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Biobased Building Materials' Contribution to a Circular Economy

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Bioeconomy – Biobased Value Creation and Business Development

Preface

The concept of biobased building materials was introduced to me last year and sparked my interest in what it was and how does it fit with the transition to a green economy. The thesis paper presented itself as an opportunity for me to delve into biobased building in the context of circularity, and the Norwegian building practices. The thesis has provided me with a great learning outcome and strengthened my interest in the biobased way of building. It has made me think of all the ancient wise knowledge that has been lost to time and space, especially in the day of rapid technological development.

I would like to thank my supervisor, Eystein Ystad, who has been there for me, from the beginning and all the way to the end. Thank you for supporting me and my project, for challenging me and for guiding me throughout this process. It would not have been possible without your supervising, and I have learnt a lot.

I would also like to give my thanks to Thore Larsgård, for setting up the master's degree in Bioeconomics at NMBU and for your enthusiasm about the field and its relevance. The interdisciplinary nature of the course and its innately sustainable focus made was a perfect and intriguing opportunity for me to revisit academics after a few years in the private sector.

Thank you all who participated in my research study, for your enthusiasm and sharing your knowledge. Special thanks to Matthew, for the introduction to biobased building and the open invitation the hempcrete workshop.

This marks the end of my two amazing years at NMBU. I am going to miss the beautiful campus and will visit for sure.

I am ready to continue the path of life as a bioeconomist, and excited for what is to come.

Abstract

This explorative thematic case study investigates how biobased building materials can contribute to a more circular building industry. The case study focuses on straw and hemp insulation, exploring three core themes: (1) the suitability and technical performance of hemp and straw as insulation materials, (2) the impact these materials have on circularity in buildings, and (3) the main factors influencing the economic viability of straw and hemp insulation, including strategies to overcome identified barriers.

The theoretical framework for the research study integrates concepts from existing literature and research on building materials based on straw and hemp. Combines widely recognized circular economic principles and concepts such as the 4-R framework, waste hierarchy and biological resource cycle with a material circularity systematic assessment system to study the materials contribution to circularity. Circular solutions need to be economically viable to realize its potential in circular contribution. In combination the core themes cover the potential of straw and hemp insulation in contribution to a more circular building industry in practice.

Despite their environmental benefits and renewable nature, significant risks and barriers hinder the widespread adoption of straw and hemp insulation in Norway. Best case scenario for these materials requires appropriate waste streams for agriculture, and the current value chain is not optimized for their production and resource supply. Moreover, the lack of industry familiarity and verified technical performance standards makes these materials likely non-viable for large scale use. At present this limits them to niche projects such as environmentally friendly homes or showcasing pilot projects. However, with increasing regulatory emphasis on sustainability and circularity, both in Norway and the EU, there is clear potential for these materials to contribute to a more circular economy. Ultimately, straw and hemp insulation materials show promise for contributing to a circular building industry, provided that these initial barriers and threats are addressed.

Table of contents

Table of figures

Table of tables

Table of attachments

1. Introduction

The building industry is commonly known as the 40% industry because buildings use about 40% of the energy consumption at society level, and 40% of material resources. Globally the industry stands for 40% of the greenhouse gas emissions. This thesis paper seeks to investigate the industry and its contribution towards a green circular economy.

1.1 Background for the study

Norway's climate goal confirms a target of 50 - 55 % reduction in greenhouse gas emissions by 2030 (Regjeringen, 2023). The government has presented numerous measures over the past decades to reduce emissions, with a significant focus on climate-friendly transportation solutions and electrification of this sector. Norwegian greenhouse gas emissions associated with the building industry have been analyzed by Asplan Viak (2019). The focus for emission reduction has typically been on the operational phase, primarily energy use and maintenance. In terms of buildings' energy consumption, mainly cheap and renewable hydroelectric power is used. Historically cheap, but with increased electrification, prices will rise, prompting a focus on energy-efficient homes (insulation, etc.) (Asplan Viak, 2019). In light of increased attention to energy and environmental impact, there is now also a focus on material usage in building and emissions and consumption during the building phase. A broader focus has been made possible due to established life cycle analysis methodology, as well as the industry's use of EPDs (Environmental Product Declarations) for building materials, for comparison of environmental performance, and standardized environmental certification (BREEAM).

A large proportion of climate contributions are thus associated with building materials, rather than with the traditional operation of buildings and building sites, nor with the building itself. Importation for building contributes to approximately 6 mtCO2, considering both the production of the goods and the contributions of inputs and transportation for such goods. Building materials account for around 52 % of the climate contributions from imports. Given the high climate contributions associated with building materials, it is essential to break down this designation and examine the types of building materials and their respective contributions to emissions. As illustrated in figure 2, the production of other non-metallic mineral products has the highest proportion of climate contributions associated with it, along with the production of metals, timber, wood products, and oil refining, chemical, and pharmaceutical industries.

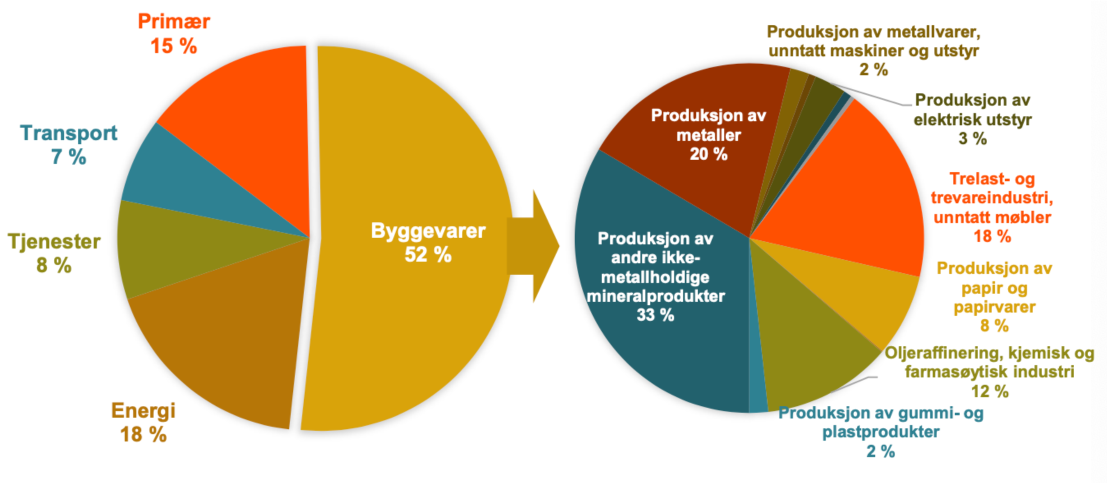

Figure 1: Allocation of climate change contribution from import, divided into the different sectors (Asplan Viak, 2019, s. 9)

Circularity in the building industry

The Directorate of Administration and Financial Management (DFØ) has published a report that assesses the status of the circular economy in the building industry (Deloitte, 2022). The report is published by Deloitte. The background for the report, in brief, is the transition from a linear to a circular economy to achieve overarching climate and environmental goals. For instance, the Norwegian building industry generates over two million tons of waste annually, which is considered a significant problem. The report suggests that the circular economy is and will remain important for the building industry in the future. They found that the main barriers to a circular building industry include delayed involvement, budgetary constraints, challenges and a lack of market for the resale of used materials, and regulatory constraints that limit opportunities. Therefore, for the industry's circularity, it is crucial to create demand for secondary resources and to implement measures so that sustainability and circularity are incorporated at an earlier stage to avoid budgetary constraints taking precedence.

Biobased building materials

In 2016 the Norwegian Government released a strategy plan regarding the Norwegian bioeconomy, to promote sustainable production of biobased products. An example of biobased products are biobased building materials. Generally, research support that biobased building materials[1] are sustainable and positively impact social welfare, based on the premise that such materials are regenerative in nature given a long enough time period. The reason why such materials are interesting from a sustainable perspective is that the energy consumption and emissions during production are lower, while a building's energy consumption when using such materials over time will also be lower. The article by Bourbia et al. (2023) gives an indication of promising bio-based materials for use in the building industry. The materials are typically known as circular materials due to the characteristics and properties of biological raw materials, with positive impact on the environment in terms of reduced greenhouse gas emissions, reduced energy consumption, utilization of natural resources, and minimal waste production. Additionally, recognized to contribute positively to human well-being and likely contribute to increased employment in more rural areas due to connections to secondary resources from agriculture. The article suggests that the use of biobased materials has a wide application in the building industry, but actual use and application will depend on local access to raw materials.

1.2 Aim and problem statement

The aim is to analyze the suitability of plants ("biomass") as building materials in a circular and economically viable building industry. The thesis focuses on the use of straw and hemp as building materials, hereafter referred to as biobased building materials or simply "materials”. The overall problem statement is as follows:

“*How can biobased building materials contribute to a more circular building industry?”*

The research study focuses on the properties of the biomass and performance as insulation materials specifically, exploring their contribution to circularity in the building industry and their economic viability to evaluate the realization of its possible contribution.

1.3 Research question

The research conducted is limited to assessing straw and hemp as biomass resources. On the biomass and material side the thesis project focuses on its theoretical and conceptual possibilities. Circularity is considered broadly, without focus on regenerating nature due to

[1] Biobased building materials means the materials in which are wholly and partly based on biological resources.

scope of the thesis project. The context of the building industry is wide, but more focused on the use of materials for residential buildings (single-family homes, houses, small and medium size apartment buildings).

Three research questions have been developed as means of answering and addressing the problem statement.

- **Research Question 1:** *How suitable are the biomasses hemp and straw for use as insulation materials and how do they perform from a technical perspective?*

- **Research Question 2:** *How does straw and hemp insulation materials impact circularity in the buildings?*

- **Research Question 3:** *What are the main factors impacting the economic viability of straw and hemp insulation materials, and how to address the main barriers?*

Essentially, the research questions have been elaborated firstly to get an understanding of the biomass as building materials, and the characteristics of such biomass and how it performs as materials. Secondly, the contribution to circularity is to assess the resource effectiveness of such materials in the transition to a circular economy. Thirdly, assessing the economic viability through its cost drivers and market considerations, impacting its potential contribution to the transition to a circular economy in practice.

1.4 Thesis structure

The thesis paper will firstly provide the theoretical framework for the conducted study, then elaborating on the method for the conducted study, presenting analyzing its results for each research question, discussing the findings with respect to the problem statement and lastly concluding the conducted study with its implications and suggestions for further study. the research questions have been elaborated firstly to get an understanding of the biomass as building materials, and the characteristics of such biomass and how it performs as materials. Secondly, the contribution to circularity is to assess the resource effectiveness of such materials in the transition to a circular economy. Thirdly, assessing the profitability (mainly costs) of such materials implies the potentiality in aiding the transition to circular economy in practice.

2. Theoretical framework

When approaching analyzing building materials and initially the level of impact on the planet in any way of form, one must first determine the variables to look at. This section will present the theoretical framework and foundation for researching and discussing biobased building materials, its contribution to added circularity and pertinent aspects concerning economic viability.

2.1 Biobased building materials

Biomass as a resource from agriculture has historically had a long range of use, also as building materials. One may perhaps get a sense of a renewed interests in such a use, due to biomass innately being a renewable resource, thus, within sustainability a viable option for material resources.

Historical use of agricultural waste for materials

Liu et. al enlightens that agricultural straws have been used for building materials (insulation) for a long time, due to its properties and low costs (Liu et al., 2016, p. 913). The materials described involve production from biomass such as hemp, timber, date palm trees, cork, alfalfa, and straw. Generally, the resources can be used for load-bearing structures, infill, insulation, and surface materials. The article (Yadav & Agarwal, 2021) suggests that biobased materials are rarely used for load-bearing elements in a structure. The article by Bourbia et al. (2023) found that biobased materials are excellent heat regulators in buildings. The research by Liu et. al. (2016) was based on theoretical and experimental studies on the materials' handling of moisture and temperature. Plant-based materials can be used as moisture moderators, improving moisture and temperature comfort, more efficient energy consumption, and enhanced indoor air quality.

2.1.1 Straw as building material

This section seeks to create a basis for understanding the connection between basic characteristics of straw, and brief indication on its most prompt area of use when it comes to being used as a building material.

Characteristics of straw

Generally, the use of straw for in building is not new. Since the 1800 hundreds straw has been used as a resource for building to its renewability and thermal insulation ability (Li et al., 2023, p. 2362). The main components of straw are cellulose, hemicellulose, lignin and dust, where the straw types depend on the species of plant it comes from which influence its components and content ratios (Li et al., 2023, p. 2362). The actual characteristic of the biomass impacts the properties of the building material, and subsequently performance Straw has been used in straw board, straw bales as mechanical building materials and insulation, and as composite material with cement. (Li et al., 2023, p. 2362). From the review article it is indicated that research and development of straw-based materials should go into the direction of mechanical materials, due to poor performance of straw and cement composite materials.

Straw based materials

Mechanical straw building materials can be defined as the "preparation of straw filling blocks and cement/concrete skeletons, with the two mechanically assembled and connected by the friction or hard contact between them" (Li et al., 2023, p. 2368). Based on research performed by Li et al. two main groups of mechanical straw building materials are presented, namely straw bale / laminated wall and envelope walls. Straw bale/laminated walls is a wall where straw bales or compressed straw boards are used. Various ways of using this type of wall in buildings have been developed in recent years due to its attractive properties (air and heat transfer, and sound insulation) (Li et al., 2023, p. 2369).

Li et al.'s research mentions that the latter building method is popular amongst engineers, with shorter building period, reliable building quality and no requirements for additional support. At the same time its mentioned that the quality of the thermal insulation, being the straw component, has a weakness in areas where water may accumulate (Li et al., 2023, p. 2369). Generally, for straw-based walls the heat exchange depends on the temperature in external surroundings. For outdoor temperatures between -5,3 to 19.1 Celsius the indoor temperature ranges from 0.5 to 16 Celsius, on average 9.8 degrees Celsius warmer indoor (Li et al., 2023, p. 2369). Examples mentioned in the review paper of Li et al indicates that use of such a straw wall is more energy efficient with 60 % reduction in energy consumption and further reduces costs by 38 % (Li et al., 2023, p. 2370).

2.1.1 Hemp as building materials

This section seeks to create a basis for understanding the connection between basic characteristics of hemp, and brief indication on its most prompt area of use when it comes to being used as a building material.

Characteristics of hemp

Industrial hemp is hemp containing less than 0,2 % Δ^9 – tetrahydrocannabinol (THC), whereas hemp with more than 0,2 % THC is considered a drug type of hemp (Ahmed et al., 2022, p. 2). Hemp has a long historical background in terms of usage, reaching back to 5000 - 4000 BC (Ahmed et al., 2022, p. 2). The western prohibition on hemp was introduced in 200th century due to its similarities and alikeness to marijuana (its closely related plant species) (Ahmed et al., 2022, p. 2). Whilst most of Europe and the Americas have lifted the prohibition on industrial hemp, cultivation of industrial hemp remains prohibited and illegal in Norway as evident from the Regulation of Drugs ("Narkotikalisten") (Helse- og omsorgsdepartementet, 2013) and Regulation of Seedlings (Landbruks- og matdepartementet, 2023). In 2018 the major three countries involved in hemp cultivation are Canada (555 853 hectares), North Korea (21 247 hectares) and France (12 900 hectares) (Ahmed et al., 2022, p. 2). Hemp is a fast-growing annual crop, with lower requirements to labor, fertilization, seeds, field operation and irrigation costs compared to cotton (Ahmed et al., 2022, p. 3).

According to researchers, industrial hemp has proven to be a successful commercial crop because of its carbon sequestering properties, high and fast biomass production and a wide range of possible product applicability's (Ahmed et al., 2022, p. 1). The growth of the resource can aid agriculture due to its soil remediation capabilities, little need for pesticides, its innate insecticide properties and ability to absorb heavy metals (Ahmed et al., 2022, p. 2). With respect to the industrial processing of hemp, it concerns four stages: retting, breaking, scutching and hackling (Ahmed et al., 2022, p. 3). It is a high-yielding biomass resource compared to wood due to its short crop rotation cycles (4 months). (Ahmed et al., 2022, p. 3). Hemp contains 47 % cellulose and 18 % lignin, with certain parts of the hemp plant containing varying degrees of cellulose and lignin (Ahmed et al., 2022, p. 3)

Biomass in building materials acts as a sink of carbon throughout its lifespan, whereas the end-of-life handling will impact release of stored CO_2. Hemp has an annual crop rotation cycle sinking carbon annually, storing carbon for a lifetime of use, thereby delaying impact of CO_2 released into the atmosphere (Ahmed et al., 2022, p. 12).

Hempcrete

Use of hemp for building materials usually ends up revolving around hempcrete when it comes to research. Hempcrete is mixture of hemp shivs or its woody core, with a mineral binder and water (Ahmed et al., 2022, p. 9), combined as a sort of composite. The properties of the composite depends on the binder type, aggregate to binder ratio, size and porosity, and level of compaction (Ahmed et al., 2022, p. 9). Hempcrete can be manufactured by spraying, molding or manual mixing and tamping, either pre-manufactured or through wet building (Ahmed et al., 2022, p. 9). In terms of application and area of use, hempcrete is deemed satisfactory as non-load bearing insulation in walls, floors and roofs (Ahmed et al., 2022, p. 9). This is due its moderate mechanical performance (Ahmed et al., 2022, p. 10). Researchers agree that its mechanical performance will increase with higher degree of compaction in the hempcrete mix, but this in turn reduces its thermal insulation and acoustic properties.

2.1.2 Technical material performance

In terms of technical material performance, a range of factors are relevant when considering building materials. For insulation materials several requirements must be met, such as, but not limited to, moisture control, temperature control, fire resistance, acoustic performance, in addition to cost and environmental impact (Liu et al., 2016, p. 913). This section will detail the performance straw bale insulation and hempcrete with respect to the factors in accordance to available research.

Moisture control

According to the review paper on straw based building materials straw performs well with respect to moisture absorption and humidity control performance (Li et al., 2023, p. 2365). This is due to the high contents of hydroxyl groups, defects, voids and fine cracks in the straw fiber. (Li et al., 2023, p. 2365). Research shows that the high relative humidity in surrounding conditions is significantly impacting the risk involved. This implies that in high humidity environments, straw based materials are at risk of molding (Li et al., 2023, p. 2365). Several alternative treatment methods can be done to enhance straws resistance to molding and decay. Most methods are however requiring harsh treatment conditions and high energy consumption, which makes it little suitable for application in large scale production (Li et al., 2023, p. 2365). Although some treatments available that are more economical and feasible, they do not provide full resistance to molding. The review paper therefore suggests that measures needs to be taken into account in the design and building to prevent moisture posing an issue for the straw based building material (Li et al., 2023, p. 2380). The hygroscopic ability of straw has a negative impact on its durability and thermal insulation performance as a building material, where surrounding humidity can increase the risk of molding but also lower the thermal performance (Li et al., 2023, p. 2375). This aspect needs to be addressed, for example by waterproofing layers encompassing the biomass, protecting it from dampness and mold (Li et al., 2023, p. 2375).

Hemp shiv is also a highly hydrophilic and porous biomass, impacting its capability to absorb and hold water. It can absorb up to 270 % water after a few minutes, and around 400 % after a two day period (Ahmed et al., 2022, p. 11). This is an interesting aspect of using biomass, in this case hemp shiv, in building materials, because building materials interact with its surroundings. The materials moisture control is vital to ensure appropriate living conditions within the building (Ahmed et al., 2022, p. 11). Due to hempcretes permeability, its able to buffer moisture levels. This offers better control of extreme humidity, decreases vapor condensation, limits micro-organism development and hence ensures indoor comfort (Ahmed et al., 2022, p. 11).

Despite its good moisture control hempcrete is not degradation proof for long term exposure to rain or extreme humidity, where deformation can occur above 60 % humidity (Ahmed et al., 2022, p. 11). A measure to aid the long term degradation proofness researchers suggests use of breathable coating or other finishing on the hempcrete wall (Ahmed et al., 2022, p. 11).

Temperature control

The temperature control involves the thermal conductivity and heat transfer properties of straw and hemp. Generally, the materials ability to control temperature relies on its material properties, the length of the path that heat flows, and the temperature difference between the two ends (Ahmed et al., 2022, p. 11). In this case commonly outdoor and indoor temperatures, and the thickness of the wall or where the material is being used or applied. Due to the porosity and structure of plant biomass, and therein, plant based materials, the ability to conduct temperature is typically lower due to and increasingly with the presence of air in the material (Ahmed et al., 2022, p. 11). This generally aids to overall better indoor quality (Ahmed et al., 2022, p. 11).

In summary straw based walls have good or even perhaps excellent thermal and insulating performance (Li et al., 2023, p. 2376). Seeing that the types of building methods and different straw building materials are different, with different configurations, types of straw used, different physical shape of straw fibers, there are several elements to such a way of building that are not yet clarified sufficiently (Li et al., 2023, p. 2376). There is also need to look further into life circulation performance, duration and quality of production process for the various types of materials and building methods, to ensure the economic feasibility and sufficient technical performance as alternative building materials (Li et al., 2023, p. 2376).

Hempcrete is a highly porous material, thus, due to the low thermal conductivity, the material will be slow in transferring heat between two points. Hempcrete as a material is therefore suitable to be used building enclosures, where heat waves in the summer are controlled, and similarly with heat loss during cold winters (Ahmed et al., 2022, p. 11). The temperature control will however in practice depend on its formulation, i.e decreased temperature control with increased density, water content, mold growth and age (Ahmed et al., 2022, p. 11). Research indicates that moisture will significantly decrease hempcretes ability to control temperature (Ahmed et al., 2022, p. 11). Furthermore, research suggests that the type of binder does not significantly influence the temperature control (Ahmed et al., 2022, p. 11).

Fire resistance

As identified by Li et. al, Fire resistance is the primary performance factor when considering building materials' safety (Li et al., 2023, p. 2363). To assess straw based building materials and their fire resistance, one assesses the pyrolysis and combustion reactions. There are therefore various treatment methods in which one can do in order to aid the fire resistance of the straw based materials, such as HCl pickling, K or P ion infiltration, flaxseed oil pretreatment, silicate glass adhesive addition, and other treatments (Li et al., 2023). Increased flame retardancy however poses other risks due to insufficient combustion of the biomass, leading to more CO_2 emissions and thus higher risk for carbon monoxide poisoning if exposed to the fire (Li et al., 2023, p. 2363). Since straw naturally contain high levels of SiO_2 the fire resistance performance is at an acceptable level, supported by numerous research reports. This suggests that straw based materials do not pose a bigger fire hazard than for example walls made of asbestos (Li et al., 2023). Hempcrete has high moisture permeability, and can delay fire spread by first allowing release of stored capillary water, and further hydraulic lime and limestone intertwining with charred hemp, resulting in fire resistance up to two hours (Ahmed et al., 2022, p. 11).

Acoustic performance

Acoustic performance of materials is important to limit unwanted noise, through good sound insulation in materials and design of living spaces (Ahmed et al., 2022, p. 11). The inherent and innate structure of hemp and hempcrete, ensures porosity in the structure and increases surface area resulting in a good sound absorption (Ahmed et al., 2022, p. 11). The time period of noise in the room is influenced, and sound waves disappear swiftly (Ahmed et al., 2022, p. 11). In terms of hempcretes acoustic performance, it is influenced by the property of the biomass used, i.e. retted is better than un-retted hemp, smaller particles is better than larger, whereas higher ratios of binder, or denser binder use, influences the acoustic performance negatively (Ahmed et al., 2022, p. 11).

Technical regulation

In Norway there is a technical regulation called TEK17 that details the technical requirements for building structures in Norway, establishing minimum standards for building. The Norwegian Building Authority is the government agency responsible for managing the regulation and rules and detailing the regulation and its requirements (Direktoratet for byggkvalitet, 2017). The regulation is applicable to all new constructions and rehabilitations. Builders are required to adhere to TEK17 functional requirements, irrespective of the contractual terms with homeowners. TEK17 replaces its predecessor, TEK10, in 2017 due to evolving societal needs and technological advancements. TEK17 was designed to provide greater flexibility, enabling the implementation of market-desired solutions. This regulation became effective on July 1, 2017.

Understanding TEK17 requires functional requirements, performance requirements, and pre-accepted performance standards. Functional requirements articulate the overarching tasks that the building must fulfill, based on societal or occupant needs, and are described qualitatively. For example, TEK17 § 3-1 details that a building material needs to have sufficient material performance, contributing to compliance with the regulation, and that the material performance needs to be documented. Performance requirements and pre-accepted performance standards specify the quantitative measures needed to meet these functional requirements. An example of certification

2.2 Circular economy and material circularity

The circular economy (CE) is a many-faceted concept in which has arisen through the sustainable economic theories, with many elaborated concepts commonly viewed as part of the circular economy principles.

2.2.1 Circular economy

Originally Pearce and Turner introduced the concept as a prerequisite for maintaining sustainability for humans on Earth (Ghisellini et al., 2015). Three economic functions make up the environment, being the provision of resources, life and support systems and for waste and emissions. Albeit the definition of circular economy is not cut through, the various definitions together hold the essences of what it concerns. The circular economy is a look on the economy of resources, acknowledging the finite nature of our resources. In short, resources should cycle through the economy at the slowest possible rate, with the highest value of usage, with minimal waste generation. The origin of the circular economy theorem arose from sustainable economics and is for many thought of as a systematic framework with means to achieve sustainable development.

Definition of Circular Economy

The CE concerns mainly minimization of waste and pollution, extension of useful life and products and materials, and regeneration of natural systems (Mhatre et al., 2020, p. 188). There is no common agreed upon definition of CE. The circular economy concept has had various definitions up through, where one can argue that these are essentially the same definitions, or that the literature does not agree to what circular economy is. Therefore, Kircher et. Al presented a review of various circular economy definitions, to capture the essence of what the circular economy concepts are, and a mostly covering definition (Kircherr et al., 2017, p. 221). The elaborated definition of CE is weighted heavily, as their definition review is combined with the general understanding of what CE comprises, with the intent for the definition to include the various elements in which CE comprises. Their comprehensive review of 114 CE definitions resulted in a densely worded definition of CE. Albeit Kircher et. Al argues it should be read as a summary of what different researchers and scholars argues that CE, but not necessarily exclusively. Their summary definition reads as follows, "*A circular economy describes an economic system that I based on business models which replace the "end-of-life" concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level* *(products, companies, consumers), meso level (eco-industrial parks) and macro level (city, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*" (Kircherr et al., 2017, pp. 224-225). The definition captures the essence of circular economy, but is not necessarily a great tool in analyzing or assessing circularity

Core principles

Overall Kircher et. All identified a framework of the concepts within the circular economy, which they used to identify the summary definition of CE. The identified elements of CE by Kircher is useful in terms of analyzing circularity in practice. The core principles of the circular economy were identified in twofold, the 4Rs and waste hierarchy and systems perspective. These principles, together with the aims and enablers, forms the basis and conceptual framework for the theory of circular economy. Due to the scope of the thesis project the 4R framework and waste hierarchy has been in focus.

2.2.2 The 4-R framework and waste hierarchy

There are a range of various concepts comprising different sets of Rs, meaning dimensions which has a waste hierarchy implemented going from the first to the final R. The waste hierarchy within the R concepts is common for all R concepts (Kircherr et al., 2017, p. 223). Kircher et. al ended up with a 4R framework due to the different definitions on circular economy referring to these four R concepts, i.e. reduce, reuse, recycle and recover. Whereas 6R, 9R and 10R frameworks includes dimensions which by their investigations is not referred to specifically in the various definitions of CE. The acknowledgement made in the concept is that recycling of resources is a downcycling, i.e. involves loss of characteristics and resource value, and thus, recycling should be a last resort measure.

Targeted dimension

The circular economy has mostly been targeting one dimension of the concept, namely recycling, (Kircherr et al., 2017) which is the dimension which over the years has gained the most traction and is highly implemented. The review of CE identified trends that literature about CE is increasingly mentioned other Rs than the four mentioned (except for reuse), indicating a discourse in the systematic approach as to what CE entails and what dimensions that needs to be considered in ensuring CE accomplishing its aims. Its pertinent to acknowledge that the 4R concept is only mentioned in 3-4 % of the definitions according to Kircher (Kircherr et al., 2017, p. 226). However, despite this the 4R concept bears weight seeing that it is part of the official EU policy on EU.

Waste hierarchy

Although Kircher describes the waste hierarchy as common in terms of the various R concepts, the waste hierarchy is not always prevalent in the definitions of CE (Kircherr et al., 2017, p. 227). The concern is that the waste hierarchy reduces the common feel-good acceptance of CE as a concept. We can compare this to the feel-good concept of "sustainability". Kircher presses that the waste hierarchy is key to avoid adoptee of CE to take the "least resistance" route down the recycling isle. The reason is that such an approach will likely not cause the necessary radical shift overall in the supply chain structure and material thinking.

2.2.3 Circularity of biological resources

The Ellen McArthur foundation has published numerous papers and articles with respect to circular economy, and various aspects on its implementation in practice. In their overall summary of CE principles, they mention the essence of biological resources and circularity. Namely the shift of material composition to biological based, and further the ability to reintroduce products and materials based on biological resources back into the biosphere (Ellen McArthur Foundation, 2020, p. 23). The biological cycle in circular economy looks somewhat different to what is referred to as the technical cycle. What differs them is whether the resources in question are biological and can safely return to the earth (Ellen Macarthur Foundation, 2022). Attachment 1 visualizes both the biological and technical loop, and their differences. The core of the biological cycle is farming practices allowing for regeneration of nature, to rebuild soils and increase biodiversity. Whilst focusing on how to do less harm to the Earth and the planet, focus should also be directed at how we can restore nature. For example, through reintroducing minerals and nutrients back into the biological cycle through composting, instead of the resources being lost.

2.2.4 Circularity in materials

When looking at materials in the CE it is prompt to make use of material specific CE concepts and methodologies, i.e. a subset of theoretical framework used to consider circularity of materials. This is useful in order to understand what elements about products in the category of building materials is relevant and important when assessing the circularity and contribution to a circular economy.

The article authored by Amarasinghe and two other authors develop a systemic framework to translate knowledge from research environments more effectively into practical applications within the building industry. The framework developed is called M-CEF$_{Bc.}$ They have built the framework on the ReSOLVE framework created by Ellen McArthur Foundation, which identifies that the three main criteria for evaluating material circularity are material specification, building design and innovation and building. There are fifteen sub-criteria for assessing material circularity, with weighted significance and connection to ReSOLVE. This framework for material circularity was opted for, due to the complexity and range of the criteria's included.

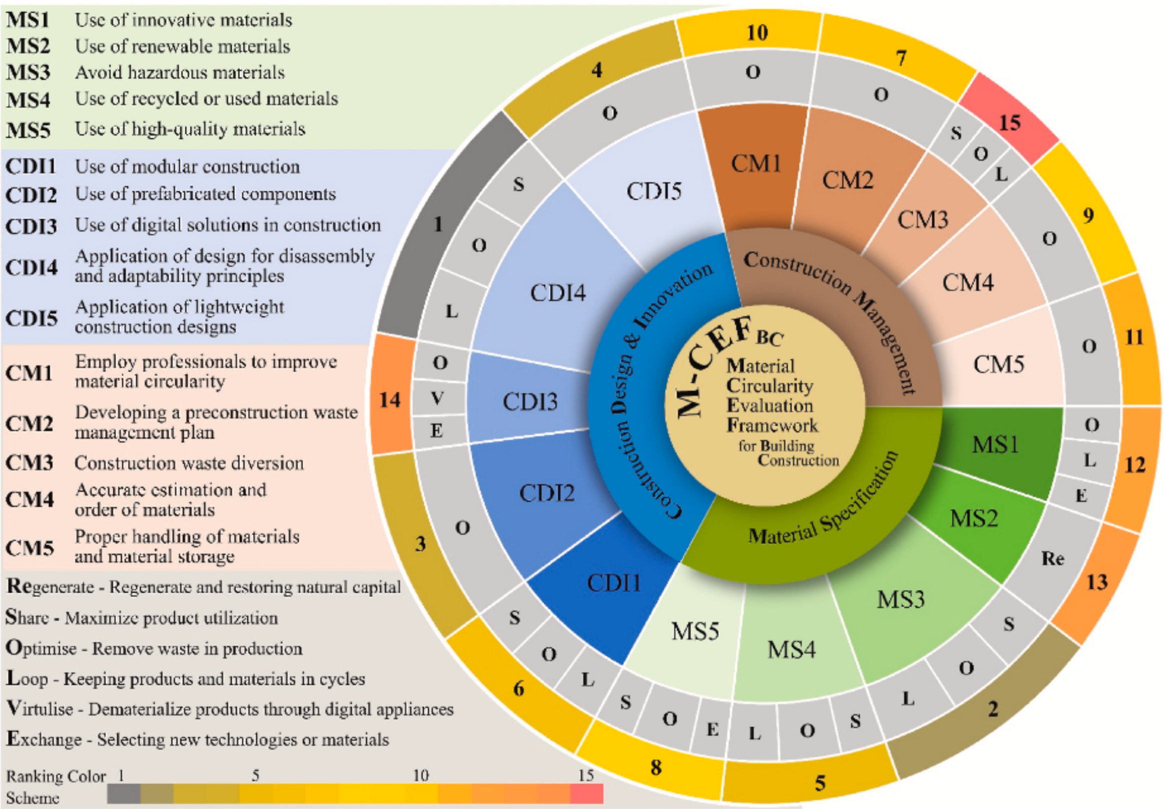

Figure 2: Systemic evaluation tool for material circularity (Amarasinghe, 2024, page 8)

The subset framework of CE goes beyond looking at waste minimization, elaborating a comprehensive approach to design products (e.g. materials) and buildings where the resources used can reiteratively be cycled through utilization and recovery. The indicators can be used to determine and assess material circularity, as opposed to more traditional CE indicators which typically measure to what extent a business is circular overall (Amarasinghe et al., 2024, p. 2).

2.3 Economic viability

The section will detail key regulatory changes with respect to circularity and sustainability, and further elaborate on aspects concerning competitive positioning and market potential for building projects.

2.3.1 Regulation and governmental strategies

Regulatory strategies, action plans and regulation in general plays a key part in addressing externalities and can be referred to as a type of externality solution, by internalizing the externalities (Ghisellini et al., 2015, p. 14). From a Norwegian perspective political regulation from the EU at large and Norway nationally will have a huge impact on the building industry, most promptly the EU taxonomy and the Norwegian strategy for attaining circular economy developed on top of EU's own strategy and action plan.

The EU Taxonomy

The EU[2] released a Taxonomy Regulation which entered into force on 12th July 2020 with six overall aims concerning climate and the environment (Directorate-General for Financial Stability), where amongst them one concerns the transition to a circular economy (Figure 6). It is essentially a classification system defining what environmentally sustainable economic activity is, with tools to enable such a transition to a net zero economy by 2050, whilst targeting the polluting sectors. The system must be followed by banks, insurance companies and large listed companies with either 500 and more employees, or more than 20 million euros on the balance sheet in total. In Norway the EU Taxonomy was ratified 1st January 2023.

[2] European Union

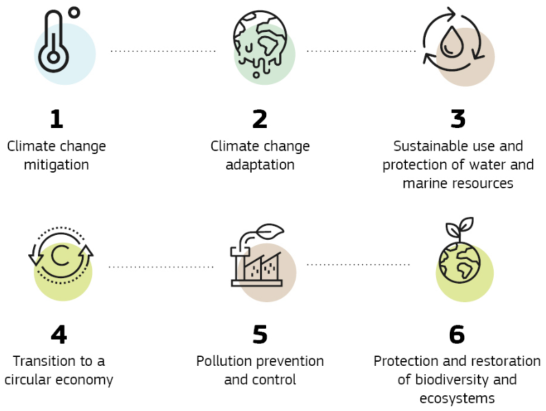

Figure 3: Overall objectives of the EU Taxonomy Regulation (Directorate-General for Financial Stability)

The EU Taxonomy concerns a huge and complex range of criterions. For the building industry some of the specifically mentioned activities covered by the EU Taxonomy are building new, installation, maintenance and repair of energy efficiency equipment and rehabilitation of buildings. The comprehensiveness of the EU Taxonomy makes it difficult to really understand how and when its criteria's will impact the building sector, however, it is for certain that the criterions and requirements will come into play. Anyhow the classification system can also aid and assist companies in identifying themselves sustainable, circular and economic practices.

Through the Norwegian EEA-agreement, decisions made by the EU will wholly or partially bind Norway to the decisions. The EU wants to limit the constraints on natural resources by doubling the use of waste streams the next ten years (Klima- og miljødepartementet, 2021). The EU Taxonomy is part of the broader European Green Deal initiatives. In addition to it, the European Green Deal recognizes the EU's strategy for circular economy as essential for accomplishing climate-neutrality within 2050, and green growth - disconnecting economic growth and increased use of resources (Klima- og miljødepartementet, 2021).

The Norwegian strategy for attaining circular economy

The Norwegian Government released in 2021 a national strategy for a green circular economy (Klima- og miljødepartementet, 2021), which is based on and further developed from EU's own strategy for a circular economy. A summary of the strategy's goal and focus areas relevant for the thesis project is included in this section.

The goal is that Norway shall be a leading country in developing a resource efficient green circular economy, where the stated vision is "*A society where resources are used and reused* *in efficient ways in toxic circuits replacing extraction, and production with new resources*". Specifically, the strategy mentions identified unlocked potential in the bioeconomy using waste streams for high-quality use or in other products, supporting development of general standards for use and re-use of biological resources to ensure safe use for humans, animals and the environment. The strategy mentions wide acknowledgement in Norway's potential for circularity within our bioeconomy and the building industry, in addition to the processing industry and trade industry.

EU released an action plan for circular economy in 2015, with a second plan in 2020 which the European Green Deal recognizes as one of the essential areas for accomplishing climate-neutrality within 2050, and green growth - disconnecting economic growth and increased use of resources. The Norwegian strategy is influenced and based on this, to see how we may from a Norwegian point of view aid the transition in the most efficient way. The four major aspects of the Norwegian and EU circular economy relationship can be put in four:

- 1) Circular economy through sustainable production and product design: To reduce climate and environmental footprints, products must be designed for low carbon production, longevity, recyclability, repairability, and resource efficiency. This involves using waste stream resources instead of virgin materials and renewable resources to replace non-renewables. Key value chains, such as building materials, should focus on low-emission materials, reuse, durability, and repairability, and use Life Cycle Assessment (LCA) in public acquisitions to increase recycling related to demolition and new construction.

- 2) Circular economy through sustainable ways to use and consume materials products and services: Consumer attitudes must shift to strengthen markets for sustainable products, waste streams, and renewable resources. Consumers, including private individuals and public bodies, play a crucial role in demanding sustainable, circular products. Nordic collaboration on the Svanemerket certification promotes circular economy by setting strict sustainability requirements, ensuring product disassembly and repairability, reducing resource and energy consumption, and promoting optimal waste handling. This certification helps consumers make sustainable choices.

- 3) Circular economy through toxic free circular circuits: The circular economy needs to be developed within the realms of toxic free economy, enabling the possibility of reusing waste streams and alleviating pollution of air, water and soil. This concerns setting boundaries and not allowing certain chemicals or toxins in products, in order to provide health benefits for vulnerable population groups, where materials with high degree of recyclability shall be prioritized. One identified product category is buildings and therein building materials.

- 4) Circular economy and value creation: Incorporating secondary and renewable resources in value chains can create new market opportunities. Norway has identified agriculture and forestry, alongside aquaculture and fishery, as key sectors for developing circularity within the bioeconomy. Biological resources can replace fossil resources, assuming increased production does not harm the environment. The primary focus is food production, with secondary uses for building materials and other goods. Waste streams from food production should be allocated for high-value purposes. Government measures, supported by Innovasjon Norge, Enova, Siva, and Doga, aim to facilitate these initiatives with economic support.

Throughout the strategy its apparent that there are opportunities in the transition to the circular economy, ensuring increased GDP whilst decoupling the growth from added environmental impacts. The strategy focuses on the commercial areas which have their own challenges and opportunities, and the overall sectors which are important in terms of highest value use of resources, ensuring food security and appropriate use and allocation of waste streams and secondary resources.

Norwegian strategy for bioeconomy

The previous Norwegian government launched a strategic plan for Norway's bioeconomy in 2016 (Nærings- og fiskeridepartmentet, 2016). As a concept bioeconomy encompasses sustainable, efficient and profitable production extraction and utilization of renewable biological resources for food, feed, ingredients, pharmaceuticals, energy, materials, chemicals, paper, textiles and other products. The plan aimed to promote sustainable, efficient, and profitable production and utilization of renewable biological resources for various purposes. The purpose is to "promote increased value creation and employment, reduced greenhouse gas emissions, and more efficient and sustainable utilization of renewable biological resources.". The strategy implies cross sectoral cooperation, supporting and promoting research and development of new and broad value chains. Promotion of new markets biobased products, through efficient production and perhaps through new standards, certification and marking of biobased products to distinguish these from non-biological alternatives. Efficient utilization and extraction of resources concerns strengthening funding schemes for research and development and promoting use of waste resources and avoidance of toxins and chemicals. To promote sustainable production and extraction the strategy is amongst other aspects directed at using biomass from agriculture and forestry within sustainable means and increase access to environmentally friendly resources and building materials. The strategy has spurred creation of dedicated research environments, bioeconomic focus area in NMBU, regional bioeconomic strategies and other cluster initiatives (Landbruks- og matdepartementet, 2022).

Public acquisition and sustainability requirements

Public and governmental bodies in Norway are major real estate owner in Norway. And as such major acquisitors of buildings and therein building materials. The Norwegian Circular Economy strategy also acknowledges the responsibility of the public and governmental bodies, as large and major owners of real estate. A few months after the strategy for circular economy came out, the government of Norway released a specific action plan for green public acquisition of goods and services (Direktoratet for forvaltning og økonomistyring, 2021). The public sector in Norway acquires goods, services and building services for about 600 billion Norwegian Kroner annually. In this responsibility there is power, where the public bodies can require their vendors to meet certain sustainable and circular requirements. How the requirements are developed and formulated are key in ensuring appropriate nudging of the industry towards sustainable and circular solutions in the long run, or simply ensuring that the most sustainable and circular solutions is awarded as such. The Norwegian Government decided that as of 1st January 2024 the climate and environment shall be weighted with at least 30 % in public acquisition (Nærings- og fiskeridepartmentet, 2023). DFØ[3] has released a comprehensive guiding scheme for public and governmental bodies to understand how to meet the legislative requirements, and how to award the most environmental and sustainable solutions. According to DFØ the most important aspect of reducing the impact from the building industry is to ensure longevity and choose materials with low climate footprint, and use of local available resources to reduce the need for transport. Overall, regulation is playing a key role in addressing climate, environmental and sustainability concerns, therefore impacting considerations on circularity in the building industry.

[3] DFØ = The Norwegian Agency for Public and Financial Management

2.3.2 Economic competitiveness

Economic competitiveness in the building industry involves understanding key factors such as substitution, costs, and pricing of building materials. How does customers perceive the alternative offering on the market, compared to alternatives (Hooley et al., 2017). These elements are crucial for a business' ability to outperform traditional building materials, enter the market and secure a competitive advantage.

Substitution

For biobased building materials substitution concerns replacing traditional building materials like concrete, steel, and plastics, i.e. must be a viable alternative to the materials traditionally used in the current market. According to Hooley et al. (2017) substitution plays an important role in competitive positioning. To gain market share, the building material must be viable and a better alternative. There needs to be something about the building material which exceeds their competitive alternatives. Additionally, other aspects beyond technical viability can promote its competitiveness, which for some reason is valued in the market and by its consumers.

Costs

Managing costs is crucial for maintaining competitiveness in the building industry. Hooley et al. (2017) emphasize that cost efficiency can provide a significant competitive advantage. This can involve optimizing and rationalizing the production processes, reducing waste from production and impacted by how easy or difficult the material is to build with. Utilizing local resources can lower transportation costs and support local economies. Additionally, existing industries and infrastructure can be beneficial, reducing initial investments and operational costs.

Pricing

Effective pricing strategies are essential for competitive positioning, where pricing should typically consider production costs, prices for alternative materials, and the experienced value for the customers (Hooley et al., 2017).

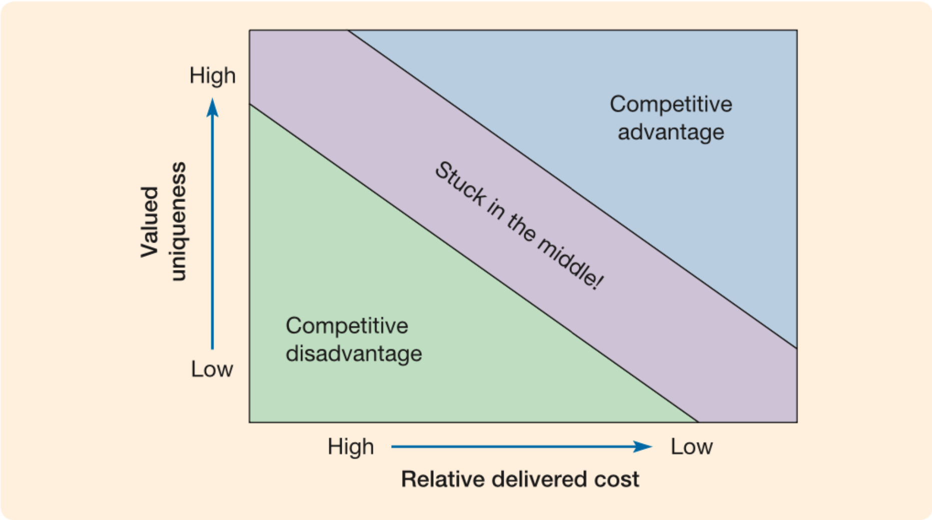

Figure 4: Cost leadership and competitive advantage (Hooley et al., 2017, p. 45)

As seen in figure 7 Hooley et. al illustrates the relationship between the costs concerning the building material, and its uniqueness, and how this plays out in terms of competitiveness. This in turn affects the pricing strategy. Pricing strategies can highlight the total cost of ownership, which includes long-term savings from energy efficiency, durability, repairability and waste management. Educating the market on these long-term benefits can justify a higher initial price compared to traditional materials. Additionally, competitive pricing can aid entering markets, avoid competition, and maximize profits.

Economic viability and externalities

The economic viability is as a term describing a projects ability to attain a holistically net positive economic contribution to society at large, considering all costs and benefits (Locher & Costa, 2020, p. 74). This includes but is not limited to social, environmental and financial costs and benefits, concerning a projects competitive ability and market potential. The theory of economic externalities is in its nature connected to sustainability and circularity regulation. This is because externalities refer to the costs or benefits of economic activities that are not reflected in market prices and are incurred by third parties or society at large (Locher & Costa, 2020, p. 74). When it comes to sustainability and circularity, the focus is on minimizing negative externalities (such as pollution and resource depletion) and maximizing positive externalities (such as environmental benefits and resource efficiency).

2.3.3 Market potential

Market potential involves understanding the market segments, targeted customers, and analyzing market dynamics. What are the characteristics of the building material in which customers may appreciate, to what segment do they belong to and what is the potential for increased demand in the market with correct positioning and targeting.

Segmentation

Market segmentation is the process of dividing the broad market for a said product into more specific groups with similar needs or characteristics. emphasize the importance of effective segmentation for targeting marketing efforts efficiently. In the building industry, segmentation can be based on factors such as the type of building (residential vs. commercial), geographic location (urban vs. rural), and sustainability focus (e.g., projects seeking green building certifications). Targeting segments that prioritize sustainability and eco-friendly building practices aligns well with the benefits of straw and hemp materials, which are renewable and have a low environmental impact. After identifying market segments, firms must select the most attractive segments to target. This involves evaluating the potential profitability and competitiveness of each segment, or which segment stands out. By effectively communicating and highlighting positive and differential benefits of a building material, companies can differentiate their products from traditional building materials and attract target customers.

Market demand and trends

Understanding market demand involves analyzing historical data, current market conditions, and future trends. It is important to understand the market and its trends, to forecast changes in demand. When looking at an industry as a whole one can perhaps anticipate future demand by staying ahead of trends. Examples made are as the growing emphasis on sustainability and green building practices. For building materials and the building industry, trends like governmental regulation or incentives otherwise aiming for sustainable or circular building can significantly impact market potential. Companies that align their products with these trends can capitalize and gain traction from increased demand for environmental or circular building materials.

2.3.4 Value chain for biobased materials

The building industry is a large and established sector, with many different actors throughout the value chain influencing the supply and demand of building materials. Bouvet AS (Bouvet ASA, 2022) conducted a study to uncover user needs and challenges related to a digital platform for reuse and resale of building materials. They elaborated a value chain for the building industry and materials. This research study focuses on hemp and straw resources, resources stemming from the agricultural sector. An amended version of the value chain was created to indicate the value chain relevant for this research study, see figure 5.

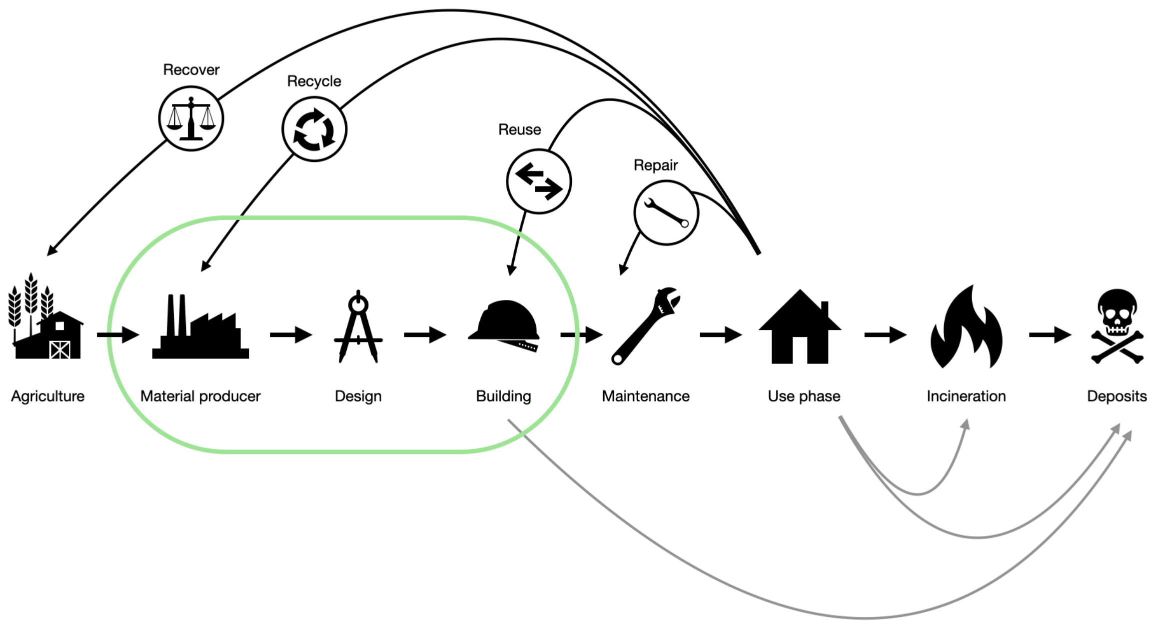

Figure 5: Value chain of materials in the building industry

As illustrated, material choice is relevant in several stages of the value chain, primarily for material producers, design and building phase. This is the point of lookout from the value chain relevant for this thesis paper. From these points in the value chain, it is important to analyze materials throughout their life cycle, as there are aspects of the materials at each stage of the value chain that can influence assessments of the material and their circularity.

3. Method

This research study has conducted an explorative thematic study, drawing inspiration from explorative case studies, a qualitative research design. The theme is biobased building materials and their contribution to circular economy.

3.1 Choice of method

The choice of theme arose from a workshop on hempcrete building on a building site in Oslo back in August 2023. Shortly after a seminar was held by Futurebuilt on building materials and a transition to a zero-emission society. The seminar touched upon the building industry and its traditions seeming ontological and buildings, meaning that it is a result of how we have interacted with nature and interhuman in our societies (Bell et al., 2022). It spurred an interest in understanding these interactions and how they play into the choice of materials in buildings and the shift towards a circular and sustainable bioeconomy.

The aim for the research study is to explore biobased materials and their unique features, to assess and identify elements in which warrants further study. Essentially a mapping exercise of biobased materials and circularity in the context of the Norwegian building industry.

When conducting the study, it was clear early on that the appropriate approach was a qualitative study. There is a need to assess qualitatively how these materials perform and circularity in practice in the building industry, by seeking out researchers and professionals with hands-on experience and knowledge. Following an inductive approach, the thesis aims to generate theory from the data collected rather than testing existing hypotheses. This emphasizes understanding the complexity of social concepts and opinions from the perspective of the participants. An exploratory case study design was chosen to provide an in-depth understanding of the application and implications of biobased materials in the context of circularity. Unlike traditional case studies that focus on a specific entity, this study explores a broader theme, allowing for a more flexible and comprehensive examination of the subject (Bell et al., 2022, p. 62). This approach is particularly suitable for exploring new or under-researched areas where existing theories may not fully apply.

3.2 Data collection

Qualitative data were collected through semi-structured interviews, allowing for flexibility in questioning while ensuring that key topics were covered across all interviews. This method enables the exploration of participants attitudes, experiences, and perceptions in depth (Bell et al., 2022, pp. 428-430).

3.2.1 Sampling

To ensure a set of data with sufficient information about the biobased materials and circularity in the context of building industry, a combination of strategic sampling and snowball sampling methods was chosen. The reason for this is to investigate the possibilities in the researched theme, and not investigating to what extent such knowledge is prevalent or negligent in the industry. Since the knowledge about these biobased materials and their contribution to circularity and profitability seems to be limited in the building industry at large, strategic sampling was implemented to ensure that the sample included a diverse range of perspectives, including material experts, architects and builders. That the participants of the research study to the extent possible had some knowledge and experience with either the biobased materials or circularity in the building industry, and most preferably both. This deliberate selection process aimed to capture the multifaceted nature of the biobased materials sector and its circularity practices (Bell et al., 2022, p. 390). The strategic sampling took place from the workshop and seminar attended in fall 2023 (architects), and through existing connections and access to builders. Snowball sampling built on the strategic sampling to identify key possible participants. The initially contacted participants referred additional participants who had relevant expertise and experience in their view, facilitating access to a broader network of knowledgeable individuals (Bell et al., 2022, p. 394). In addition, when collecting the pool of possible participants with experience from other countries and jurisdictions were welcomed, and participants based in other countries were allowed. Overall, sampling was done through using existing relationships, broad searches online for actors operating with straw or hemp building materials.

Three overarching types of participants were identified throughout the process when reaching out to participants, namely the makers (material experts, producers), architects and the builders (entrepreneurs, real estate development etc.). In total 8 participants accepted and were interviewed typically within a week after acceptance. Their participant ID connected to area of professional background is included under table 1. Most of the participants are based in Norway, with some A total of 23 requests for participation were made.

Table 1 Overview over research participants

Participant ID	Category
Participant 1	Architect
Participant 3	Architect
Participant 7	Architect
Participant 2	Builder
Participant 4	Builder
Participant 8	Builder
Participant 5	Material performance
Participant 6	Material performance

3.2.2 Interview guide

The interview guide is based on the research questions, where introductory questions about the participant, background etc. is collected to establish the context in which they are providing the responses to the questions. The interview guide is included in the attachment 2 and shows a series of questions in general form, with subcategories that may are relevant to query depending on their answers. The interview guide was prepared and approved with the thesis counsellor to ensure its appropriateness. There was minor but no major alterations to the guide and the questions throughout the data collection process.

The interview guide creates the basis for the interviews conducted, where some of the questions are relevant for the interview depending on the participant and their responses. It includes open-ended questions focused on participants' experiences with biobased materials, their views on circularity, and the challenges and opportunities they encountered. This allows for the participant to steer and guide the conversation to various topics in which they want to talk about or come to think of. Interviews were conducted in either Norwegian or English based on the participants preference. The intent was to assess the contribution biobased building materials has to a profitable industry by looking at cost bearers for production, the market and willingness to pay. The interviews were conducted in beginning of May and then in the beginning of June. The reason for the delay in between was lack of respondents in the first round of reaching out to participants.

3.3 Data analysis

Thematic analysis was used to analyze the interview data, following the process outlined by Bell, Bryman, and Harley (2022).

3.3.1 Transcription of interviews

The research study conducted had one researcher. For the researcher to be invested and fully present in the interview, all the of interviews were recorded in Microsoft Teams. All participants gave explicit confirmation for the interview to be recorded and were informed that the recording was for transcription purposes and will be deleted shortly thereafter and by end of the research study. The recordings were transcribed verbatim using Open Ai's transcription software called Whisper. The Norwegian National Library has trained their own version of the AI language model, Autotekst, which was used for the transcription of interviews conducted in Norwegian and English. The software is available for all Norwegian registered students, where the software uses secure crypted serves with the University of Oslo and was deleted right after transcription. To ensure data validity, the recordings were listened to whilst comparing to the transcriptions. Almost no changes were made to the transcriptions due to the accuracy in the transcription software.

3.3.2 Coding of qualitative data

The coding process was guided by thematic grounded theory, which involved generating codes and themes directly from the data without preconceived categories. According to Bell et. al (2022, p. 542) this method ensures that the analysis remains grounded in the participants' perspectives and experiences. This could be either repetitions, analogies, transitions or theory related material. Throughout this process, constant comparison and iteration was employed to refine coding categories (Bell et al., 2022, p. 532). Note that preconceived themes and overarching nodes or categories were kept in mind for the coding to ease the analysis of the data. The codes were coded towards overarching or subcategories, also to suggest relationships between codes. The data software Nvivo was used to ease the coding, and to more easily change sub coding and top-level coding throughout the coding process and iterations. One round of initial coding was done after the first three interviews, whilst complete and final coding were performed once all eight interviews were conducted.

Based on grounded theory and steps and considerations for grounded theory the methodology for the coding conducted in this research occurred is described as follows:

- **Step 1:** Reviewing and reading the transcriptions without making any coding or specific notes throughout. General remarks were made at the end of the interviews to indicate subcategories and key words in a memo, referred to as iterative coding memo.

- **Step 2:** Thorough review of transcribed interviews for each participant, coding the theme or category. The codes were from the start included as sub-categories connecting to the research questions. New codes were added as the interviews were examined. This was done in Nvivo.

- **Step 3:** Review of coding, to assess which are similar, which concern the same theme or category.

- **Step 4:** Iterations with re-examination of the interviews based on the coding, whilst continuously changing the coding until saturation of the codes and setup with top-level and sub-codes- Axial coding was also done by connecting codes to different settings, showing their relationships etc. and written down in the iterative coding memo.

- **Step 5:** After iterations etc. the codes identified were connected to key words and concepts in the theoretical framework.

The codes and mapping to research questions and key concepts can be found in the attachments (Attachment 3 to 5). Note that alterations to the coding and its presentation in the research study were changed after the mapping of the coding was done, but it does indicate the overall codes. Theoretical saturation was not accomplished, at least not verified, in the project due to the low number of participants. However, some saturation was seen for certain themes and categories

3.4 Data quality

Data quality in business research is key in ensuring that research conducted, and its findings can be relied upon, possible to replicate to verify findings and that the research is valid. Although there is some debate as to the relevance of reliability and validity for qualitative research, there are ways to use the concepts of reliability and validity to increase the data quality in research studies without relying too heavily on their definitions.

3.4.1 Reliability

Reliability is concerned with the question of whether the results of a study are repeatable and to the extent one can depend on the research conducted and its findings. It can be divided into internal and external reliability (Bell et al., 2022, p. 368).

External reliability

LeCompte and Goetz recognizes the difficulty in ensuring internal reliability, i.e. how replicable is the study if another researcher or researchers were to conduct the same study. Some aspects of the study's replicability cannot be handled such as the time and setting. In theory one could imagine another researching searching for the same type of informants and asking the same type of question, leading to the same findings. In terms of the research design replicability should be possible, where the identified types of participants etc. are also likely to have been suggested by another researcher. However, the use of strategic and snowballing sampling makes the pool of participants more random, and more vulnerable. Especially considering non-responsive potential participants, and that the number of potential participants identified to perhaps have experience and knowledge with these types of resources, materials and the Norwegian industry are seemingly quite low. The external reliability could have been increased by more methodical steps in the strategic sampling, i.e. which search words were used to find which participant etc.

Internal reliability

The internal reliability refers to how reliable are the observations and what has been seen or heard. For semi-structural interviews, conducted with only one researcher, it was imperative for the interviews to be recorded to aid accuracy in what the participants said. The interviews were further transcribed verbatim with software, and further proofread to ensure its quality. This resulted in a time effective transcription process, with an accurate data set for the coding process. The coding process however followed the structure in accordance with the theory mentioned, however, even the coding process is a subjective aspect in which the research enacts in their own interest and knowledge. An emphasize was therefore put on taking the qualitative data with its face value, and limited reading into the data prior to analysis and discussion.

In addition, when conducting semi-structured interviews, the researcher can impact and influence the participant by providing their own opinions and disclosing biases. To increase the reliability of the project the participants were allowed to take their time, steer the conversation into the aspects until they were complete in answering the question. Focus was on limiting any comments on their responses. The reliability could have been increased in more iterations on the interview guide, such that the questions were as open as possible. The reliability could also have been increased by having kept a journal to document their thoughts, decisions, and potential biases throughout the research process and interviews. This aids identification and mitigation of personal bias affecting the research.

3.4.2 Validity

A further criterion of research connected to the reliability is validity. Validity is concerned with the integrity of conclusions that are generated from a piece of research (Bell et al., 2022, p. 48), in explanation how believable are the findings and do they apply generally.

Internal validity

A strength of qualitative studies is the internal validity of such studies, i.e. the match between observations and developed theoretical ideas (Bell et al., 2022, p. 369). For a case study the internal validity depends on the interaction between the researcher and participants and tends to be weaker for semi-structural interviews. The idea and purpose of the opted for research design was for the theme to be explored and synthesized through the researcher as its medium, guiding what aspects of the theme which should be investigated. The internal validity for this research study could have been strengthened by having initial conversation and in-depth interviews with each of the participants, instead of up-front interviews where the researcher and participant were not familiar to each other. The coding process however generally followed the structure in accordance with the theory mentioned.

External validity

It concerns to what extent can the research study's findings be applied and generalized. As Bell. et. al validity in qualitative research is concerned with the accuracy and truthfulness of the findings. Qualitative data were collected from a diverse range of participants, which aids the integrity. The small sample with participants reduces the study's external validity, also considering the three main types of participants furthering scattering and spreading the qualitative data. The use of systematic coding procedures and constant comparison technique should support the external validity of the findings when discussed in relation to the research questions, and especially the problem statement at large. However, the concepts and codes identified in the research should on their own be considered with caution. Weaknesses with the chosen research design and conducted case study suggests that the findings should be used in accordance. The research study should be viewed as a conceptual and explorative mapping of interest and concepts arising from examining the theme of biobased materials and circularity. The validity of the identified areas within the theme can fully be valid, whilst these should be treated as indications on what warrants further study.

The reliability and validity of the research study is outlined above and should be kept in mind when considering and using the findings of the study. Other alternative criteria's more relevant for qualitative studies could, or maybe should, have been chosen to ensure reliability and validity throughout the research study, such as approaching the study's credibility, transferability, dependability and confirmability. Due to the limited scope of a research study, and time frame, the approach was not taken.

3.5 Ethical considerations

In research studies ethical principles can ensure that minimizing ethical risks involved with the research study. The main areas of ethical issues for qualitative interviews concerns risk for harm, invasion of privacy, lack of informed consent, and involvement of deception (Bell et al., 2022, p. 122). Ethical consideration considering these principles was in focus throughout the research process. Their privacy is ensured in the anonymity of the participants in the assignment, minimizing any type of risk for harm as a result for participation in the study (reputation etc.). Due to low number of participants, and that the knowledge about the theme is scarce, limited information has been provided in the thesis about the participants specific background, age, business background etc. However, there is a risk that participants can be indirectly identified through their input, context of the research study and information otherwise presented in the research. Participants were informed appropriately from the beginning and throughout, receiving information about the research study, interview guide and with the option to always withdraw their consent to participate. Approvals were explicitly received over email for setting up the interviews, where oral explicit approvals were made prior to the recording of the interviewing started. The participants were aware of the right to withdraw their consent at any time, or to say no to being recorded. Throughout the interview process the participants were informed and reminded that they can answer how they would like, and to only share whatever they would like to. Participants could also indicate if they were not comfortable with citing certain phrases or what they have said, where such requests were fully complied with and is not a part of the data set.

4. Results

The qualitative interview data has been coded into various concepts and categories relating to the three research questions for the study. The qualitative results of the interviews are presented, analyzed and discussed for each research question respectively.

4.1 Research question 1 – Biomass as materials

Research question 1 addresses the suitability of biomasses hemp and straw as insulation materials, and how it performs from a technical perspective.

4.1.1 About biomass as materials

Overall, the respondents had some familiarity to bio-based building in general, i.e. the concept of building with materials that are based in its whole or partly on biological resources. Mainly only the architects and material producers had knowledge about the biomasses hemp or straw and building materials based on these, where three participants had no knowledge or heard of such materials.

Fundamental characteristics

*"So, plant resources are incredible, intelligent machines, right?" (*Participant 3*).* Participant 3 detailed the holistic view of how plants have various areas of use areas due to the properties of the plant. Hemp and its wood-type biomass and oils was mentioned, with its pure and more distinct fibers when compared to other natural fibers such as in timber and straw (Participant 1 and 3). For hemp, the plant has innate characteristics due to which it is used as a soil remediation product, where participant 3 uses examples used as clean up in toxic waste sites. Further, participant 3 highlights that there is a fundamental difference between straw and hemp. Straw is the waste product of grain production, whereas hemp is a plant with various areas of use due to its different components. Straw as a biomass differs from hemp because it is like a hollow stock, botanically more like grass and shrubs. It is essentially like the hemp shiv, which is a part of the hemp plant. In addition, straw does not have any nutritional value in itself (Participant 3).

The common aspect of straw and hemp is the natural fibers according to Participant 1. Participant 5 argues that there are small differences in the fiber between (natural) fibers, this does not necessarily have much weight in terms of the materials they are used in. The participant indicates that the fibers in hemp are purer and more distinct in hemp, compared to other natural fibers such as in timber and straw (Participant 1). The hemp plant produces a special kind of wood fiber at its core, a "woody core". The woody core is efficient in transporting water throughout the plant (Participant 3). Participant 3 argues that the wood fiber in hemp is interesting due to its capability to hold and release a lot of moisture, described as being hygroscopic. This is like what wood fibers can do in timber and like wool fibers (Participant 3).

Biomass growth

Hemp is a plant that's grows very quickly according to Participant 3, and it has known to be able to be grown in different areas across the earth. Whilst plants grow carbon are being stored into the biomass. Grain and hemp are both plant species in which has annual growth cycles. Wood has a growth cycle about 60 – 70 years, implying a less "effective" storage of carbon in timber than in grains and hemp.

Biobased building

A major part of the participants provided qualitative data about building materials made of biomass, whilst also mentioning materials made of straw and hemp specifically. Overall, the participants talked about biobased building materials, as an umbrella term, for building materials made wholly or partly of biological resources, and the interplay with other non-biobased materials. Overall, the building materials´ performance and the trust to the material perforce is the foundation for current building practices, creating a threshold for use of unfamiliar and/or novel materials. Their responses are presented first through building materials made of biomass is viewed and the available material palette, and then with respect to their performance factors and regulated requirements in this respect.

Material palette

"One can imagine a flora of things you can create from these resources" said participant 1, creating the basis for the presentation of the material palette identified in the qualitative data. Participant 5 says that in general you can use various biobased materials for "everything". Materials using a biological component also has another component, either mineral, plastics or various polymers, i.e. often a composite material. The material palette concerns the typical type of materials in which are based on straw or hemp, including highlighting relationships to mineral building materials. but pinpoints to where such materials are the most relevant to use.

Generally, the participants mention that straw and hemp can be used for load bearing. Straw bales can be compressed to such an extent it takes load. Hempcrete can also take load if sufficiently mixed with mineral. However, both impairs insulation possibilities. The characteristics of the fibers in straw and hemp are especially interesting when used to make insulation materials, especially hempcrete[4] (Participant 1, 3 and 7). The participants has also mentioned straw and hemp in plating material, being interesting due to its lignin which acts as a glue when these are compressed into plates.

Insulation materials

Participant 3 refers to most insulation as "fluffy insulation", referring to straw insulation, hempcrete and other insulation traditional materials that has a lot of air pockets in them. The key for insulation is that you have a form of air pocket where air stands still, where the fibers are hollow and heavy (Participant 3 and 6). This is due to the resources having a structure with suits such area of use. Participant 5 supports this, whilst also mentioning typical areas of usage for biobased insulation products are in indoor insulation, outdoor, roof, floor etc. Participant 6 is also firstly familiar with using biomass in insulation materials, and further emphasizes that its optimal due to large volumes needed to fill the walls.

For hemp several of the participants are familiar to hempcrete. Hempcrete can be created through "wet building", but also as prefabricated bricks or wall components (Participant 3). For the mixture of hempcrete the ratio between plant and mineral components impacts the thermal capabilities. Less mineral and more plant-fiber is relevant where there is a cooler climate, and the opposite in warmer climate. One needs to find the appropriate recipe depending on where the hempcrete shall be used, to ensure appropriate levels insulation. Hempcrete is suggested as the best biobased way to rehabilitate insulation in older buildings due its various technical properties being beneficial for such usage (Participant 5). For straw-based materials it will act as insulation materials when used with a load bearing structure, where participant 3 also mentions use of straw in prefabricated wall components. This typically involves a layer of clay plastering in the wall to ensure optimal moisture levels.

A building system

When participants have been talking about various building materials that can be made of straw and hemp, they have talked about materials based on biomass in general. The mentioning of timber as a biological resource used for building was talked about by every

[4] Hempcrete is a composite building material where hemp is mixed with a binder, lime, and water.

participant. A timber load bearing system works with a range of biobased insulation and plating materials, but also with petrochemical or energy intensive insulation materials such as glass wool. In addition to timber, participants have mentioned the use mineral resources as complementing the biomaterials[5]. The categories of biomaterials and clay-based materials complement each other very well on several areas, and further believes that the point of intersection between these materials will become developed in the years ahead (Informant 1 and 5. The data indicates that one cannot talk about straw and hemp in building without also talking about clay and lime. As participant 3 puts it, "*Its a building system",* and further saying they are *"age old companions"* of fiber building. Further exemplifying their point by saying you cannot simply compare hempcrete with for example glass wool since it is a building system. For constructing residential housing and cabins it is generally possible to replace the standard building materials with biobased alternatives (Participant 3). Its without doubt possible for smaller buildings, but for larger buildings, and airports etc., more work needs to be done in the research to assess this.

Participant 7 challenges for examples specifically for hempcrete that perhaps the use of lime should be replace with clay. References were made to the traditional use of adobe blocks in architecture and building, where clay was mixed with a type of straw. The reason for use of straw was because it was a fiber. Fiber has tensile force, which can hold what its mixed with together. In the example of adobe clay is the load bearing component, where fiber holds it together. Participant 3 supports the notion of seeing straw and hemp in building together with clay.

Breathable building logic

In total the examples go to show that the use of straw and hemp as building materials implies using mineral components such as clay and lime as components, and together a building system in which is seen to complement each other better than use of glass wool or oil-based products. Participants further explain the reasons between a capillary open building and capillary closed building. The example drawn is the building of a wall, which essentially is a layer of things (Participant 3). A capillary open system moisture needs to be able to pass through the wall without accumulating. Several of the participants refers to this as a wall being "breathable". Accumulation of moisture can cause rot and mold. A capillary closed system is the opposite, where moisture is not allowed to go through the wall. It is in the capillary open building where the interplay between biological and mineral resources come into play. The

[5] Biomaterials used as referring to materials wholly made of biological resources.

participant specifies that clay and lime on a wall does not allow water in liquid form to pass, but water in vapor form can, where a capillary open building lets the water go through. Participant 7 also highlights the symbiosis with the plant-based insulation materials and mineral plastered walls.

Alternative materials

The participants mentioned a range of different types of biomasses as options for building materials, some more known and established than others. Use of timber as materials were mentioned by the participants throughout in the load bearing structure, plating and as insulation (wood wool). These are referred to as lightweight building materials, contrary to concrete and steel. In terms of load bearing, it can either be poles (Participant 3) or use of cross laminated timber (CLT) (Participant 6). Participant 5 also specifically mentioned an insulation material made of grass, similar to glass wool and wood wool. Natural wool insulation was mentioned by participant 7, where wool was also discussed as a biomass by participant 3. The use of seagrass or seaweed as materials were mentioned by several participants, both the historical use in walls as fiber (Participant 1, 5 and 7), but also as a potential interesting biomass to use in building materials to store and lock the carbon through its lifespan (Participant 6). Participant 6 also mentioned the use of linen in insulation.

As participant 3 mentioned it is not easy to identify exactly what the alternatives to straw and hemp-based materials are, simply because it is very much a building system. The participant mentions that the use of concrete in building is typically part of a steel building system. Concrete is used as insulation in walls with steel poles for load bearing. A biobased building system that involves a timber frame can involve non-biobased "fluffy" insulation materials such as glass wool, plastic insulation and spray foam alternatives (polyurethane), according to Participant 5 and 6. These typically involve petroleum-based products, or energy intensive production processes. In addition, rock wool can be used, which is less energy intensive than the recently mentioned alternatives. For plating gypsum is the most common choice. A capillary closed building type is also typically connected with the use of plastics in the wall, as it entails a plastic barrier in the building which ensures that moisture cannot enter and pass through the wall building.

4.1.2 Material performance and trust

Across the board the participants' states that focus on material performance is key when opting for and using building materials. The participants have directly and indirectly provided input on the performance factors with respect to certain types of resources or materials, divided into various performance factors pertinent to the materials.

Moisture control

Moisture can be controlled satisfactory when exposed to vapor due to the hygroscopicity of the strawbales and hempcrete (Participant 3 and 7). If moisture however gets trapped in the structure, this causes molding and rot over time (Participant 1, 3, 6 and 7). The straw and hemp-based insulation materials do require some sorts of protection against water rain. Straw insulation needs a layer of clay plastering to protect against the liquid water (rain). Hempcrete can sustain some liquid water, although not proper rain over time (Participant 3). Generally, plastic insulation is preferred from a technical side since it is not prone to moisture issues (Participant 1). Glass and rock wool are also prone to moisture, and its use require that neither vapor or liquid water get in touch with the materials or gets trapped (Participant 5).

Measuring the performance for moisture control for a said wall is measured by the "u-value" (Participant 6), whereas the measurement for moisture control for the insulation material is measured by "lambda" (participant 5). The u-value is measured from the lambda, by considering the thickness of the wall. Participant 5 mentions that the performance of moisture control is measured after building is finished. From their experience biobased insulation products tend to perform better than glass wool over 15 - 20 years, where the worst insulation product in terms of performance is polyurethane insulation, glass wool, rock wool and then biobased insulation materials. For reference biobased insulation loses 0.01 - 0.02 in lambda values over 15 - 20 years, however, this is not typically something that is measured. The participant also mentions that there is little discussion about this aspect, and the performance over time compared to biobased insulation alternatives.

Temperature control

Participants 3 and 4 mentions the difference in thermal conductivity and therein temperature control for buildings with pure mineral insulation (e.g. concrete) and buildings with "fluffy" insulation[6]. To exemplify the effect, concrete building will over time store the temperature from

[6] Fluffy insulation refers to insulation materials that are porous and full of air.

the outside in the walls due to its high thermal conductivity (participant 3 and 7). Meaning that it will act cool indoors when facing warm weather outdoors, since the building cools down over night from the colder temperatures compared to the daytime with sun. However, a building with fluffy insulation can more quickly change temperature due to its lower thermal conductivity. Hempcrete is mentioned as especially good in temperature control, but the mixture for it needs to be adjusted to match the weather and temperature in the area in which its being used (Participant 3). Colder climates imply less mineral and more fiber, whilst warmer climate implies the opposite. For the mineral resource clay both participant 3 and 7 mentions thermal inertia[7], as positivity for such use in walls in general Further, both participant 3 and 4 mentions, energy efficacy in buildings and housing has been of special importance in Norway in recent years. This implies the principle of making our buildings airtight. One of the participants mentions that the "industry's" argument made against straw bale insulation and hempcrete in capillary open building is that it is leaking air, and thereby heat (Participant 3). However, they mention that a capillary open building is about letting moisture pass through the wall, and not air, and in their view the critique is not sound.

Indoor air quality

A typical solution to meeting the requirements for sufficient air quality is use of mechanical ventilation systems. Typically, a lightweight metal system for transmission of air in and out of buildings using fans (Participant 3, 4 and 6). This is due to the focus on energy efficiency and focus on airtight buildings. Both makes a general reference various sorts of biobased materials being hygroscopic, or more commonly worded, they are breathing building materials. For indoor air quality this entails that the building materials can hold moisture when the air is humid, and release once the air is dry (Participant 3, 5 and 7). The results of this biomass characteristic stabilize the indoor climate in buildings (Participant 3, 4 and 5). Moisture levels indoors and outdoors impact the flow of moisture. Participants highlights that the perks of straw and hemp insulation materials is that with the absorption and release of moisture, the same is true for CO_2 and VOCs[8] - leading to improved air quality in buildings. Participant 4, 5 and 7 supports the notion of using breathing materials in buildings to better the indoor air climate, and one states that the building industry needs to focus on how to build with less need on electrical components (Participant 4). In practice breathable biobased insulation has seen have major positive impact on indoor air quality (Participant 5) and is said to be a specific advantages with biobased building.

[7] Thermal inertia means the degree of slowness with which its temperature reaches that of the environment

[8] Volatile Organic Compounds

Fire resistance

Fire resistance can be tested by measuring the surface spread of flame, but also how long it takes for the material in question to disintegrate (Participant 3 and 6). A requirement for fire resistance can for example be 90 minutes of resistance. A common issue plant-based insulation alternatives is that they are prone to fire, implying that you need a "fire strategy" when using such materials (Participant 1 and 3). Using clay plastering as a shield for potential fire, since clay becomes ceramic or pottery when burnt (participant 1, 3 and 7), is an example of such a strategy. Clay plastering withstands more than two hours of fire, at which point they turned the machine off (Participant 7). Limestone is not flammable either, it does not burn (Participant 3). They further mention that any adding of "mineral material" to the building envelope aids add fire resistance, not just clay plastering for examples, but also where the mineral is mixed with the plant fiber (e.g. hempcrete). For example, rockwool and glass wool are both considered non-flammable.

For straw bale insulation with a certain compression straw is much less flammable than when uncompressed (Participant 3, 6 and 7). Comparison is made between compressed straw and the old yellow phone book, drawing the picture of trying to put one on fire. The participant mentions that it will char on the surface, but it will as such do not burn. For hempcrete testing has been done on its fire resistance, where in one of the tests the machine was turned off after four hours because it has not burnt (Participant 3). Further noting that a four-hour long fire rating is a very high fire rating.

Acoustic performance

Several participants mention the basic principle of wanting heavy materials due to its innate acoustic benefits, whereby lightweight materials, such as timber, are not very acoustically beneficial (Participant 1 and 4). However, hempcrete has been mentioned to have very great acoustic performance. Participant 7 mentions that also straw-based insulation has very good acoustic performance.

Technical regulation and requirements

In Norway there is a technical regulation detailing requirements to building, where the requirements differ between the type of building in question (e.g. residential house vs. apartment building). Further, meeting certain industry standards is of importance and having certain certifications impacts material usage in general. Technical regulations may apply differently depending on the type of building in question, e.g. residential houses compared to large apartment buildings (Informant 2, 4 and 6). It is the builder that oversees the building meeting the stipulated requirements. Today the technical regulation is what the participant referred to as performance-based, instead of detailing exactly how any wall should be built. There is example is by comparing to 20 years ago, where the technical regulation would say that perhaps a wall should have this specific setup, this much insulation etc., or what they call a “recipe”. Today the regulation rather indicates or requires that a wall shall have this level of fire resistance, this value for temperature control and this value for stiffness. It is up to the builder or contractor on how they would like to meet the performance requirements and can make various choices in this space as long as the requirements are met. This makes builders responsible for the performance of the buildings, and therein requires that the materials chosen for the building meet certain performance requirements.

In Norway the most recent technical regulation is commonly called TEK 17, the current technical regulation which can be updated and changed in the future with iterations (Participant 6). In addition, they also mention a portal containing large range of building recipes called Byggforsk. These are building recipes on how to design building to satisfy the technical regulation, but it is not exhaustive to all building that is within the regulation.

Standards and certification

Technical requirement raised to building materials are standardized through harmonized standards, typically European from a Norwegian perspective (Participant 6). There are in addition national addendums to these standards. These are related to the various technical regulations in different jurisdictions. In this respect the participant notes that the European certification CE does not in itself say anything about whether the building materials meet the harmonized European standards but is a certification that allows the material producer or like to sell the product. In addition to harmonized European or national standards, there are also product specific standards (e.g CEN). These may be adopted by Norway. In terms of European, national and product specific standards, these work in a continuous interplay with each other. They are essentially in place for a purchaser of any material to understand whether the technical requirements are met for said purpose using this specific building material. In addition, various certification systems exist with respect to sustainability, and EPD which confirms various data points about a building material (Participant 6). Svanemerket is mentioned as one certification known in the industry in Norway.

A material producer can approach a verified independent third party to test and verify the technical performance of a product, to get a European or national standard or other type of certification. The building material will be tested however suitable for their intended use and relevant performance factors and will pass with a technical grading or fail. European independent agencies and technical tests done there can also be used to get Norwegian standards approved too (Participant 6). In addition, instead of having the material producer or similar testing the technical performance of a product, a technical assessment can also be made on a building (Participant 1 and 6). However, this implies added costs, and is only for that specific building.

Documentation

Trust in technical material performance has been mentioned as of utmost importance by all participants. As participant 6 puts it, the reasons for all the various requirements to performance is with consideration to health, safety and the environment, you shall be safe in buildings essentially. Its therefore important that materials used in buildings, and buildings meets the requirements, although they may be strict or perhaps too complicated. Documentation about materials is also important to be able to document that a building is satisfactory, and that one knows what the building consists of. There is a trust aspect in the materials that are chosen in buildings. This is an example why use of virgin resources in building materials may be easier to work with in terms of material performance, because you know exactly what resource and material you are working with (Participant 6).
The industry often seeks documented technical performance in accordance with the standards they know, typically Norwegian standards (Participant 6 and 8).

4.1.3 Discussion – RQ1

The first research question is essentially a two-fold question, firstly querying the suitability the biomasses have for use as building materials and material palette, and secondly how the building materials perform technically. The analysis of the qualitative data is discussed below.

Suitability

The results of the qualitative interviews suggests that use of straw and hemp in building materials and building in general is not a new concept. There is also a distinction between the two, where straw is more comparable to a part of the hemp plant, and hemp to the type of grain grown. Straw is a product of grain production essentially food production, where the straw has varying characteristics depending on the type of grain. This impacts its potential use in materials. Hemp is a plant that has several use cases as a plant, for food, ropes, textile fibers, soil remediation and in building. There are indications that the remnants of the hemp plant after being used for these various purposes, is what has been used a building material. This therefore makes straw and hemp as biomasses different, but in some sense also similar, that both concern use of waste streams in building materials.

The main aspects of the biomass which has been emphasized as suitable for use as building materials is their fibers, and that it is renewable with short growth cycles. Secondly, is the lignin suitable for plating material. The data suggests that the fibers from the hemp plant are more high-quality than straw, but that both have good hygroscopic abilities. The hygroscopic abilities play well into the functioning as building materials, and for some of the participants they describe the characteristics of the biomasses as being inherently technological. Short growth cycles entail more resource abundancy within means of sustainable production. This combined with the inherent aspect of the biomass having embodied carbon, makes them especially interesting. The data shows that this is because using resources with embodied carbon as materials in buildings delay the release of the embodied carbon into the atmosphere, for however long the use case for the material is. The embodied carbon aspect, and effectively storage of carbon in buildings, is a known aspect for the use of timber in the building industry. However, the fast-growing aspect combined with embodied carbon aspect of the waste stream resources makes them perhaps especially suitable for use as building materials.

Material palette

The qualitative research in this project and research mentioned in the theoretical framework under part 2 indicate that straw and hemp can be used to produce a range of building materials that perform satisfactorily. Although the qualitative data does support this, it clearly suggests that the use of straw and hemp for insulation purposes is the most suitable area of use, referring to its hygroscopicity and porosity. Either strawbale insulation or hempcrete. This is supported in the theoretical framework Secondly, the use of straw and hemp for plating material has been suggested, especially due to the lignin present in the biomass which under compression or pressure acts like a natural glue without the need of additives. The qualitative data also suggests that straw and hemp as building materials are complimented and symbiotic with the use of natural mineral based minerals, such as clay and lime plastering. This symbiosis is more distinct and clearer in the qualitative data, compared to the theoretical framework. In addition, the use of straw and hemp insulation is seen as highly complimenting to timber ways of building (compared to steel and concrete building). As mentioned with the suitability, the mineral components can also be added in the production of the material as seen with hempcrete. The analysis suggests that the use of straw and hemp materials essentially should not be considered without the use of other biobased materials and natural minerals. The qualitative data indicates that there is some hesitancy to the use of lime in hempcrete due to it being energy intensive, and instead points to the possibilities of combining hemp with clay as an alternative. Clay is suggested as a better alternative due to its seemingly vast availability, and that it can be recycled many times without losing its characteristics. This suggests that more research should be done alternatives to lime mineral component in hempcrete.

Material performance

Although the data indicates that straw and hemp are suitable and usable for insulation purposes, the modern building sector is fundamentally dependent on trust in the safety, health and performance of buildings, therein the building materials.

The indoor air quality and acoustic properties are both seen as areas in which these building materials perform well and indicated as their distinct highlighted featured. When straw and hemp insulation materials are used in a capillary open building system, the moisture control is satisfactory for water and moisture in vapor form, due to the hygroscopicity of the materials. The theoretical framework in 2.1 suggests that treatment methods are available to avoid molding or rot. However, if the capillary open building logic can address the innate weaknesses in the biomass, one may avoid the negative impacts of harsh treatment methods. In terms of fire resistance, the data indicates that both straw bale and hempcrete as insulation products meet the industry standards. The theoretical framework indicates that there are some weaknesses to fire resistance for these materials, where there are various treatments that can address these. However, the qualitative research suggests that using these materials with natural mineral components and capillary open logic also should address the potential weaknesses in such materials. The data seems to suggest that a biobased capillary open logic ensures the fire resistance when using these types of materials, albeit unclear if entirely required.

In general straw bale insulation acts satisfactory in temperature control, where hempcrete is indicated to perform as it is a highlighted feature of the material. In the Nordic climate we want buildings that can be warm in the winter, thus, the mixture of mineral and fiber ratio in the hempcrete need to be appropriate. At present the exact mixture relevant for the Nordic climate does not seem exact, but this does not mean that there is no an ideal mixture for the Nordic climate. Prior research by third parties suggests that both straw bale building and hempcrete are energy efficient and can be used in saving energy costs.

Documented performance and standards

In Norway, technical regulations such as TEK17 sets fundamental requirements for building new and rehabilitation. The regulation is performance based, which means it specifies the desired outcomes (e.g., levels of fire resistance, temperature control, indoor air quality) rather than requiring or demanding use of specific building ways or materials (i.e., no specific "recipe" for wall construction). This shift gives builders greater flexibility in how they achieve compliance, making them responsible for ensuring that their chosen materials and construction methods meet the stipulated performance criteria. The Byggforsk portal supplements TEK17 by providing "building recipes" or guidelines for meeting these requirements, though it is not exhaustive.

Since the regulation is performance based this implies that the builders must know and trust the performance of any material used in the building. Due to this and TEK17 the qualitative shows that its imperative that materials have documented testing or relevant certifications in order to be a viable material in building. The documentation needs to be done by an authorized and recognized agency, such as SINTEF. European agencies can also be used.
For straw bale insulation and hempcrete, whom research suggests performs satisfactorily, it is not clear whether any products on market has such certifications or technical approvals. The data does suggest that testing through European authorized agencies would be enough to gain the level of technical documentation, however, the data also suggests that the Norwegian industry rely on known and Norwegian standards. This poses a challenge, seeing that builders need to be able to document the performance of a building.

Sub-conclusion

The research conducted supports that straw and hemp are suitable for use in buildings as insulation materials. Research indicates that straw bale and hempcrete perform satisfactory generally, highlighting their acoustic performance and aid to indoor air quality. Hempcrete seems to also perform especially well in temperature control, where the appropriate mixture for production needs to be adapted for the colder Norwegian climate. However, the use and their suitability are contingent on a biobased and mineral capillary open building logic. This is because the biobased way of building with timber and minerals addresses areas of weaknesses when using straw and hemp as materials. Open capillary building is the type of building that fits with their properties. However, even though these materials according to research performs satisfactory in terms of a range of performance factors it is yet to be documented and certified in terms of the Norwegian technical regulation. Even though the data does suggest that they would pass such tests and standards, the building industry requires actual certification or standard testing for the builder to know that they are meeting the minimum legal requirements.

4.2 Research question 2 – Circularity in building

Overall, the participants indicate that circularity in the building industry relates to aspects pertaining generation of waste, building circular, materiality and handling of waste. Their input has either focused building practices or materiality.

4.2.1 Building circular

In practice building new or rehabilitating a building involves using a recipe describing the technical solutions, materiality etc. All of which is delivered and decided by typically the contractor of the building (Participant 2 and 4).

Building design and management

Materiality is typically decided by the contractor through input from architects, building engineers and material experts, combined with other aspects tied to profitability. Both participant 3 and 6 mentions the fact that architects seemingly have a different position in Norway when it comes to being involved in the actual building phase. They indicate a negative impact, that decision making taken in the building process ends up being more focused on economics, and less able to consider circularity and sustainability. Most of the participants' points to a needed change in attitude to aid circularity in building projects and change in how the decision making is done.

In general, the participants say that thorough planning and design of projects aid circularity in the sense of less waste generation and more circular buildings (Participant 3, 6, 7 and 8). Most of the participants mentions various concepts of mapping of reuse potential modularity, design for disassembly and prefabrication of building elements. Modularity is mentioned by several participants, highlighting that buildings and building components should be more modular to make buildings and building elements more adaptable for changing use. For design for disassembly, it involves for example focusing on mechanical connections when building, instead of using screws and nails (Participant 1). This also entail using less use of casting, glue, grouting and welding. Participant 2 nuances this by indicating that there is a big difference in how easy it is to separate materials from each other based on whether they are glued together or nailed together, or even screws compared to nails. Further, according to participant 1 to the participant it is very much about the order in which you build with, and for large buildings its especially relevant to ensure that a building can safely be disassembled. This can also entail prefabricated elements, and products that are designed for dis-assembly. This entails less waste generation on-site (Participant 4), with easier and more feasible disassembly practices, which further aids possibilities for reuse (Participant 5, 6 and 8). Digital solutions are mentioned as concepts which can aid circularity, and sustainability measures, in the building industry (Participant 3 and 6).

For building projects to be circular you need to consider the entire life cycle, the totality (Participant 6). The carpenters need to know what they should do with the material, and do it satisfactory, and avoid damages in the building. The life cycle of a building material is not decided in the production phase, the producers therefore need to know what will happen with the material when its delivered. The participant 6 suggests that with every material advise on appropriate use should be given. A principle to live by, they suggest, is to use materials in the right way. We should design correctly, use the right material quality, build correctly, build in a way that allows for maintenance and repair – that is when the life cycle is considered.

4.2.2 Materiality and use phase

Materiality is important when looking at a building's performance throughout its lifetime, and how to ensure a long use phase.

Durability

Participant 4 and 8 says that it is a big focus on durability and longevity when it comes to choosing materials, where many actors focus more on the requirements. Participant 4 and 5 argues that a focus on high-quality materials aids circularity. The use of maintenance-free materials has increased, e.g. timber boards that doesn't need repainting or are durable for a long time. This requires that something is added to the timber or that it is treated with something. Participant 6 mentions that this focus does typically not aid circularity, as the treatment required to ensure long durability in e.g. timber ends up as an environmental issue in the other end, causing the appropriate waste treatment to be incineration for example. Their point is that this does not aid circularity, and that one needs to take into account the EOL treatment (Participant 6). In materiality one generally wants to avoid any component being glued together (Participant 2). Participant 3 and 7 argues that by principle you need to acquire something new then it should firstly be biobased. Participant 5 points out that the focus on longevity and durability is backwards. Some materials are treated or designed in such a way that it can last for 150 years, when the actual need for longevity is likely much shorter 30-50 years. At the same time a lot of focus is on cheap materials, which does not have a long lifetime.

Repair and maintenance

Materials in general are not designed to be repaired, hence, does not typically allow for easy repairment or even maintenance (participant 3). As participant 6 puts it, repairing and maintaining buildings and its materials is part of the materials extended lifetime. Participant 3 and 7 argues that when using biobased materials in building, it is a good thing and very useful. "When you build with hemp and straw and wood and clay and lime and other natural materials, you can replace every bit of that building piece by piece, and it will be the same building, and it will last forever" (Participant 3). An example is being made for CLT-walls and patination, where one can either choose to coat the walls to avoid the process occurring, or simply allow for maintenance in five years e.g. dusting down the walls (Participant 3). They go further to say that one of the advantages to biobased materials is allowing for the maintenance. The waste from the maintenance, and even production, can be composted. They further argue that the invitation of maintenance into biobased building allows you to decrease the use of materials and resources that are problematic from a circular perspective.

Circular materials

Most participants mentioned the notion of material producers or market actors starting to identify waste streams in the economy or industry which can be used for building materials. This can be waste streams from within the building industry, such as clay bricks and concrete, or other industries. These actors are emphasized as key in ensuring circularity in the building industry causing incentives to not throw away the waste, but rather delivering it to an actor who will use it in their business. Specifically, participant 5 states that biobased closed loop materials are their focus to ensure circularity. Jointly, they agree that materials made of waste resources should be used in the industry to aid circularity and sustainability. Both straw and hemp are mentioned in this respect, amongst other mineral based building materials (Participant 1, 3 and 7). The notion of storing carbon in buildings has also been mentioned by several participants (Participant 3, 6 and 7), which is an aspect which needs to be considered when thinking about circularity. Specifically, referring to biobased building in general using timber, but especially use of plant-based building materials which short growth cycles which causes a more rapid storage of carbon (Participant 1, 3 and 6).

Materials that are composite with a range of different types of materials, or essentially toxic chemicals, petrochemical or anything oil-based, should be avoided to the extent possible. These are considered non-circular materials. This implies avoiding plastics in building or treated timber with toxicity issues at the EOL. Participants mentions this with respect to both circularity and sustainability more broadly.

4.2.3 Waste generation and handling

Building in general entails building something new from the ground up and rehabilitation, often demolition. Whilst building, in any form, waste is generated, and requires appropriate handling.

Waste generation

Demolition in general causes large amounts of waste, where several of the participants are describing the amount of demolition waste as a huge issue considering circularity in the industry (Participant 2, 4, and 8). Building a new building, or rehabilitation, causes what is usually referred to as production or building waste (Participant 2). Production waste generated in volumes consist of spoilage, damaged material, packaging, protective materials, ordering too much and poor quality materials (2, 4 and 6). Biobased materials are somewhat more exposed to variance in quality due to the properties of biomass, however, this depends a lot on the material producer and vendor (Participant 4).

Waste handling

Traditionally the building industry has been focused on a good degree of sorting building and demolition waste (Participant 1, 2, 4 and 8). This has resulted in good degrees of sorting in general on building sites, converting the waste into waste fractions which can be dealt with however appropriate. The sorting degree is typically above 90 %, with the remainder typically being mixed waste. The building industry has not been particularly good at reducing the amount of waste generated. However, waste management plans aiming for lower amounts of waste generation now appears on the agenda, where it is become popular to set ambitious goals for reducing waste generation (Participant 1 and 8). There is also a requirement in Norway to map the possibilities for reuse before demolishing buildings (Participant 6).

Reuse

Reuse of materials and elements in buildings are pointed out as a focus area by all the participants. This is because at present demolition and building new is still sought after, therefore finding areas of use for materials and elements in buildings to be demolished is imperative or building new buildings with a high degree of used materials. However, it is described as challenging to do this in practice, and that it requires a lot of planning and is time consuming (Participant 2, 4 and 8). It is also costly to disassemble and pick a building apart, compared to just demolishing it (Participant 4 and 6). Participant 2, 4 and 8 mentions that this in practice is challenging, since it is very hard and time consuming to disassemble buildings prior to demolition, often you do not know exactly what materials is in the existing building due to lack of documentation – simply not feasible. There are mentions of up-and-coming marketplaces for used materials, where participant 6 also mentions up and coming "sharing concepts" of areas, or components of buildings.

With respect to the straw and hemp-based materials the participants cannot see that these are any easier to reuse than other materials. Further to which the participants agree that its typically easier to be able to reuse materials in which has a certain monetary value. However, participant 6 argues that there is a large potential in reusing large building components, but that the challenge is that it is very time consuming to de-construct to enable reuse.

Sorting and recycling

Builders sort waste into a range of different waste fractions as participant 2 puts it, mainly divided into various sorting of materials and then into what they refer to as dangerous waste. This is when building new, or refurbishing, i.e. not referring to sorting of demolition waste. As participant 2, 4 and 8 says, the degree of waste sorting is quite high, meaning more than 90 % of building waste. However, the participants acknowledge that a good sorting grade does not solve the challenge of high volumes of waste generation. The last category is subject to regulation requiring appropriate handling. The data does not indicate that building sites sort compostable waste to any extent, other than untreated wood. A focus on the environment has transitioned the industry away from delivering waste from sites to deposits, and now to recycling stations.

On the material side participant 1, 2 and 8 mentions that more and more actors collect various types of waste to produce a new material which is partly or wholly based on recycled material, for examples recycled timber or clay bricks. Participant 3 and 7 mentions that when a material is recycled there is the aspect of down cycling, that it loses value in its inherent characteristics. Participant 7 pin-pinpoints here that in nature, the term downcycling does not really exist, referring to the natural circle of life for biological matter and minerals. Both participant 1, 3 and 7 mentions that unburnt clay (e.g. clay plastering) can be recycled into the circular loop again and again, without its characteristics being lost.

Incineration

Most of the participant's states that most of the timber being sorted on building sites ends up being incinerated. Mostly because a lot of timber is treated with various types of chemicals which cannot be recycled, or needs to be treated to enable recycling, and also partly due to lack of demand established use of the waste stream connected to the recycling stations. Incineration is from a circular aspect unwanted because we lose the material from the resource cycle, and CO_2 is released into the atmosphere. The use of the material at its highest usage is broken (participant 6).

Compost

With respect to building materials using straw, hemp and minerals, natural resources, without use of petrochemical resources, participant 1, 3, 6 and 7 mentions that these can in theory be composted. Put in a pile and decomposition occurs and can be reused in agriculture and in soil. Participant 1, 3 and 7 views this as a benefit for using straw and hemp-based insulation materials, seeing that waste from production, throughout lifetime and at end of use, can be composted. Again, referring to the notion of no downcycling as such occurring in nature when referring to composting, and that this process is simply mimicking the natural cycle of organic compounds and minerals in nature. Participant 1 mentions for example that composted clay should provide no challenge compost used in food production, assuming appropriate decomposition and soil mixture. They urge that composting should be welcomed and celebrated.

According to participant 1 there are recycling stations with composting, but this varies from municipality to municipality. A real example was mentioned about what will happen at the recycling station if you would bring clay, hemp, lime etc. (Participant 7). If you try to take it to gardening waste, i.e. what typically is composted, they will not let you bring it there, because its building waste. It needed to go to incineration. As far as they know there are no recycling stations where you can bring fully compostable building material for composting, e.g. hempcrete, clay plasters, lime etc. Same goes for timber according to participant 4, stating that with the high volume of timber used in Norway there should be established value chains for recycling timber instead of incineration.

4.2.4 Discussion – RQ2

Circularity is very dependent on the building practices, not just the materiality of buildings. It therefore comprises the circular materiality, but also appropriate detailing, use, building and EOL-handling.

Material circularity

The material specification decides the starting point. Hemp and straw are both resources that may stem from cultivation of annual crop plants, hence, have theoretical ability to be a renewable resource over time. The qualitative data, supported by the theoretical framework, clearly suggests that the use of these resources in materials also imply the use of natural mineral resources. Clay and lime are clear examples of minerals either currently used in the same material (hempcrete), or used in the building envelope for a wall (clay plastering, lime plastering). Qualitative data suggests further that alternatives to hempcrete involving hemp and clay as are viewed as especially interesting and positive, referring to resource availability. Minerals are generally considered non-renewable resources; however, material circularity is improved if recycled lime or clay is used in the materials. The qualitative data suggests that it is viewed as circular that the resources for straw insulation and hempcrete are based on waste streams and waste products from other industrial and agricultural production. In addition, the data suggests that these materials avoid the use of hazardous materials. Straw bale insulation and hempcrete does not imply chemical or toxic pretreatments methods. In turn the materials may in theory be composted after its lifetime, which can in turn provide value back to e.g. agriculture and food production. Any waste from repair or maintenance can be composted too. For straw bale insulation and hempcrete the data supports that these materials are seemingly without any pretreatment or chemicals with impairs waste treatment. However, the use of mineral component in the materials and in the way of building impacts the sustainability and renewable aspect of the materials, therein the circularity.

Building design and innovation

Straw insulation and hempcrete are possible as prefabricated products, where the exact market availability is unsure. Wet building of hempcrete results in little waste production but does imply labor hours. Biobased building with mineral materials were talked about as something in which welcomes maintenance, where references were made to extended lifetime, creating job opportunities etc. It is unclear still whether the sort of celebration of being repairable is a general circular notion, or something that is tied specifically to straw bale insulation and hempcrete. However, the data does suggest that this straw insulation and hempcrete circular in that they are part of a building system allowing for repair and maintenance as part of extending its lifetime. Building with straw insulation, hempcrete, with mineral plastering, is highly complementary to the timber way of building. The data does suggest that the use of straw insulation and hempcrete with biobased building practices will contribute to circularity in building projects, as its circular in its design using renewable and regenerative resources.

Building management

A major issue to ensure circularity in building projects relates to the management on site. Huge amounts of waste are generated, simply by overordering materials, in optimal handling of materials and storage and little focus on limiting the generation of waste. Certain waste is worse than others, such as dangerous waste, waste with chemical treatments and mixed waste, where a lot goes to incineration. The theoretical framework suggest that professionals should be employed to ensure material circularity in building management. This point is interesting considering the aspect that in Norway the involvement of architects, typically with a more holistic view of the project, have little say. The data supports that a distinct gap between the design phase and building phase implies a less holistic view on building in general, and less circularity. The architects participating in the research project had clear and specific understanding about circularity and sustainability. Although the data does not suggest clearly that the involvement of architects throughout the building phase and building management, it implies that circularity is aided if professionals focused on this are involved in the building.

The 4-R Framework

With respect to the 4-R framework the qualitative data is in line with the expectations presented in the theoretical data, namely that most of the focus is on the recycling of resources. Even more prevalent is the focus on sorting waste and waste conversion, i.e. irrespective of whether the waste is being recycled or recovered by any means. The data does suggest a shift in focus on just sorting, to waste reduction. A range of approaches to reducing use of resources was mentioned, such as more thorough planning, design for disassembly etc., however, adopting any of these solutions require even more costs in an already low margin industry. Simply put, there are solutions to several circularity issues, but the issue is in which solutions are more easily adoptable. At present circularity concerning reusing is focused on the most expensive or energy intensive materials in existing buildings. Choosing materials that are renewable, recycled, whilst meeting the same technical alternatives as industry standards are easier than changing the way we built. At the same time arguments are made that these need to happen in parallel, to ensure circularity overall and in the long term.

The data further shows that focus on reuse is gaining traction, but that there are a range of practical challenges in seeing this through on a macro level. With respect to mixed waste and various treated materials dispelling changes of recycling, these are generally put to incineration in recycling stations or by other means used in energy recovery. On a micro level business are popping up trying to use certain waste streams, to create a demand for these instead of being incinerated or deposited. However, the data suggests that without better infrastructure or systematic thinking, it will also be hard to attain circularity. Data indicates that measures on meso and macro level are required to enable cycling waste streams, from the building industry but also from other.

The theoretical recovery aspect of composting of straw insulation and hempcrete, also including other natural mineral based materials has been brought up in the data. However, no practical solutions exist as far as the participants know, to be able to compost building materials. To the extent such materials are fully compostable, and all the while the industry have large challenges in changing attitudes regarding view on building new, rehabilitation and demolition, opting to use such materials in buildings could be seen as highly ideal. This is because these resources are implied to be circular in their materiality, and the resources may over time be fully introduced back into the cycle as waste for compost and use in agriculture etc. This is supported by Ellen Macarthur's biological cycle referred to in 2.2.4 and attachment

1. However, this does to a certain extent contradict or at least challenge the waste hierarchy logic in the circular economy and the 4-R framework. However, seeing that the resources in question are either fully (straw insulation) or partly (hempcrete) renewable in their resource use, with a short resource production time frame, it cannot be denied that such a combination contributes to circularity. The building industry seem to be far off adhering to these fundamental circular principles, where a lot of biological matter is being incinerated, causing the resources to leave the resource cycle and release carbon into the atmosphere. The waste hierarchy principles do however still apply for the use of renewable biological resources as building materials, e.g. straw bale insulation and hempcrete, meaning that the lifetime of such materials should be extended however long before compost.

Sub-conclusion

Data indicates more about the way to circular building than providing data on the circularity of straw insulation and hempcrete. Theoretically the data indicates that straw insulation and hempcrete have positive circular impact in building projects, due to being made on renewable resources, potentially waste stream resources and without use of toxic chemicals. Using these insulation materials in biobased building in general seems to aid circularity throughout and allow for repair and maintenance to extend the lifetime of the building. Use of such materials would however not be considered circular if the production is not sustainable, or for sole purpose of producing biomass for producing building materials. Since the materials can be composted, waste from maintenance and after use can be reintroduced into the cycle.

4.3 Research question 3 – Economic viability

Research question 3 investigates the economic aspects which impact straw and hemp-based insulation materials' economic viability, where the results of the qualitative interviews and analysis is presented below.

4.3.1 Cost drivers and externalities

Overall, the participants mention a building industry with low margins, constraint on resources and time. Several aspects drive the costs and influences the market potential for straw and hemp-based insulation.

Production costs

Resource availability determines the costs on biomass, where the availability on biomass is prone to extreme weather and depends on the demand for the main product (for waste stream). E.g. for straw as a waste product of grain production the availability and price will depend on the market for grain. Further to which, hemp is noted as a more expensive biomass, with not too much current availability in Europe (Participant 5). Hemp is currently not available as a local resource in Norway and needs to be imported. Participant 7 mentions the history of increased costs for straw due to availability constraints. Participant 1 has the impression that straw is easily available.

Hemp and straw based insulation materials does not have any rational production in Norway yet. Production costs for fiber-based insulation materials in general are getting lower in for example France and Netherlands, where the impression is that countries based on petroleum in various forms are halting behind (Participant 5). Production costs for hemp and straw insulation could become more competitive if the resources used come from waste streams of existing industry. The production costs depend on the demand for straw and hemp, e.g. demand for biomass in biofuel production (Participant 7). Participant also point at higher production costs due to lack of optimal cultivation and value chain for dispersing and selling any available biomass (Participant 1, 3 and 5).

In terms of the production of hempcrete and straw insulation it referred to as low in energy usage (Participant 1, 3 and 7), where the main components of these insulation materials can be brought straight from the agricultural production. In this regard, lime for use in hempcrete is noted as being energy intensive to produce (Participant 1). To get a material technically verified costs will incur, typically for the material producer (Participant 6). Costs for fire resistance testing etc. are quite expensive, and often its seen that the technical tests and assessments that needs to be carried out are too expensive for smaller and novel businesses selling a novel or innovative building material.

Building costs

Generally, the main cost in the building industry is the material costs and the labor costs. The ratio between the two has seemingly changed in the last five to ten years. For rehabilitation this has shifted from about a 50/50 ratio to more of a 90/10 ratio with labor costs at the top (Participant 2). Participant 4 supports the principle, saying that the materials is the cheaper part of the building action, where the ration is perhaps 65/35 to labor costs for building new.

Overall, the participants say that the margins in the industry are low, with focus on a fast as possible building time to limit labor costs, whilst limiting costs where possible in terms of material costs. Hourly rates for building workers have risen in a different tempo than for materials. This impacts costs in relation to the installation and buildings. Participant 6 mentions that in the time when the material costs were more expensive than labor, we paid more attention to building more appropriately. Referring to the horizontal boards on housing in Vestlandet. "It comes from a time where materials were more expensive than the humans. The time of humans" (Participant 6).

Biobased building costs

With reference to a specific housing project where hempcrete was built in the walls, with CLT load bearing structure, clay plastering, wood outward panels and limited amount of plastics, it is estimated that the biobased way of building costs approx. 30 % more than industry practice (Participant 3). This currently presumes that the builder knows about the materials and how to build, where the inclusion of time consumed in learning and establishing the knowledge sufficient to build would incur more labor costs. Further, biobased buildings require the welcoming of maintenance and repairability, effectively labor costs throughout the lifetime (Participant 3). For houses with hemp and straw insulation machinal ventilation systems are not needed, alleviating fixed costs in the building process, some maintenance aspects and running costs for energy. Participants 3 and 4 indicates that ventilation systems for a house cost about 200 000 – 300 000 Norwegian Kroner, to give gist of the costs involved which may be spared with a biobased house. However, housing without mechanical ventilation may incur a lower energy rating, and further may impact the availability for a "green loan" to reduce capital costs. This is seemingly due to the energy rating system in Norway not appropriately considering the biobased capillary open building (Participant 3). For such a project building cost can be reduced through community-based learning workshops, where the builder receives working hours in exchange of providing knowledge about this way of building. In this example hempcrete, built through wet building on site (Participant 3 and hempcrete workshop).

Externalities

With respect to life cycle costing as mentioned by participants 3 and 6, externalities come into play. Examples are forever chemicals, environmental toxins, plastics and other petrochemical components which don't decompose and release forever chemicals, likely causing health issues in animals and humans (Participant 3). The point the participants were making is that life cycle costing considering the material cost, running and operation costs and perhaps basic waste handling costs, does not consider all “costs” which may be tied to the building materials. They emphasize that to attain circularity, and thereby sustainability, externalities need to somehow be taken into account. Taking an example with impregnated timber, there is added material costs in making the timber impregnated and as such more durable, but in the end, there are added externalities (Participant 6). Reuse of materials reduces carbon costs, depending on the documented effect on carbon footprint (Participant 1). However, participants also state that there is little room for added costs due to circularity and sustainability due to low margins in the industry (Participant 3 and 4). Participant 8 also mentions the ability save carbon costs, with some added material costs. At the same time, they remark that in the current age of higher capital costs (interest rates) their experience is that it is harder to justify acquiring materials with lower carbon costs. Participants see the prospective of stored carbon in biobased materials as an advantage but emphasizes that at present it is not enough (Participant 2, 4, 6 and 8). Straw and hemp-based insulation materials provide positive externalities with aids to indoor air quality and acoustics, low carbon intensive production, no use of toxins, chemicals and stores carbon in buildings.

To handle increased costs for materials that have less externalities participants refer to regulations, taxes and funding schemes. There needs to be something in place that gives incentives to choose more circular, sustainable and healthier solutions, if not it will “come down to the pennies” (Participant 4 and 6). In relation to addressing challenges in getting novel or innovative building materials technically approved they see that the actors are highly dependent on the Norwegian policy implementation system (“virkemiddelapparatet”) (Participant 6).

4.3.2 Collaborative value creation

Major regulatory changes and strategies on national and EU level impact the building industry, in foreseen and unforeseen ways. This implies looking at our relationship to resource use and seeking out collaborative value creating across sectors and industries potential in ensuring economic viability, circularity and sustainability.

Norwegian bioeconomy

The prospective use of hemp in the Norwegian bioeconomy is not new according to participant 3, who further refers to 200-hundred-year-old guides about growing hemp to be a self-sufficient farmer. Participant 7 states that we have cultivated hemp for thousands of years in Norway. Participant also says: "*And it has been a long tradition, until one started importing synthetic fibers",* and further connecting the end of cultivation of industrial hemp with making cannabis illegal. Both participants are implying that hemp has been part of farm economies and farm thinking in Norway for a long time. Participant 3 envisions that the cultivation of hemp can be used in agroforestry, referring to the soil remediation properties of hemp. Possibly also the cultivation of grain (straw), although with some uncertainty. For agricultural purposes hemp can be grown in shoulder season or in a fallow season (Participant 3). The critique against hemp cultivation in Norway is the amount of available arable land. However, in theory hemp can be grown in all kinds of landscapes in Norway, not just on agriculturally terraformed landscapes (referring to arable lands and similar). In addition to the infrastructure in terms of policing, harvesting and processing it, resulting in such growth not being economically viable in Norway (Participant 3). Participant 5 argues that the availability today of hemp in volumes in Europe is too little to be able to sustain large scale industrial use of the resource.

With limited arable land in Norway the qualitative data does suggest challenging where one could grow hemp in Norway, and by which practices. Referring to non-arable land growth and using soil remediation properties in hemp to aid sustainable agricultural production and extraction. The critique about hemp being a non-viable option (at least in Norway) is made is within the "walls of industrial agriculture" (Informant 3), implying cultivating a single crop on a flat piece of land. In their view hemp is interesting, but not as a competing crop to grain (straw), but as part of an agricultural revolution. A revolution involving moving away from artificial fertilizers, monocropping, terraforming and tillage. This also translates to forestry where we need to seek solutions to avoid depleting the natural capital of our forests (Participant 3 and 7).

Existing waste streams

Participant 1 mentions to tread carefully in indicating what resources we are in abundance of, pointing to the history of humans depleting resources. The participant goes further to indicate that their impression is that straw is an available resource since it is a waste product of grain production without current major areas of use, referring to the straw bales lying on fields and plains around in Norway. They referred to older practice of plowing the straw into the soil. There have been attempts in agriculture to use straw in or as animal feed and store it in silos during dry summers. Straw is also used in stables and hen houses, although the volumes are limited. Participant 3 supports this, generally, saying that industrial agriculture produces large amounts of straw. Typically, through monocropping of land areas. Further adding that unused straw is typically burnt since there is too much of it, without any apparent areas for use. Participant 7 is more critical to straw as a building material resource, due to the way the grain production is being operated and run. The focus on fast growing grain and use of artificial fertilizers is raised as a reason. In addition, the participant refers to Denmark having abundance of straw and closer relationship to using straw in building materials, pointing out that the Norwegian climate is wetter. This combined with attempting to grow the best grain type for Norwegian conditions and its wet climate, results in straw types with shorter lengths. According to the participant this results in challenges in producing straw bales, due to the shorter length. They also mention the challenge with straw as a waste product is availability, its highly dependent on the grain production, and refers to historical points in time where drought have caused significant decrease in the availability.

4.3.3 Market for biobased materials

A range of aspects affecting the market for biobased materials has been identified and scrutinized in the qualitative data.

Attitudes

The participants mentions that the price and technical function is of the utmost importance, far beyond sustainable, circular and biobased interests due to low economical margins. Generally, long lasting durable materials are demanded (Participant 4 and 6) throughout the market and has been a trend for some time. There is some demand for high quality products, but the market is not too big for this (Participant 4). We have been taught that things are supposed to be polished, smooth and clean (Participant 7).

Some stigma has probably been related to low carbon plant-based materials, however, at present interest increasing a lot (Participant 1, 3, 7 and 8). Reference is made to various forums in architecture where these materials have been spoken about a lot (Participant 1 and 7). Participant 8 also mentions a seminar referring to these types of materials. Change in attitude is anticipated going forward, however, a challenge is that interest is not enough. Architects have seemingly for long been interested, but the technical jurisdiction of the industry are more skeptical or constraint. Due to wanting to build with materials that are familiar, that one knows and understands. A hypothetical example is that for an experienced engineer that has been in the industry for a long time, it is hard to get them to build with hemp (Participant 1). This notion is supported by others, stating that it is scary to use “novel” or unfamiliar materials because you need time to understand how they act over time, to be able to mitigate and limit risk involved. They describe the change in attitudes in the building industry as slow, but that there is a precautionary aspect behind it, and not just the industry being traditional.

Customer interests

Participant 5 talks about a shift in the interest and attitudes in the market, referring to Netherlands, Germany and Belgium. Mentioning a shift from concrete to timber building, and then now from fossil-based building to biobased building. The participants have throughout the interview mentioned that there is some interest in biobased materials, sustainable options, circular thinking and local materials, especially for building materials based on annual growth resources (Participant 1). Interest in carbon storage is due to regulations, requiring and demanding environmentally friendly, sustainable and circular (Participant 4, 6). Participant 8 mentions that circular economy is on the top of the agenda and in focus, likely caused by the EU taxonomy and circular economy being a prioritized area. At the same time, they mention that the focus on biobased materials falls on the outside. Participant 2 mentions that in winning contract award that environmental and sustainability considerations are valued more, albeit somewhat unspecific. They get a score on environmental and sustainability. This is because of the value-added aspects. However, the willingness to pay is at present low. Participant 5 argues that in the long-term choosing the right materials albeit a bit more expensive will be worth it, because your house is not built off troublesome materials.

For biobased building materials specifically the notion of having better indoor air quality, avoiding having materials with toxic chemicals and sustainability are the relevant value-added factors. Essentially having healthier buildings (Participant 3 and 7). There is also value added in using local resources, meaning local jobs, to produce the building materials. (Participant 1, 3, 5 and 7).

Knowledge

Despite interests in the market for more sustainable and circular building materials, one needs to know about the materials (Participant 5). What is on the market, what can it be used for, etc. Several participants refer to our neighboring countries Denmark and Sweden, referring to what seems to be a larger and more diverse range of biobased products in wholesale material sellers and network of vendors (Participant 3, 4 and 7). At the same time there is a sense with the participants that material availability is increasing in Norway for biobased and mineral building materials. In terms of costs and uncertainties the participants mention that materials in which are known to them are easier to budget, because they are more accurately aware of the risk involved for the materials and potential added costs. Participants indicates hesitancy in using materials that are unfamiliar, because of the higher risk.

With reference to trust in material performance, building materials that have in place authorized technical testing results, technical documentation, certification or meeting certain standards, are the preferred choice. However, Participant 6 details that testing of various performance factors is not necessarily cheap. The actual cost for getting a building material depends on the intended use, and appropriate testing. However, it is viewed as expensive, especially for novel businesses with low liquidity.

Circular business cases

Participants 1, 6, 7 and 8 mentions a pilot project in Oslo, KA13, which piloted reusing materials in the entire building. The project was piloted by MAD Architects to create a building with fully reused components, and lesser focus on the price tag for such a focus. (Participant 6 her). Participant 8 mentions that for us to build with more biobased materials "people" would want to go and see it, feel it, and points to a lack of examples for buildings with hemp and straw insulation materials. The building industry needs that someone has tried the building material out, tested it, developed it and scrutinized the production process to save costs. Someone needs to walk the line first. This is not necessarily related to using novel or innovative materials, but creating a demand for materials in which does not have recent history of being used or building in new ways (Participant 5 and 7). Participant 6 mentions an enterprise model for the development of a project in Trondheim, the SEB-laboratory. The enterprise model is called Samspillenterprise ("Interaction Enterprise") and builds on the notion that the actors related to the drawing, designing, engineering and building enter one enterprise together. This involves that all actors are equally responsible and liable to ensure appropriate costs throughout the project, and in this instance also focus on energy efficiency and carbon footprint. Exceeded costs in the building will for example not just be borne by the builder, but by all actors in the enterprise. They view this as a key aspect in attaining low carbon footprint and optimal solutions (e.g. circular solutions) in the building industry. Participant 7 also argues that one needs to consider the entire value chain for such projects.

The ones that draw, engineer and build the buildings needs to account for the entirety, to create circular supply and demand. Closing the loops as participant 5 would say.

4.3.4 Discussion – RQ3

The analyzed data suggest clear factors influencing the economic viability of straw and hemp-based insulation materials in the building industry. However, with the challenges, opportunities lie. The discussion of the analyzed data can be found below.

Production costs

The data indicates that straw insulation and hempcrete have low production costs, in cases where the waste resource allocation is optimal creating a rational production process. The data suggests that historical use of straw and hemp in buildings has been due to local availability, focusing more on local resource availability and economics than focus on material performance and environmental factors compared to other building alternatives. Biomass resource availability and value chain affects supply of hempcrete and straw insulation, and at present the data suggests it is not streamlined and therefore no rational production is possible yet. This is due to non-existent of inefficient infrastructure in the value chain. The price of biomass (production resource) steers the overall costs for the building materials, causing higher relative costs compared to alternatives. However, the data does suggest that when the value chain for resource allocation is developed, production costs are considered low and an advantage for such materials. Straw insulation is "just" straw, where hempcrete can be mixed on site. The data and theoretical framework support that straw bale and hempcrete require low degree of processing and treatment, where processing is concerned with lime in hempcrete.

Building costs

The building industry has low margins, driven by high costs on labor. The data does not suggest that these materials are any easier to build with or require lower building costs as such than its alternatives. Furthermore, the data does indicate that its overall more expensive to build with straw insulation and hempcrete in biobased building practices. However, the data does not identify whether this is due to costs for these exact materials, or if it is related to costs relating to the biobased or capillary open logic. Furthermore, the data does support that a biobased building with straw insulation or hempcrete does alleviate costs for ventilation systems. This saves costs in building and costs throughout lifetime concerning maintenance and energy usage. Overall, there is little data providing any estimations on the overall added costs, but for one specific project the added costs was estimated to be 30 % more due this way of building. This was in a case of hempcrete, where the hemp was imported and built through wet building on site. Community based building was also suggested as a way to reduce costs, especially prior to builders being familiar with using and building with the materials.

Supply of biomass

Qualitative data suggests that there are added benefits in emphasizing the relationship between agriculture and agroforestry for the straw and hemp. This can ensure the availability of biomass for material production. Straw as a waste product is likely more due to grain production being established. Whereas the hemp cultivation at present is low and non-existent in Norway where industrial hemp is illegal. In a Norwegian context the extent of resource availability of straw from grain production remains uncertain, also how the type of straw available here performs specifically as insulation. Hempcrete is at present as such not a viable option in terms of local resources at present, seeing it is illegal to cultivate. However, the data does support that there are opportunities developing value chain for appropriate resource production. Henceforth potentially enabling larger scale production of such materials in Norway. Whereby the opportunities apply for both the agricultural and agroforestry industry, and the building industry. The cross sectoral and industrial aspect is highly supported and promoted by the Norwegian strategies for circular economy and bioeconomy as mentioned in section 2.3.1. Policy implementation systems put in place to promote such collaboration providing funding or similar can increase lower the resource availability and costs for production, increasing the competitivity of both straw insulation and hempcrete as examples.

Market demand

Although, there is not enough data to indicate the customer segment for straw and hemp insulation, the data does indicate that it at least concerns customers raising a residential building or cabin. Overall, the participants indicate a limited market for biobased building and therein straw and hemp-based building materials. There is high demand for durable long-lasting materials without need for maintenance. However, its recognized to have very big possibilities long term where there is increasing interest in the last 5 years. Especially amongst architects in the building industry sitting with the initial design of buildings. Currently, there is little established knowledge and awareness for these types of materials and how to use them and also limited availability. As discussed in 4.1 the data and theoretical framework indicates that the building materials are viable substitutes for certain materials or ways of building. However, due to the seeming lack of having technical testing and standard verifications in place, these materials are likely not actual substitutes. On a micro level business are practically required to get their straw or hemp insulation material tested for various performance factors, in order to get the verification and documentation in place. This increases the threshold for entering the market early on and is a barrier.

For those potential customers that are aware of the materials, the increased costs for these materials impairs demand. However, the interest for straw insulation and hempcrete relates to aspects which addresses negative externalities concerning the building industry, e.g. low carbon intensity, carbon storage, no toxins and chemicals, indoor air quality etc. This is an opportunity for these materials, however, contingent on regulation or other means giving potential buyers an incentive to opt for such materials. The EU Taxonomy will have major impact on the building industry, all though not quite yet clear how it will play out and exactly when. There is however no doubt that materials that do meet the EU Taxonomy's requirements for circularity and sustainability, will become more sought after. This will drive demand in the market for materials with positive externalities, and lower demand for materials with negative externalities. At present the effects of the EU Taxonomy and other regulation is not easily perceived, but it is expected with assurance that the effects will come, shifting the demand in the market towards sustainable and circular solutions.

Sector and industry collaboration

With a limited market for straw insulation and hempcrete in the Norwegian market the data provides some basis for approaches in which may create a larger market for such materials. The enterprise model where the risk and benefit lie with all relevant actors for the building process seems like an interesting approach to ensuring an overview over a project, not just from a circular perspective, but economically and for its sustainability. If such a project were to involve straw insulation or hempcrete, it could act as a pilot project to drive some demand for these resources and these materials. Such a business model seems very much in line with Norway's strategy in promoting economic growth, more sustainable and environmental production and building, whilst reducing the footprint for a range of factors.

In addition, the Norwegian strategies for circular economy and bioeconomy promotes collaboration between sectors and industries. Seeing that Norway already has an established timber industry, promoting biobased insulation materials based on waste streams is highly symbiotic to established value chains and building practices for this industry. Whilst also potentially collaborating with the agricultural and forestry sectors for diverging waste streams to production. In theory it seems like the exact industrial symbiotic collaboration that the strategies clearly promote and wants.

The use of pilot projects in an early stage can address many of the barriers for straw and hemp insulation. Pilot projects utilizing these materials can address the lack of knowledge and familiarity builders has for these materials, whilst also ensuring testing and verification of their performance. This implies however an owner or builder who can disregard the added costs and uncertainties, with incentives to do such a project. Such a project could also use community-based building to share knowledge at large with students, builders etc. who wants to learn more, whilst reducing costs at the same time. Opportunities lie in small scale pilot projects, where companies can do this as a corporate social responsibility project, or for customers who are willing to pay significantly more for a circular and sustainable house or cabin.

Sub-conclusion

The data identifies that the prospective of profitability of straw insulation and hempcrete in the Norwegian market is challenged by unfamiliarity and lack of trust in the materials, with challenges in the value chain causing challenges in costs and availability. The costs in relation to the materials are uncertain, but the data seems to suggest a possible competitive advantage in low production costs if waste streams are appropriately allocated from agriculture to material producers. However, there is clear need for official testing and validation of the material performance before such materials can enter the market in practice and at scale. With the EU taxonomy and Norwegian strategies adjusting the market for negative externalities and promoting positive externalities, the market demand for materials such as straw insulation and hempcrete is likely to increase. Overall, the data suggests that collaboration with agriculture will aid in lower costs for straw bale insulation and hempcrete, where current and coming regulation promotes such cross-industry collaboration. An approach to entering the market at present can be through pilot projects showcasing the materials and the way of building, combined with leaning on cross industrial cooperation with agriculture. Suggested as an opportune way to address the main factors impeding its profitability and viability in the current market.

5. Overall discussion

The aim of the research for this thesis paper was to begin investigating how straw and hemp insulation materials may contribute to a more circular building industry and its economic viability. Subject of the research has been straw and hemp, seeking to enlighten how these plant biomasses do as building materials, how do they perform in the circular economy and how do they perform in the building industry economically.

5.1 Reasons for use of analytical tool

Essentially the research has resulted in analyzing the strengths, weaknesses, opportunities and threats concerning biobased building materials in Norway, either using straw bale or hempcrete as insulation materials. The reasons why and necessary clarification for the SWOT-analysis is included in this subsection.

5.1.1 Reasons for use of SWOT

The SWOT analysis is a known analytical tool used to identify key factors affecting an organization and markets (Hooley et al., 2017). Through looking at the strengths and weaknesses for the organization being the internal sphere, together with opportunities and threats being the external sphere, the SWOT analysis aids developing a strategy to achieve its intended goals. Practically speaking SWOT has a range of pragmatic and practical uses, not just for analyzing an organization, but also a product, material or building projects. Its advantage as an analytical tool for the purpose of this thesis project is holistic and insightful mapping of findings and sub conclusions concerning the research questions, to the overarching problem statement of the thesis.

5.1.2 Internal and external

The SWOT concerns aspects on the internal and external level. For the overall analysis and discussion. With reference to the value chain elaborated under 2.3.4 the internal level concerns aspects to the biomass of straw and hemp building materials relevant from the perspective of the material producers, designers and builders at micro level. This is in line with the type of participants included in the conducted study. The external level concerns aspects and factors pertaining to straw and hemp building materials from the building industry at large, and governmental level at national and European Union level (meso and macro level).

The distinction made is to focus the strengths and weaknesses on the aspects which closely concern straw and hemp as biomass, and their use as insulation materials and how these perform from a technical, circular and economical perspective at micro level. Whilst factors affecting the micro level, such as the building industry at large, governmental regulation etc. are kept in the external level.

5.2 SWOT-analysis

The SWOT-analysis and its elements is presented below, discussing the strengths, weaknesses for straw and hemp insulation materials from the perspective of material producers, building designer (architects) and builders, and the opportunities and threats in the context of the building industry at large and governmental strategies and regulation.

5.2.1 Strengths

Straw and hemp are both annual crop plants with embodied carbon, meaning fast growth and as such counts as a renewable resource. The renewable resource may come from waste streams from food production or hemp cultivation in agriculture, and any use of the resource prolongs the storage of carbon throughout its lifetime. In the material palette possible from straw and hemp, there is strong indications that these perform particularly well as insulation materials due to their hygroscopicity and porosity. Being innate characteristics of the biomass, making them suitable for use in or as building materials. Their acoustic properties and contribution to indoor air quality stands out as strengths compared to alternative materials. Hempcrete seems to perform somewhat more optimal in terms of temperature control due to its mineral component impacting the heat conductivity in combination with the biomass. The use of a renewable resource for building materials are free or low in toxins and chemicals, since its either fully biological or combined with naturally occurring minerals and water. As a result, the building materials are considered theoretically fully compostable. There is strength in a material challenging the notion of downcycling. Research shows that both insulation materials, in a biobased capillary open way of building, generally perform satisfactory in terms of a range of technical requirements. Housing built this way with either material does not need a mechanical ventilation system and acts as a carbon storage throughout its lifetime.

5.2.2 Weaknesses

The fact that the insulation materials are made of biomass makes them prone to molding and rot if moisture gets trapped, or to collection or long-term exposure of water. Generally, the dependency straw and hemp insulation have for a certain way of building, either capillary open or biobased, may pose challenges since this is not seemingly known for builders in Norway. The further dependency on minerals, as nonrenewable resources. For hempcrete specifically the lime component of the product can be viewed as a weakness due to it being an energy intensive material and related industry. The use of clay was viewed as a better alternative for hemp use, at least worth conducting more research into. Clay is less energy intensive as a resource, and indicated to be in some abundance, however, it is still a non-renewable resource and a weakness (although with some hesitancy). In terms of their circularity the research provides weak evidence to indicate whether these materials are easier to repair, maintain or long-lasting than other materials. Considering current focus and demand for longevity and durable materials, this is considered a weakness. The costs involved with straw bale insulation and hempcrete is at present viewed as costly, with low willingness to pay in general for sustainable, circular or healthier materials.

5.2.3 Opportunities

Building materials can be cultivated through food production and fiber production in agriculture, where there are identified opportunities in connecting and strengthening agriculture to the value chain of material production and use. From a Norwegian perspective the biobased way of building is opportune due to the existing and established timber industry and seen as highly complementary to each other in creating a material palette and potentially fully biobased buildings. The research does indicate that the biobased capillary open way of building generally is a building logic which synergizes with repair and maintenance and thus an extended lifetime. Should changes in the attitudes and labor costs support such a focus in the industry at large, the biobased way of building will provide opportunities. Circularity can be aided in the use of professionals on material circularity throughout the building phase. The research clearly indicates increased interest in materials such as straw insulation and hempcrete, and the biobased way of building. In Norway there seem to be opportunity in involving architects throughout or farther into the building process, as they typically are naturally affiliated with material knowledge and competency and can weigh in on decision making together with engineers, consultants and builders. The actors in the industry are also aware and targeted by regulation and other policy implementation systems, such as the EU

Taxonomy and Norwegian strategies on circular economy and bioeconomy. Regulation and systems meant to incentivize sustainable, environmental and circular solutions at large. By promoting positive externalities, whilst demoting negative externalities, the market should shift towards interest in building materials with low carbon footprint, sustainable production, contributing to healthier indoor environments. Therefore, representing major opportunities for straw bale insulation and hempcrete, due to positive externalities and its potential in sustainable production of resources for material production through agriculture. Actors in the industry recognize various pilot project's value in spreading knowledge and providing valuable experience for the industry and its actors at large. At present such projects can contribute to making straw and hemp insulation materials more known and familiar, for builders to understand and trust them when used in buildings, whilst also already now start to address the lack of technical approvals and testing through existing or coming funding schemes.

5.2.4 Threats

Although straw bale insulation is somewhat known in a historical context, modern day use the insulation material and hempcrete is seemingly essentially totally unfamiliar to builders and the industry at large. The industry is heavily reliant on standardized approvals and testing of materials, or hands on experience over time with the materials and their performance. These aspects are important and reasoned in safety and health for the buildings in which we live in and surrounds ourselves with. The lack of familiarity, experience and documented technical performance for these materials, and the capillary open way of building, is a major threat for these materials. Further emphasized by added costs involved in carrying out technical testing, research and development. In addition, the data seems to suggest that even though some technical testing has occurred with documentation, actual and discretionary experience with and trust in their performance is key for the contractor or builder when choosing the materiality of a building. Research suggest that sorting of composting resources do not yet occur, whilst recycling stations have yet to accept compost from building materials. There is also currently no current infrastructure for the collection and distribution for recycled mineral lime and clay. The building industry is considered economically constraint at present, impacting the transition towards sustainable and circular solutions. High labor costs push the industry in a maintenance free direction instead of allowing maintenance and repair for extended lifetime. For hempcrete specifically, the fact that cultivation of industrial hemp is illegal with no indications of it changing any time soon, and Norway's limited arable land and lack of infrastructure for non-arable farming at large scale, makes hempcrete a non-local alternative. This does impact some of the considerations for hempcrete at large from a Norwegian perspective, especially at present.

5.2.5 Visual representation of SWOT analysis

A summary of the SWOT-analysis has been visually presented in figure 8.

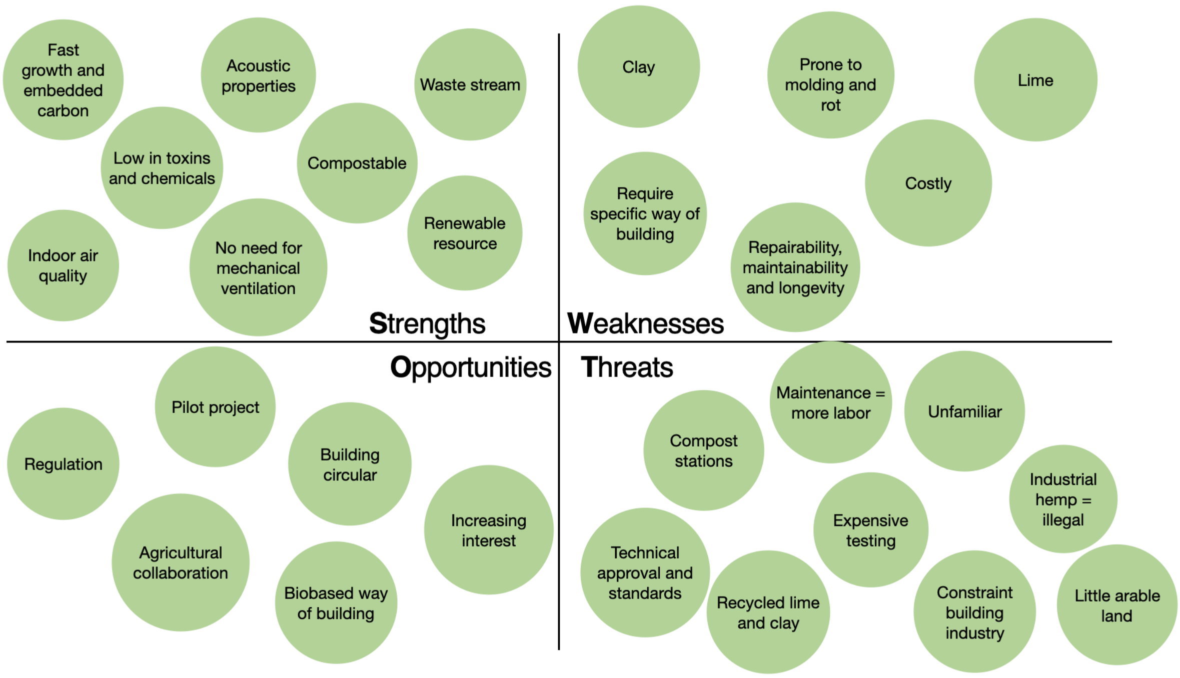

Figure 6: SWOT presentation of findings

5.3 Evaluation of SWOT

The strengths and opportunities indicate biobased materials' competitive advantages, whereas the weaknesses and threats indicate the biobased materials' risk in the building industry.

5.3.1 Competitive advantage

Straw and hemp insulation materials offer a competitive edge due to their renewable nature and environmental benefits. They grow quickly, possibly based on waste from agriculture and food production, and are ideal for insulation due to their natural properties like hygroscopicity and porosity. Hempcrete, for example, excels in thermal performance thanks to its mineral content. These are too produced without toxins, compostable – overall aligning with circular economy principles. With the current focus circular economy and sustainability on European and national level, there are advantages in the strengths for straw and hemp insulation. Large regulatory systems are also promoting products based on waste streams, and also those who spur cross-sectoral or industry collaboration. One industry can lean on another, to create a complex local bioeconomy with a bioeconomic circular value chain. Engaging architects and actors in the industry in pilot projects helps build trust and understanding, addressing challenges such as regulatory approvals. Overall, straw and hemp present a sustainable, high-performance alternative for standard insulation materials, with large potential to meet growing demand for environmentally friendly, sustainable and circular building materials.

5.3.2 Risk

Use of straw and hemp in buildings faces significant risks for builders. These materials are susceptible to issues such as molding and rotting if exposed to moisture, which requires a specific way of building with capillary open logic. Builders in Norway are seemingly unfamiliar with this specific building logic, complicating their use of straw and hemp insulation since they do not know their performance. The lack of standard approvals and testing for these materials further impairs their acceptance as viable building materials in the building industry. Builders rely heavily on documented material performance, making the unfamiliarity and viewed risks for using straw or hemp insulation solutions a significant barrier. The absence of infrastructure for composting building materials and recycling of essential components like mineral lime and clay amplifies these challenges. The biobased way of buildings reliance on lime and clay makes the solutions more vulnerable. Additionally, hempcrete's reliance on lime, adds to its production costs and environmental footprint. Concerns also arise regarding the circularity of these materials, how easy are they to repair or maintain compared to traditional alternatives. High costs and limited willingness to pay for sustainable or circular materials in the current market context pose additional risks in developing and opting for straw and hemp insulation in buildings. The regulatory constraint on industrial hemp impairs several of the competitive aspects hempcrete, and also further the aspect of limited arable land should industrial hemp become legal. This limits the ability of local production, increases dependency on import of hemp, impacting the viability of hempcrete as a local circular and sustainable solution.

5.3.3 Overall evaluation

When taking into consideration the competitive advantage and risks involved with choosing straw or hemp insulation in buildings there are at present significant risks and barriers. Also considering that rational production and likely appropriate availability of materials require Essentially making these materials require volumes of waste streams, where the existing value chain for such allocation is lacking or far from optimal. In combination, straw and hemp insulation materials are essentially non-viable in Norway at present, unless for very niche projects, such as environmentally friendly houses, cabins, or pilot projects spearheaded and funded by major companies or institutions. However, conscious of major regulatory measures, it is clear that the building industry must address its environmental issues by employing sustainable and circular practices. spearheaded and funded by major companies or institutions. A major challenge impairing the materials' viability is the sound need for technically verified and documented testing of various performance factors in accordance to industry standard and technical regulation. However, conscious of major regulatory measures, it is without doubt building industry must address its environmental issues by employing sustainable and circular practices. The aspects of straw and hemp insulation which does contribute to circularity in the building industry, combined with the possibility for cross-sectional collaboration, seems to be exactly the type of value creation that the regulatory measures want to promote.

6. Conclusion

This chapter summarizes the research study providing a conclusion on the conducted explorative thematic study, its implications and suggestions for further study.

6.1 Answer to problem statement

Straw and hemp insulation materials shows clear potential for aid to circularity, and in practice shows promise for economic viability to realize the circular contribution. This is due to the use of straw and hemp as renewable resources that may theoretically come from waste streams of agricultural food and fiber production. The insulation materials of these resources act as temporary carbon storage in buildings, which lifetime can be extended through maintenance and repair which produces only compostable waste. The materials themselves can also be composted after its use, if they are not reused in any way or form. However, the use of these materials presumes a specific way of building which is amicably unfamiliar to the Norwegian industry. The unfamiliarity and lack of verified and documented technical testing and performance, impairs builders trust in their performance and in practice makes them non-viable substitutes. This poses a barrier for these materials, and their way of building, to contribute to a circular industry in Norway in practice. Despite the barriers for scale, the research study does suggest that pilot projects, and other niche circular or sustainable projects, are at present seen as viable buildings projects for straw and hemp insulation. Such projects are suggested as an approach to address the threats and weaknesses of straw and hemp insulation, by showcasing the materials in practice and document their technical performance. In sum this exploratory case study argues that there is promising potential in straw and hemp insulation materials' contribution to a circular and economically viable building industry.

6.2 Implications of the study

Theoretically the research study confirms that straw and hemp generally are suitable for use in building materials, especially as insulation materials. In addition, to consider using straw and hemp insulation in buildings one essentially needs to consider opting for a biobased building as a concept. The fact that needs for testing documentation impairs the materials' viability can inform policy makers to realize that funding schemes or similar must address the financial barrier for businesses trying to enter the market with novel sustainable materials to aid the shift towards a circular and sustainable economy. The findings of the research have most prominently holistic implications for the industry and supports challenging fundamental principles about pretreatment of materials to be maintenance free, or to cultivate building materials through agriculture. The weakness of the study lies with the low number of participants, a broad theme as the case for the explorative study, and without any iterations in the interview process. The results are based on a scattered data set, and thereby conceptual and indicatory. The findings from the research study should be treated in accordance with the nature of an exploratory case study and this research study's weaknesses.

6.3 Suggestion for further research

The research study conducted suggests several areas of further research. Firstly, mapping of available biomass waste streams from Norwegian agriculture, to be used in analyzing what secondary resources are available for use in production of for example building materials. Research could also investigate and assess the potential of using biomass from aquaculture, such as seaweed, for use as building materials. The study indicates that sustainability and circularity imply sustainable production and availability, thus, a more comprehensive and holistic mapping of available secondary resources in Norway, and their best areas of use could aid the transition to a more circular economy. For hempcrete specifically further research can involve assessing the appropriate mixture of fiber and lime for the Nordic or Norwegian climate, and the effects of substituting lime with clay on its performance as a building material. Further research should be made into capillary open building logic in the context of Norway, and how our energy rating system and perhaps other standards and certifications may not appropriately consider or rate solutions involving biobased building materials.

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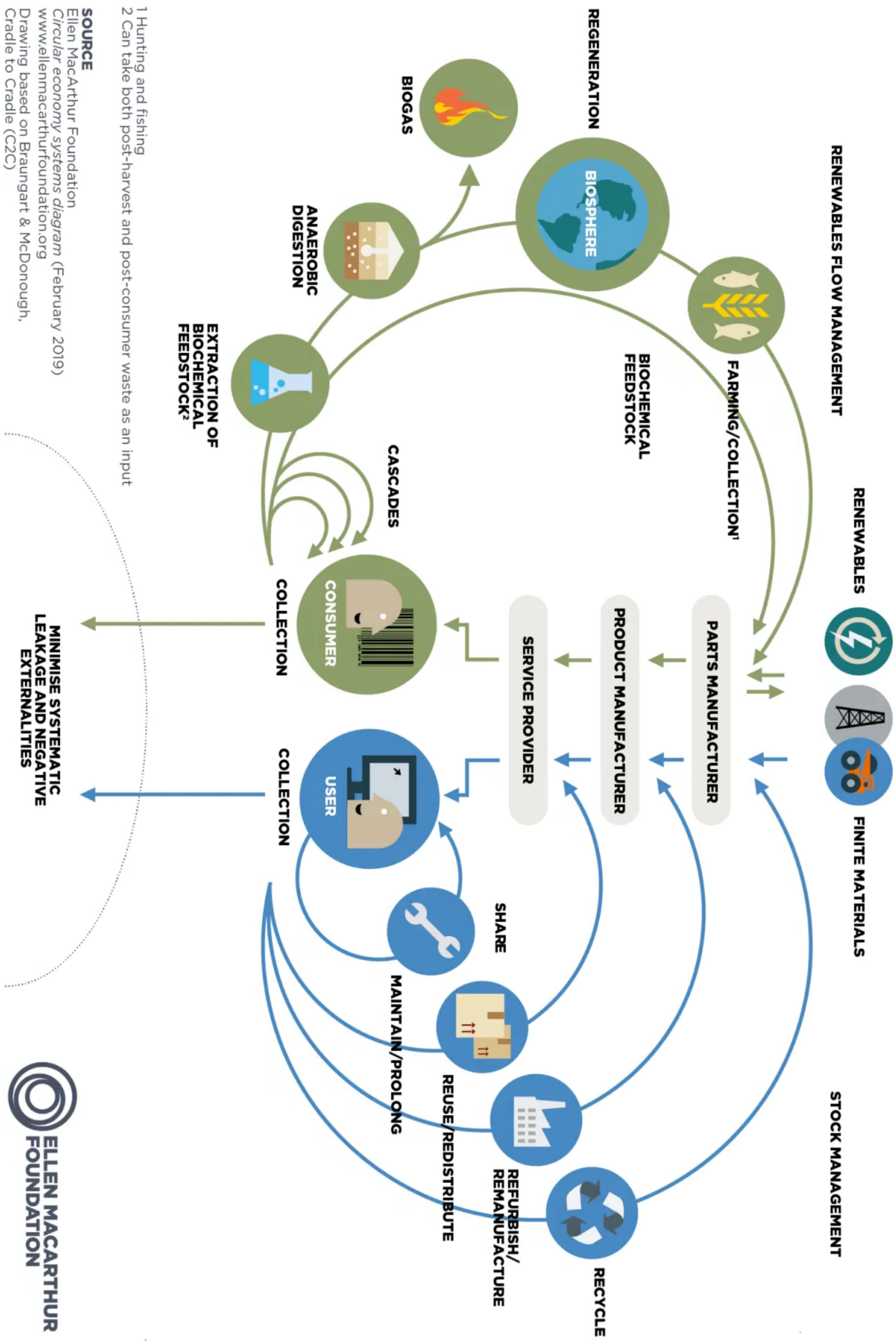
Attachment 1



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Attachment 2

Interview Guide

Problem statement: How can biobased building materials contribute to a more circular and profitable construction industry?

Introductory questions:

- What is you educational or business background?
- Can you describe how you view the challenges and opportunities in the building industry concerning the transition to a circular economy?
- Please describe your knowledge with biobased materials, specifically based on hemp or straw.

Research Question 1: How suitable is biomass for use as building materials, and what materials can be made?

- 1.A – How suitable is biomass as materials?
- 1.B – What materials can be made from biomass and what are they used for?

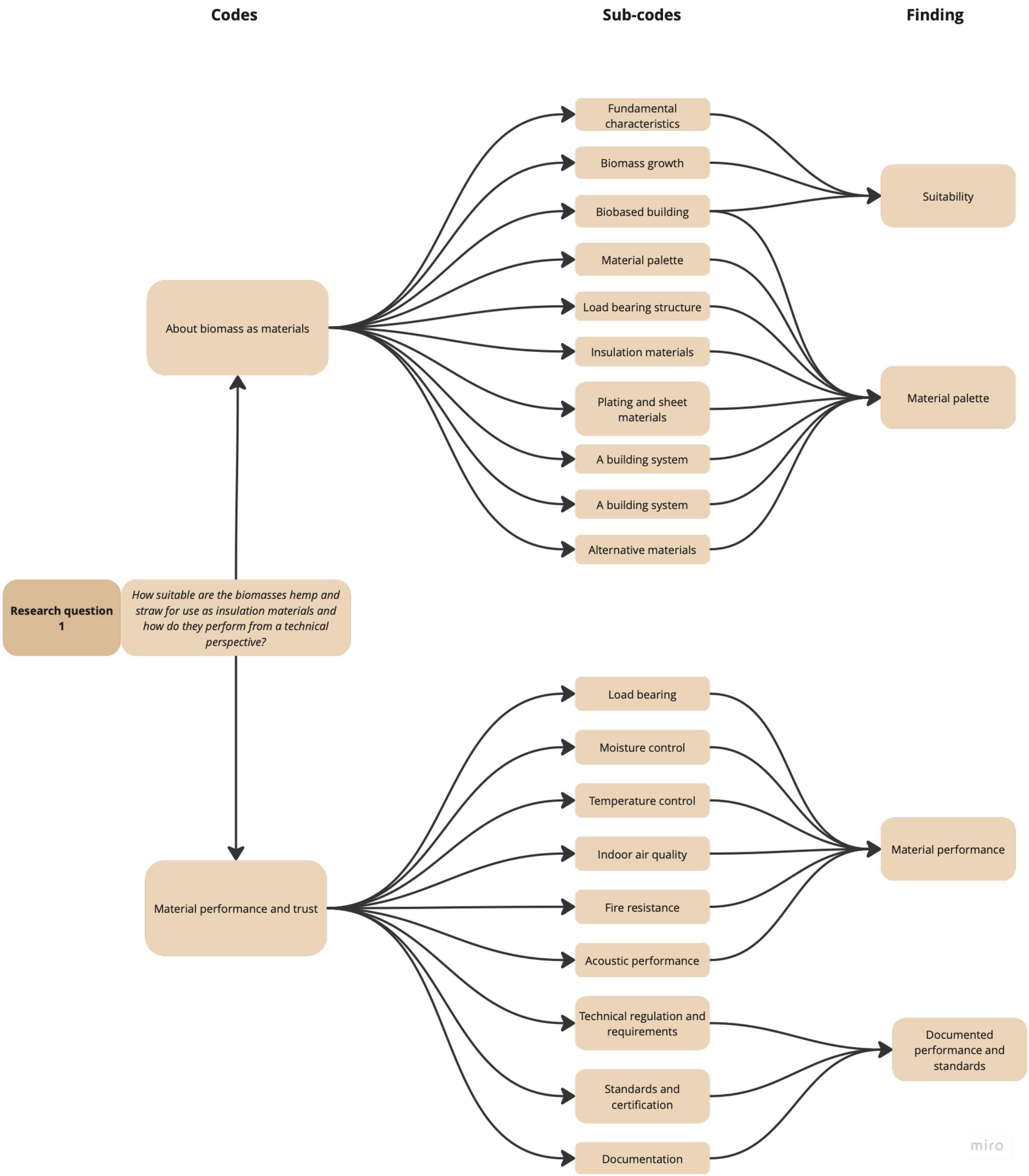
Research Question 2: How to ensure circularity ensure in construction projects regarding material use?

- 2.A What is important to reduce material use?
- 2.B What aspects of materials are important regarding maintenance and repair, and what should be avoided?
- 2.C What opportunities exist for the reuse of building materials, and what is needed for it to happen in practice?
- 2.D What is important regarding waste reduction?
- 2.E What is important for ensuring good and efficient waste management?

Research Question 3: Describe the costs associated with building materials made from plants (hemp/straw) and their profitability and competitiveness.

- 3.A Costs: How would you describe the costs associated with building materials based on plants (straw/hemp)?
- 3.B What is the market like for such materials?
- 3.C What is the competitiveness of such materials, and any other so-called sustainable, circular, or "green" materials?

Attachment 3



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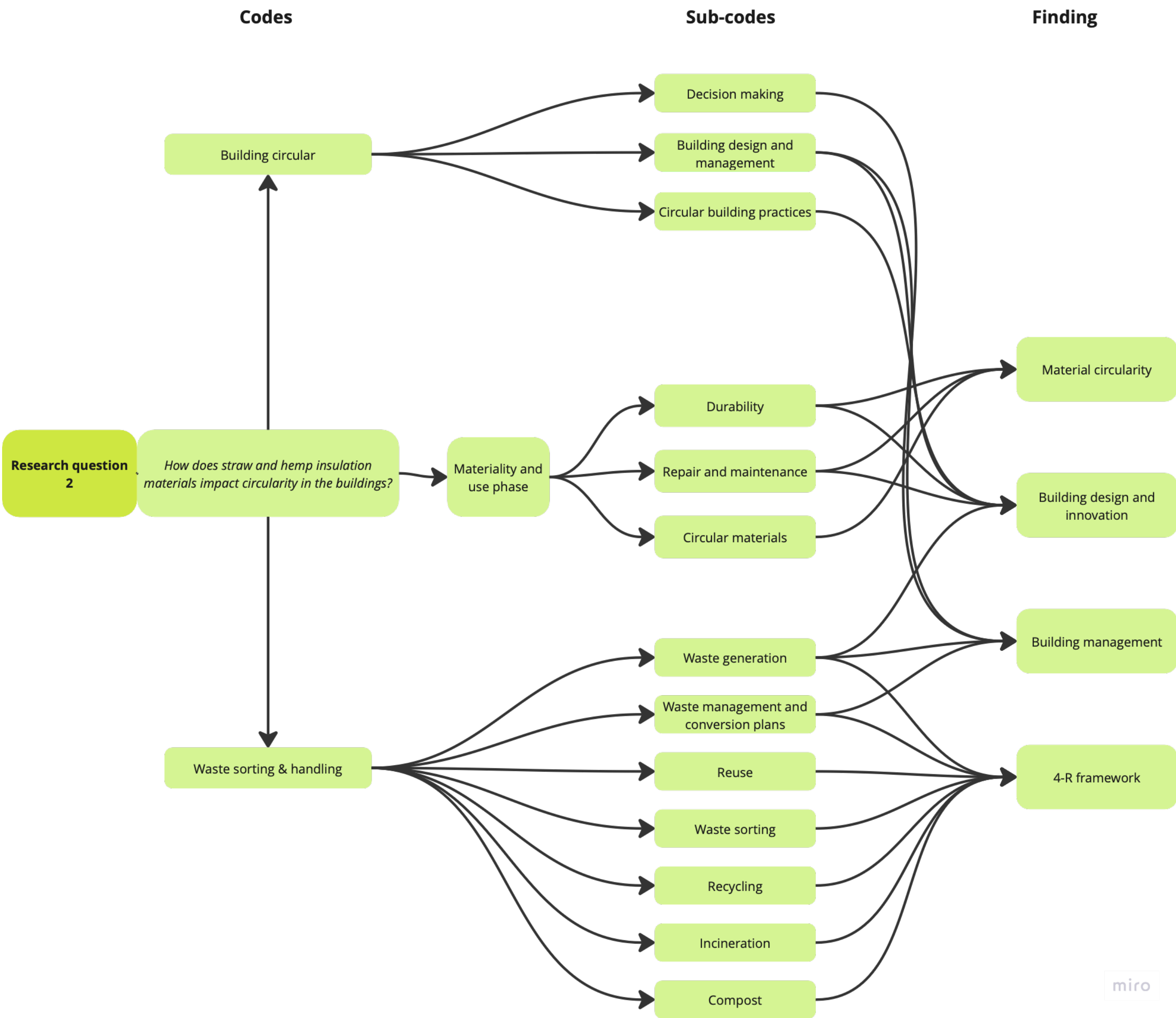

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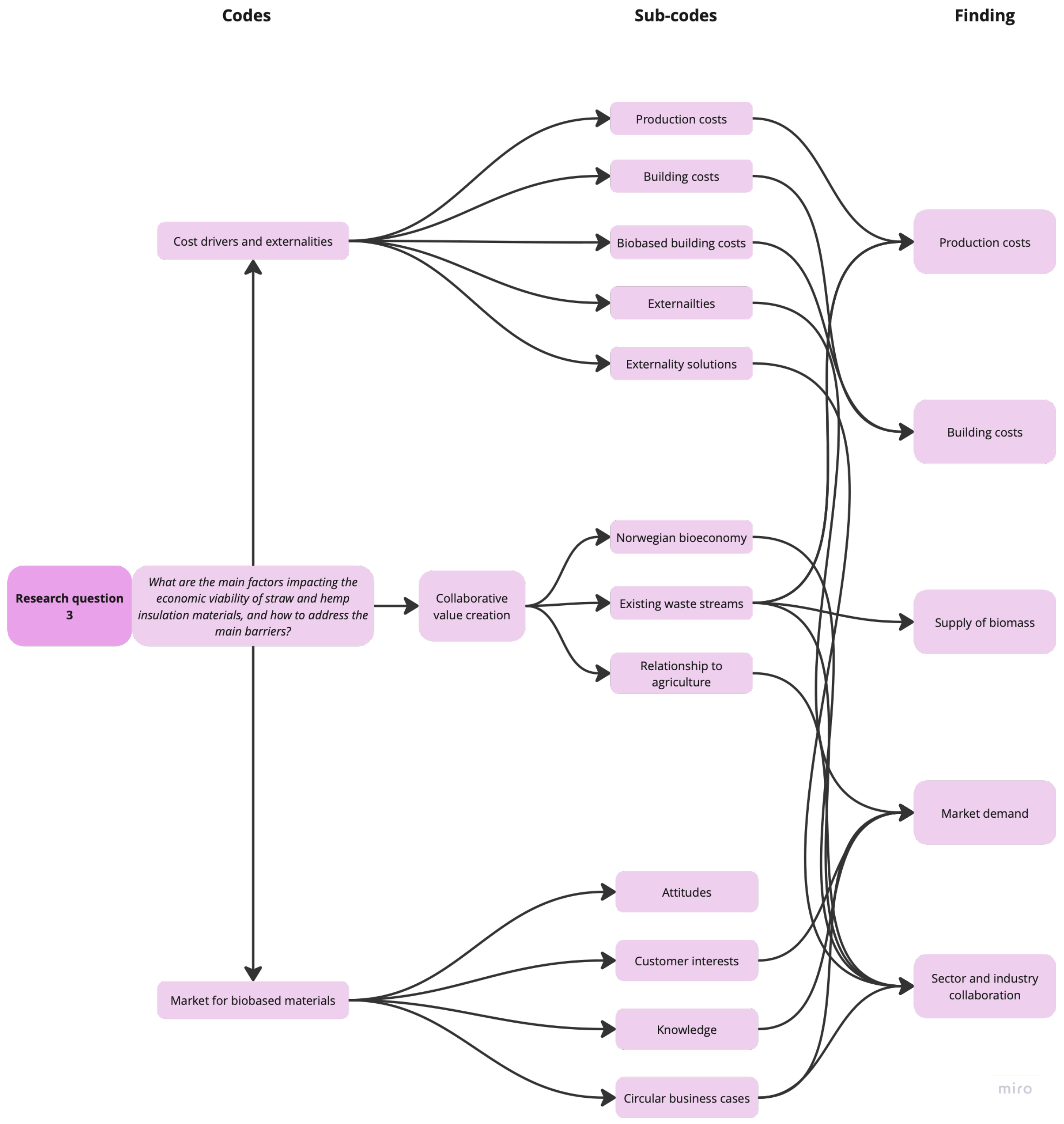

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