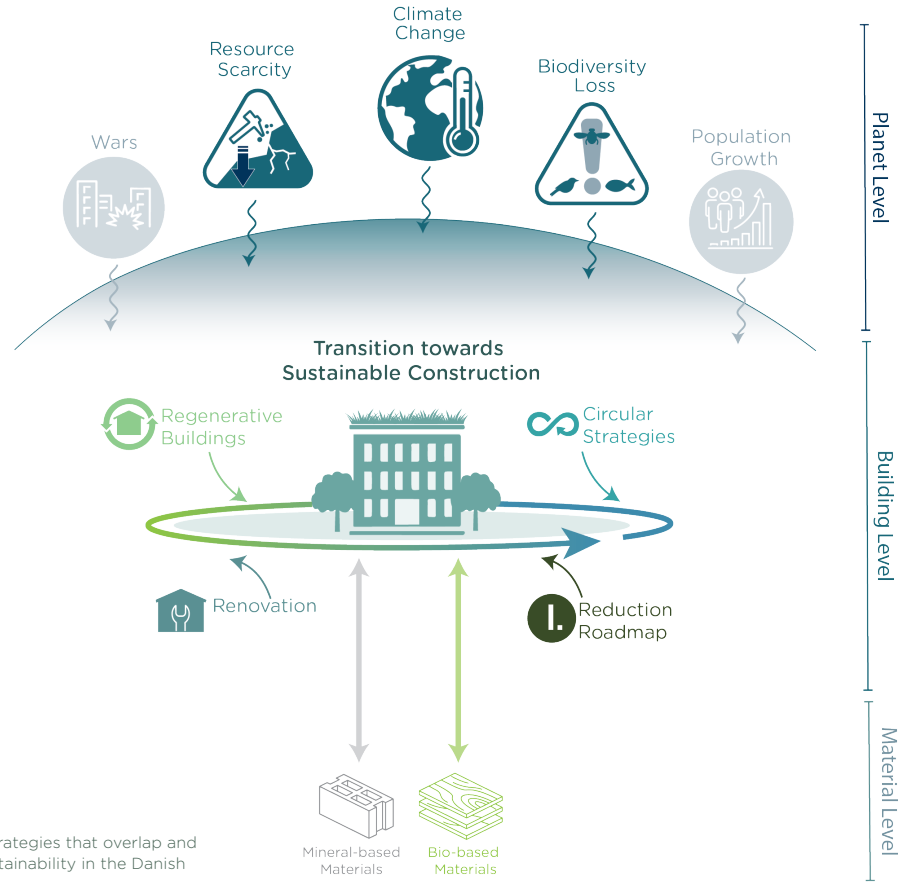

Figure 13
On-going discourses and strategies that overlap and collectivly contribute to sustainability in the Danish building industry

A call-to-action campaign was organized to urge politicians to amend the legislation, and more than 610 different actors, including various prominent players in the building industry, endorsed the adoption of the Reduction Roadmap in legislation (Reduction Roadmap, n.d.).

The widespread embrace of the movement demonstrates a readiness within the industry for an urgent and more sustainable strategy to construction, thereby facilitating the adoption of bio-based materials.

Furthermore, the Reduction Roadmap can be seen as an opportunity for bio-based materials, as it advocates for reduced levels of CO2 emissions in new construction through legislation.

Consequently, achieving these emissions targets will require the utilization of low-carbon materials such as bio-based ones (Reduction Roadmap, n.d.).

Regeneration

The sustainability discourse focusing on harm reduction emerged in the second half of the 20th century responding to increasing environmental concerns regarding pollution, population growth, and resource depletion. Even though this understanding of sustainability has guided valuable responses such as setting net-zero strategies or carbon neutrality goals, it has been proven insufficient (Robinson & Cole, 2015).

Responding to the recognized limitations of this approach, "net-positive" notions have emerged changing the narrative from one that focuses on reducing the negative impact or doing "less bad", to one that emphasizes the need to add value or "do good" (Robinson & Cole, 2015).

The net-positive concept of regeneration represents such a transformative change of perceptions and practices as it moves away from a "degenerative" mindset to one that focuses on restoring and regenerating the environment. It shifts from the traditional, unsustainable model of "take, make, use, dispose " towards the adoption of processes and practices that are circular and regenerative, where the use of resources is slowed down and living systems regenerate and repair (Birgisdottir et al., 2023).

> *"The 21st century will face a radical paradigm shift in how we produce materials for the construction of our habitat. While the period of the first industrial revolution, in the 18th and 19th century has resulted in a conversion from regenerative (agrarian) to non regenerative material sources (mines), our time might experience the reverse: a shift towards cultivating, breeding, raising, farming, or growing future resources going hand in hand with a reorientation of biological production methods and goals."*
>
> *Hebel & Heisel*

The increasing recognition of incorporating regenerative practices to tackle the current combined crisis offers an opportunity for bio-based building materials to be more widely produced and incorporated. They are considered regenerative materials sourced from renewable and biodegradable resources, capable of restoring degraded land and ecosystems due to properties such as cleaning and enhancing the nutrients of soils, increasing the amount of insects and wildlife, among others (VIA University College, 2024).

Circular Economy

In the face of worsening crises such as climate change and resource scarcity, the Circular Economy movement is gaining increasing recognition worldwide, as circularity proves to be one of the most effective tools for reducing embodied emissions in buildings and consumption of virgin materials (Arup, 2024).

The European Union (EU) has been actively promoting the transition to a circular economy through various initiatives, strategies, and legislations (Sandak, 2019). In March 2022, the European Commission launched actions to accelerate this transition, including reducing dependency on third countries, promoting recycling and recovery of raw materials, ensuring the right to repair products, and sustainable waste management by 2023. In 2024, a certification system for carbon removals and a digital product passport were adopted, ensuring precise measurements and extended carbon storage (Parlamento Europeu, 2024).

The circular economy model represents a departure from the traditional linear economic model, which follows a take-make-consume-dispose pattern. Unlike the linear model, which heavily depends on large quantities of raw materials and energy, the circular economy aims to optimize resource utilization and diminish environmental impact by focusing on extending the lifespan of

materials and products and minimizing waste (Kirchherr et al., 2017).

Denmark has a high consumption of virgin materials, with figures around 24.5 tonnes per person per year, significantly exceeding the EU average of 17.8 tonnes and the global average of 12 tonnes per person. Furthermore, this value is more than three times higher than the considered sustainable level of 8 tonnes per capita. Despite having good recycling processes, the country is only 4% circular, falling below the global circularity of 7.2%. (Circle Economy, 2024).

The circular economy presents a window of opportunity for bio-based materials, as their characteristics align with the circular principles. Bio-based materials come from renewable sources such as plants and biomass, which continuously grow, reducing the dependence on finite resources. Moreover, they can be recycled, reused, processed into other products, they can also become the source for another sector such as biomass fuel, and if no chemicals are added, they can close the loop by being decomposed into the soil (Arup, 2024).

Renovation

Currently, around 75% of the building stock in the European Union (EU) is energy-inefficient (European Commission, 2020). Around 85% of these buildings will still stand by the year 2050, therefore the energy renovation of the existing building stock is emphasized as a key action in the European Green Deal (Bürgin, 2023). Today, the energy-related renovation rate in Europe is about 1% per year, which is not sufficient to meet the global targets established by the Paris Agreement. Consequently, throughout the EU, an emerging renovation wave initiative aims to renovate 35 million inefficient buildings by 2030, increasing the annual renovation rate to 3% (Schoenefeld, 2023).

Recent research indicates that the heating system remains the primary consideration in improving energy efficiency in existing buildings. Following the selection of the heating system, the type of insulation becomes the secondary factor, with the chosen material impacting sustainable solutions. Recent studies show that an ideal renovation scenario involves replacing fossil fuel-based heating systems with alternatives like heat pumps, accompanied by ample insulation, particularly using bio-based materials (Galimshina et al., 2022).

Bio-based materials are viewed as promising alternatives, as they can reduce carbon emissions associated with existing buildings, lowering the overall carbon footprint (Pittau et al., 2019). They offer versatility particularly in renovations and transformations, being applicable in various functions such as structural, insulation, cladding, etc. (Kuittinen, 2023). Moreover, their hygrothermal properties contribute to maintaining a stable indoor temperature and a high level of comfort, while simultaneously reducing energy consumption and CO2 emissions (Galimshina et al., 2022).

Feldballe School, Rønde, Denmark
Source: Henning Larsen

5
Discussion

Wadden Sea Centre building, Jutland, Denmark
Source: TUDelft
Photograph by Adam Mørk

The Wadden Sea Centre's facade is constructed from 25,000 bundles of reed that were sourced locally. These reeds were dried on-site in the salty coastal air, and require very little maintenance over time. Additionally, the centre uses Robinia wood, also known as Black Locust, which is known for its strength and longevity, and sourced within Europe.

5. Discussion

5.1. Realization of the state of development of bio-based materials

According to Geels (2019), for bio-based to not fail and become mainstream in the regime, it is necessary to pass through four phases of development (Geels, 2019). The phases as expressed and defined by the theory helps this research understand the current state of development of bio-based materials as well as what actions are needed in order to accelerate their establishment within the building industry.

Even though bio-based present a certain degree of variability in their development, applicability, and availability, they exhibit characteristics that align closely with the experimentation phase (phase one), as will be described below. During this phase, there is significant trial-and-error learning with innovative solutions throughout R&D initiatives and demonstration projects. Moreover, it is a period marked by considerable uncertainty, lack of social support, and frequent failures. According to transition theories, sustainable transitions take decades to unfold, from 10 to 20 years, and considering the urgency of the combined crisis, the acceleration of their uptake is deemed necessary (Geels, 2019).

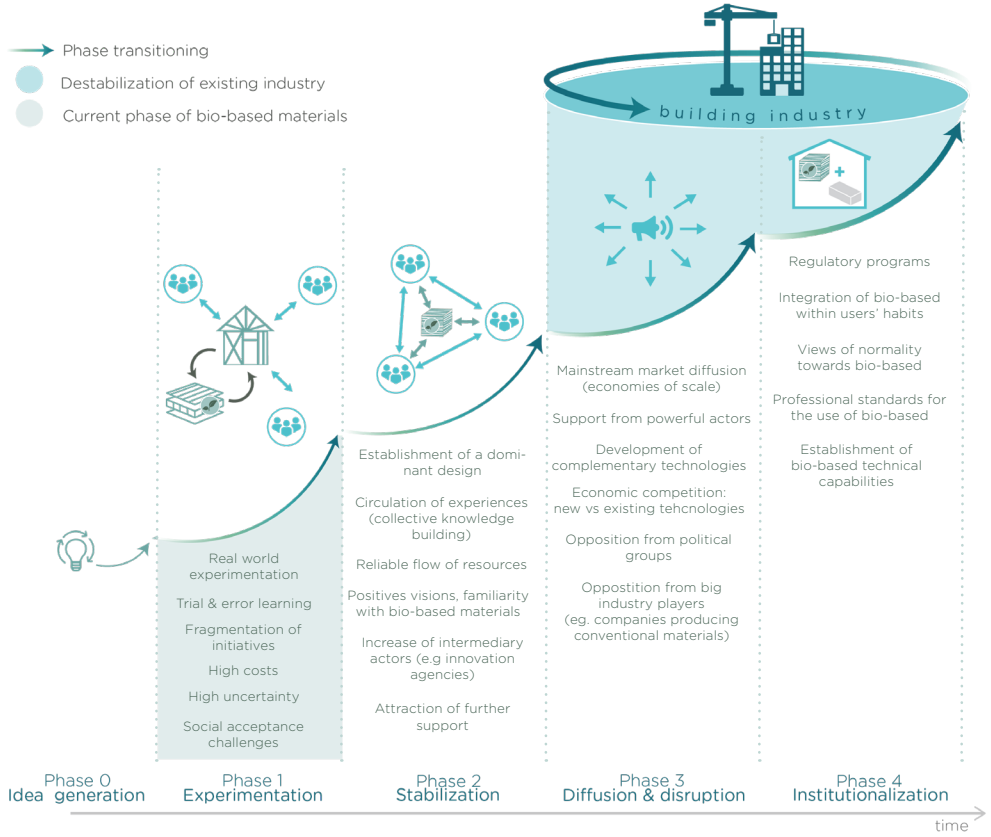

Figure 14
Transition phases and their characteristics for bio-based materials to enter in the Danish building industry, inspired by Geels et al. (2017)

Experimentation and Demonstration Projects

In Denmark, bio-based building materials are still largely in the experimental and demonstration stages. Numerous projects are exploring the application and performance of these materials, but many remain in conceptual phases or are used in isolated, small-scale initiatives. For example, projects such as the Wood: UpHigh initiative and various demonstration projects described in section 4.2.5 (e.g. Feldballe School) showcase ongoing efforts to test and understand the performance and feasibility of these materials in real-world settings which is crucial in Phase 1.

Uncertainty and Learning Processes

This phase is characterized by substantial uncertainty concerning the technological and economic viability, social acceptance, and political acceptability of the innovations. This uncertainty is evident in Denmark's bio-based materials sector. Although successful cases are showcasing the potential of bio-based materials, the overall knowledge remains limited. Bio-based materials in Denmark lack comprehensive data catalogues.

certifications, standards, and testing compared to conventional materials, highlighting the uncertainty and learning process still present in this niche.

High Rates of Failure and Fragmentation

The phase is also characterized by a high likelihood of failure and the burnout of innovators. The Danish industry faces challenges in scaling up the use of bio-based materials due to their higher costs, lack of economies of scale, and limited market accessibility. The fragmentation of initiatives, with many projects remaining isolated, further validating the status of bio-based existing within phase one. Despite the increasing number of projects and collaborative networks, the efforts are made mainly individually and not collectively reducing their potential large scale adoption and widespread impact.

Building Momentum and Collaborative Networks

While there is an indication of increasing recognition and support from various stakeholders, bio-based materials still require substantial development to overcome their current limitations. The facilitation of involvement of more powerful actors, such as funding associations, academic institutions, and engineering consultancies, from collaborative networks, like "Træ i byggeriet", will help to build the momentum needed for future phases.

Socio-Cultural Challenges

Bio-based materials also face socio-cultural challenges. As they are currently in a nascent phase of development, they are unfamiliar materials to the public. As such, their functionality is still surrounded by myths, leading to the perception of being unreliable or unsafe, which limits their social acceptance.

5.2. Addressing the combined crisis: an incomplete response

The adoption of bio-based building materials has the potential to address two critical environmental challenges: climate change and resource scarcity. By mitigating CO2 emissions and offering renewable alternatives to conventional building materials, bio-based materials can significantly contribute to a more sustainable building industry in Denmark. However, to ensure a truly sustainable transition, it is essential to regard all components of the environmental combined crisis as equally critical challenges, including biodiversity loss.

The analysis of this research showcased that even though biodiversity is a severe concern that necessitates urgent resolution, it is not considered enough within the scope of widely adopting bio-based building materials in the construction practices. This seems to be partially a result

Source: Adobe stock

Source: Adobe stock

of the uncertainty surrounding bio-based materials, given their premature stage of development, combined with the general complexity of tracing biodiversity impacts. However, the connection of bio-based materials with biodiversity is clear, as essentially their production demands cultivation of crops, and if they get established as a mainstream way of construction, this demand will increase. Without proper land management (type of land utilized, whether it is farmland, harvested forests, brown fields) and production processes, there is a potential risk that the increase of bio-based material crops could lead to deforestation, disruption or eradication of natural ecosystems. Such outcomes would undermine the very environmental goals that bio-based materials aim to achieve. Therefore, it is crucial to incorporate biodiversity considerations and potential implications from the early stages of bio-based material development and implementation.

Currently, preliminary research on biodiversity implications of bio-based building materials is extremely limited, and the sustainable transition of the construction industry is primarily focused on mitigating CO2 emissions. It is essential to bring the discussion of biodiversity to the same level of importance as CO2 reduction and resource scarcity. This gap in research poses a risk, as it limits the ability to foresee and mitigate potential negative effects on ecosystems. A proactive approach is needed, one that includes comprehensive studies and assessments to understand and consider the ecological effects of increased bio-based crop production for construction. This holistic understanding will help ensure that the transition towards bio-based materials is based on well-informed decisions and contributes positively to all aspects of sustainability, balancing climate mitigation, resource efficiency, and biodiversity preservation.

6 Recommendations

Photograph by Adam Mørk

6. Recommendations

This section has the scope of answering the main research question: "How can the use of bio-based materials be accelerated while addressing the combined environmental crisis?".

It builds on the information presented in the analysis and discussion, aiming to recommend steps to accelerate the transition from one phase to another, inspired by the phases of the transition of MLP (Geels, 2019). The steps for mainstreaming bio-based practices begin with an initial phase of experimentation, move to a second phase of knowledge stabilization, followed by a third phase of knowledge diffusion, and culminate in the institutionalization of bio-based within the Danish building industry.

To accelerate the transition of bio-based materials, the recommended actions must overcome existing barriers (lock-ins) in a sustainable way, which means addressing also the challenges posed by the combined crisis. This can be achieved by following principles such as those of circularity, renovation, and regeneration. These principles influence how sustainability is understood and guide actions towards achieving it. As they are complementary and overlapping, they can provide a comprehensive approach to address the combined crisis while accelerating the transition of bio-based materials.

6.1 From Phase 1 to Phase 2:

From the experimentation phase to the stabilization phase

What

For bio-based to transition towards phase two, the perspective of how knowledge is managed needs to change. Instead of guarding knowledge as a market advantage, there should be a shift towards a culture of sharing and collectively building technical knowledge from empirical insights resulting from experimentation projects as well as research. As such, progress can be made more rapidly and efficiently.

In addition, it is essential to create positive cultural visions surrounding the use of bio-based materials. This involves overcoming traditional negative perceptions related to them, such as concerns about fire resistance, moisture, longevity, and maintenance. By addressing these issues, broader acceptance and consideration can be achieved. Knowledge consolidated through research and practice must be widely disseminated to break down myths and misconceptions about bio-based materials. Therefore to achieve this evolution the following actions are recommended.

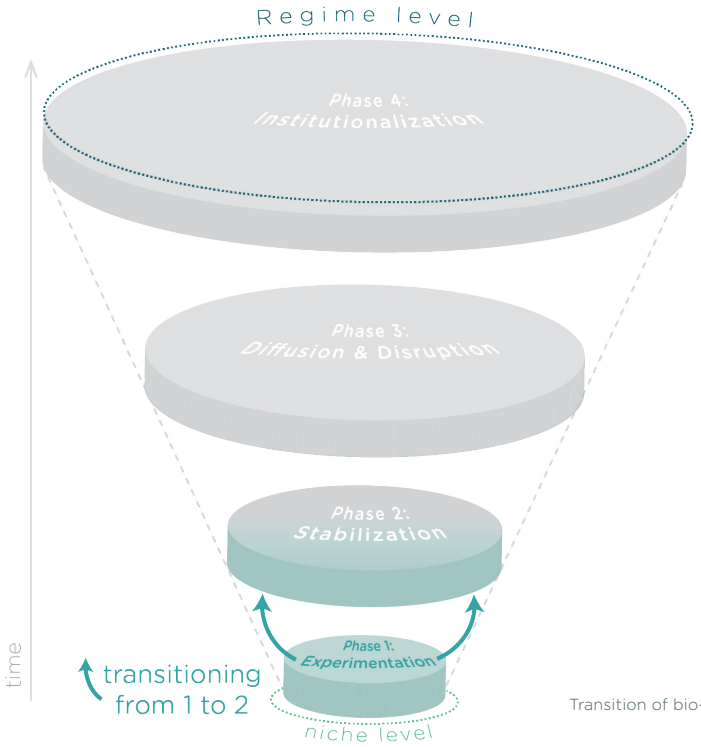

Figure 15
Transition of bio-based materials from phase 1 to 2, inspired by Geels, 2019

How

Build knowledge collectively relevant to the resources needed for the production of bio-based materials

- Organize workshops and seminars on sustainable farming practices and biodiversity conservation.
- Create platforms for knowledge sharing among farmers, builders, researchers, and biologists.
- Coordinate and increase research focusing on the connection between biodiversity and potential crops for construction that can enhance it or degrade it
- Increase the support of tools to assess and measure potential biodiversity losses associated with the cultivation and production of bio-based materials.

Build knowledge collectively for material performance, design and properties

- Labs, transboundary networks, associations, knowledge centers, and think tanks for bio-based building materials on a national level.
- Platforms (eg. C40) European & global: creating and exchanging knowledge, best practices.
- Create research programs that involve multiple stakeholders and are part of an open-source platform.
- Focus on designing the materials based on circular principles. (e.g. easy to be adapted, disassembled etc)
- Research on how to avoid the use of chemical additives that might compromise bio-based materials from safely re-entering into the biological loop

Creating a positive narratives that break down the Myths

- Develop science communication campaigns for non-scientific audiences to phase out myths and misconceptions about bio-based materials and to increase familiarity with their benefits and applications.
- Establish vocational school programs involving diverse stakeholders, such as architects, craftsmen, and researchers, designed to equip professionals with the skills and knowledge necessary for constructing buildings using bio-based materials.
- Work with ethical banks, such as Triodos Bank, to offer mortgages with lower interest rates for projects using bio-based materials. This strategy aims to increase demand and make bio-based materials more competitive (Westermann, 2023)
- Develop a set of pre-approved solutions and standardized solutions for use across various professional fields (Gottlieb et al, 2023)
- Increase the collaboration with standardization committees and associations to create standards and specifications for bio-based building materials e.g alment teknisk fælleseje (general technical knowledge)
- Support testing and certification processes in order to address concerns such as fire resistance and moisture.
- Build small but impactful demonstration projects. Prioritize small scale projects like affordable housing and community center structure, rather than large-scale developments.

6.2 From phase 2 to phase 3:

From the stabilization phase to the diffusion phase

What

For bio-based materials to transition towards the third phase where they enter the regime, several actions are necessary. Firstly, to diffuse into mainstream markets, it is essential to ensure the availability of resources and the development of a supportive supply chain. This may entail the reallocation of resources as current bio-based resources are mainly used for energy and food purposes. Breaking down the sectors' silo thinking and fostering synergies where sectors can dialogue and collaboratively find solutions to optimize resource use and achieve a common goal becomes imperative.

Moreover, to transition to the third phase, it is also necessary to develop complementary technologies, such as appropriate machinery for the large-scale processing and production of bio-based building materials. This will enable the production of bio-based materials to meet the demands of mainstream markets.

How

Reallocation and Availability of Resources

- Advocating for national incentive programs that support the partnerships between different sectors, like construction, energy, agriculture and food.
- Create a national strategy to allocate public financial resources to set up a bio-based market.
- Create subsidy programmes that promote the use of bio-based materials in construction projects.
- Introduce incentives for farmers, particularly in connection with cooperatives, to encourage the production and supply of crops for bio-based. These incentives could include financial support, technical assistance, and access to markets, stimulating increased participation in bio-based material production.
- Advocating for national strategies that promote regenerative agriculture practices when planting and harvesting crops used for the production of bio-based materials.
- Increasing financial support or incentives for farmers to transition towards regenerative agriculture as well as provision of advisory services.
- Avoid further disruption of natural ecosystems as much as possible by utilizing existing agricultural land for producing the crops for bio-based.

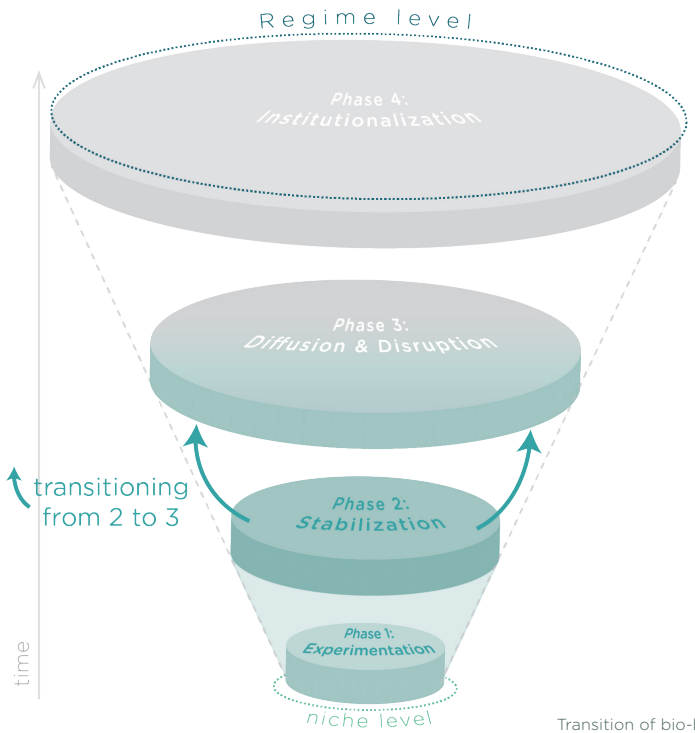

Figure 16
Transition of bio-based materials from phase 2 to 3, inspired by Geels, 2019

Breaking Silo Thinking and Fostering Synergies

- Create partnerships that focus on the symbiosis between the sectors of construction, energy, agriculture, and food, to achieve efficient distribution and exchange of bio-based resources and reduce the demand for extraction.
- Forming unions that bring together stakeholders from different sectors to facilitate knowledge sharing and collaborative projects that map the issues and the synergies across industries
- Map and document the knowledge about the potential availability of different types of bio-based materials at regional and national levels, while considering conflicting interests and competing sectors.

How

Development of Complementary Technologies

- Increasing the financial support, especially towards SMEs, for the development of complementary technologies essential for the use and production of bio-based materials.
- Involvement of certification bodies for bio-based building materials to enhance their credibility and ensure quality standards, such as Nordic Swan EcoLabel
- Create Centre of Excellence for Research, Design and Innovation regarding bio-based materials with different stakeholders
- Stimulate and support the creation of cooperatives with local farmers/ producers that share the facilities and benefits creating an extended

Addressing Economic, Political, and Cultural Struggles

- Advocate for adjustments to the building code, suchas lowering CO2 emission limits and modifying requirements (safety and health standards) to facilitate the use of bio-based materials.
- Advocate for national policies and strategies that mandate the use of a specified percentage of bio-based materials in construction.
- Supporting the establisment of bio-based in the mainstream market

Supporting the establisment of bio-based in the mainstream market

- Create financial incentives, such as tax reductions or subsidies, to attract interest from companies for bio-based materials production and commercialization.

6.3 From phase 3 to phase 4:

Form diffusion phase to institutionalization phase

What

To surpass the tensions that may arise in the previous phase from the regime's resistance to maintain its stability, actions that contribute to the institutionalization and anchoring of bio-based materials within the Danish building industry will be recommended. These actions will enable bio-based materials to move to the fourth phase, where bio-based materials replace part of the conventional materials and become institutionalized and anchored in regulatory programs, user habits and professional standards.

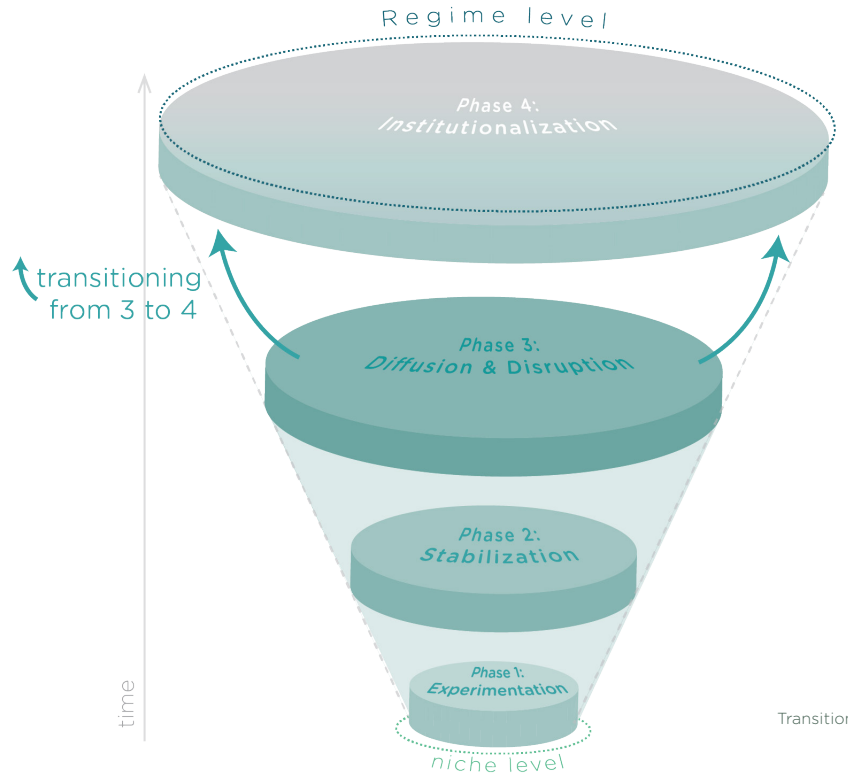

Figure 17
Transition of bio-based materials from phase 3 to 4 inspired by Geels, 2019

How

Actions to contribute to the institutionalization and anchoring of bio-based materials within the Danish building industry

- Establish adjustments to the building code, such as lowering CO2 emission limits and modifying requirements to facilitate the use of bio-based materials.
- Establish policies and strategies at the national level that mandate the use of a specified percentage of bio-based materials in construction.
- Advocate for regulatory alignment with reduction roadmap suggestions to ensure that regulatory frameworks support the transition to bio-based materials. This alignment will facilitate the implementation of sustainable practices and contribute to the reduction of carbon emissions within the building industry.
- Establish regulatory measures for implementing regenerative agriculture practices when planting and harvesting crops for bio-based materials production
- Regularly monitor and report on biodiversity outcomes to ensure continuous protection and improvement

Source: Adobe Stock

7 Conclusions & Reflections

7. Conclusions & Reflections

7.1 Conclusions

This study began with gaining an in-depth understanding of the current status of bio-based building materials through reviewing literature and conducting several interviews with diverse actors relevant to the Danish building industry, most of them familiar with the use of different bio-based materials.

The analysis of the gathered insights, supported by the theoretical framework of Multi-level Perspective (MLP), revealed that the Danish building industry is resistant to change due to the complex interplay between factors associated with the supply-chain, economics, risks, technologies, socio-cultural beliefs and tendencies, knowledge, and regulations. This showcased that achieving sustainable transitions in the Danish building industry requires a comprehensive approach that addresses each of these lock-in mechanisms. It was also realized that bio-based materials in Denmark are still in the early stages of development, primarily in the experimentation phase characterized by trial-and-error learning and significant uncertainty, and therefore they still have a long way to go to mainstream in the market.

Moreover, the analysis showcased that research surrounding bio-based materials as part of the sustainable transition of the building industry is primarily focused on their capacity to mitigate CO2 emissions, overlooking their potential implications on other systems. It was identified that preliminary research or expressed concerns regarding the impact of bio-based building materials on biodiversity is extremely limited. This represents a significant gap that needs to be addressed at the same level of importance as CO2 reduction and resource scarcity if the combined crisis wants to be tackled.

At the same time, the use of MLP helped to recommend potential actions that can be done to accelerate the use of bio-based materials and meet the needs of the combined crisis. These actions revolve around building knowledge collectively, breaking down myths, fostering synergies between different sectors, increasing the availability of biobased resources, developing complementary technologies and finally actions to contribute to the institutionalization and anchoring of bio-based materials within the Danish building industry.

Finally, when analyzing the discourses that frame sustainability, this research found out some areas for improvement. Further research and consideration are needed regarding the incorporation of regenerative and circular practices to harness the full potential of bio-based materials to eliminate waste, and reduce consumption and production. Moreover, considering the current renovation initiatives, there is a great potential for biogenic to contribute to lower the carbon footprint of the existing building stock which is not seized due to their nascent state of development and the restrictions imposed by the regulation. More efforts are needed to address these aspects if the use of bio-based materials is meant to be in a way that addresses the combined climate crisIs.

7.2 Reflections

Reflections on Methods

Throughout the course of our thesis, we found that the methodological approach employed, while effective in many respects, had its limitations. Conducting the interviews at the beginning of the research process to gather data to identify problems areas is a process that diverges from our usual practice in the past. This reverse approach, applied without having a problem area identified, led the group to handling an enormous amount of information, that even connected to bio-based materials, was too broad to be fully seized and opened too many possibilities of research. We could have performed less interviews at the beginning of the research process and then once the problem area was identified, we could have organized another round of interviews more targeted towards the specific problem of interest.

Moreover, even though the interviews provided valuable insights into the problem areas, the scope of these insights could have been significantly broadened if we had included a more diverse range of sectors and actors with divergent opinions, such as advocates for the traditional building materials or representatives of agriculture or energy sector. By focusing predominantly on actors part of the construction sector that act in favor of bio-based materials, we may have missed out on critical perspectives and understandings that could have enriched our findings.

Reflections on Theories

The process of integrating theories into our work presented its own set of challenges. While Multi-Level Perspective (MLP) framework provided a structured way to present our data, we had faced the challenge of ensuring that the narrative would remain interesting and accessible to readers not familiarized with this theory.

Reflections on External Factors

It is acknowledged that the industry is currently undergoing some regulatory revisions, and given the timing of the research, some of these changes may not be fully captured in our thesis. A similar situation may occur regarding the latest publications from research institutions and organizations, as their ongoing efforts are continuously contributing with new knowledge in the field which may also not be fully seized.

Source: Adobe Stock

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