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# Roadmap for the transition to biogenic building materials: A socio-technical analysis of barriers and drivers in the Danish construction industry

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A B S T R A C T

The threat of climate change and global resource scarcity has prompted changes in the way that goods are produced and consumed in the construction industry. An important way for the industry to contribute to the green transition is to substitute conventional building materials with biogenic materials that require less energy to produce and bind atmospheric carbon in their growth, thus effectively capturing and storing carbon inside the building stock. An increased use of biogenic materials not only necessitates new technical development but also major changes in existing production and consumption practices. While extant research has investigated barriers in relation to the uptake of low-carbon building materials, less attention has been placed on investigating the measures that support the transition to increased use of biogenic materials. Drawing on insights from socio-technical transition analysis, the paper explores barriers and drivers that influence the uptake and diffusion of biogenic materials in the Danish construction industry. Sixty distinct barriers are identified including cultural, infrastructural, technological, market, political, techno-scientific, and industrial network barriers. The study also identifies measures, which could contribute to an increased use of biogenic materials. These findings are combined in a roadmap for a transition towards an increased use of biogenic materials in the construction industry.

## 1. Introduction

The construction industry is often highlighted as one of the most significant contributors to environmental degradation due to its $CO_2$ emissions and high consumption of non-renewable resources (Opoku, 2019; World Green Building Council, 2019). Consequently, measures to reduce the environmental impact of producing buildings, in particular regarding energy consumption (Rasmussen et al., 2020; Eberhardt et al., 2022), have been promoted both nationally and internationally. A focus on operational energy consumption is, however, not synonymous with sustainability from a broader perspective as the rapidly growing global population will necessitate a need for building more urban capacity in the next 40 years than has been built the past 4.000 years (Eberhardt et al., 2019). Due to the high levels of embodied energy and $CO_2$ emissions of the materials used (Taffese et al., 2019), focus has increasingly been directed towards issues of sustainable consumption and production to reduce the industry's contribution to climate change and resource scarcity. In the Circular Economy Action Plan, the European Commission (2020) has e.g., drawn up guidelines to promote recycling and reuse of materials, and countries worldwide have started to investigate how biogenic materials and associated notions such as bioeconomy, sustainability, circular economy, and green growth can be used to reduce the $CO_2$ footprint of buildings and building activities (cf. De Besi and McCormick, 2015; Norouzi et al., 2021).

Research has, however, shown that there are many barriers to the use of non-conventional building materials as replacements for conventional ones. These relate to diverse issues such as a lack of commercial benefits, ineffective dissemination of information on new materials, missing technical documentation (Zhang and Canning, 2011), unsatisfactory performance, an established culture which favors conventional materials (Markström et al., 2016), and a lack of standards, legislative restrictions, and local availability of materials and technologies (Giesekam et al., 2014, 2016). Due to the breadth and scope of the problem in hand, studies have addressed the question of barriers specific to the use of non-conventional materials from a multitude of perspectives. Dodoo et al. (2009), Vefago and Avellaneda (2013), and Hurtado et al. (2016), e.g., examined it from a perspective of the technical properties of materials, whereas Castro-Lacouture et al. (2009), Akadiri (2015), and

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Gounder et al. (2021) focused on patterns related to their use and consumption, and Hurlimann et al. (2018) and Göswein et al. (2022) on the role of policy instruments and regulatory frameworks.

While these studies have advanced our understanding, they have tended to focus on barriers to 'green building' or 'non-conventional' materials in general and have moreover approached the issue from each their uni-disciplinary perspective, focusing on either the consumption or production part of the problem. This, however, provides only a partial perspective on the complexities of the scale and type of change implied when trying to instigate change in a highly institutionalized setting (Leiringer et al., 2022). Knoeri et al. (2011) thus argue that consumption and production are not two separate domains. Rather, a series of dynamic interdependencies exist between consumption and production practices (Geels et al., 2015), and intertwining technological, regulatory, and social factors all contribute to shaping the use of building materials. The efforts necessary to introduce non-conventional, and in particular biogenic, construction materials are therefore not a question of changing discrete elements, but one of coordinating and aligning processes and interactions on multiple levels to achieve a transition. As Geels et al. (2016a) suggest, low-carbon transitions are multi-facetted processes that "*entail co-evolutionary changes in technologies, markets, institutional frameworks, cultural meanings and everyday life practices*" (Geels et al., 2015: 2) to succeed.

This is something that has so far received only scant attention in research on the use of non-conventional materials. To address this gap in the literature, we ask the following research questions: (1) what are the main barriers and drivers that influence the uptake and diffusion of biogenic materials, and (2) how can measures to achieve a transition to increased use of biogenic construction materials be governed? Drawing on findings from a study on the use of biogenic materials in the Danish construction industry, this paper applies insights from socio-technical transition analysis (cf. Geels et al., 2015). We show how biogenic materials can be conceptualized as emergent niche innovations, which struggle against existing socio-technical regimes characterized by path dependency and lock-in mechanisms (Geels et al., 2016a). We identify barriers to the use of biogenic materials in a Danish context and use these in outlining a roadmap for the transition towards a construction industry that is configured around the use of biogenic building materials. In doing so, we contribute with knowledge on systemic barriers to, and drivers of, biogenic materials, which may inform future policy making.

The remaining paper is organized as follows: Section 2 presents the theoretical framework of the study. Here, we first introduce the topic of innovation in construction with a focus on highlighting its systemic nature. Then, we present the concepts of socio-technical transitions and strategic niche management, which are used as the theoretical basis for the study. Section 3 details the methods of study. In section 4, the findings are presented, followed by section 5, where a roadmap for increased use of bio-based materials is established. Finally, section 6 summarizes the main conclusions and contributions.

## 2. Innovation, transition theory and strategic niche management

To better understand the particularities surrounding the transition to biogenic construction materials, we start by situating this topic within the broader context of innovations in complex systems (Gann and Salter, 2000) with the purpose of illustrating the systemic interdependencies between the various factors that influence the uptake of a new practice. On this basis, the concept of *socio-technical transitions* (e.g., Geels, 2004, 2019; Markard et al., 2012) is then mobilized as a framework to identify barriers and analyze potential drivers of increased use of biogenic materials in a systemic perspective. This concept is rooted in socio-technical innovation research and is highly useful for understanding how technologies gain societal prevalence, including barriers and opportunities for their diffusion.

### 2.1. Innovation in construction

The creation of buildings is a complex process where economics, knowledge, and accessibility to materials, legislation, and execution practices influence choice of materials and design. It is therefore necessary to consider not only technical but also economic, cultural, and institutional barriers and drivers when understanding and facilitating the managed evolution of innovations in the construction industry (Meacham and van Straalen, 2018).

When discussing conditions for innovation in the construction industry, it is common to describe the industry as being fragmented, risk averse and characterized by sub-optimization (cf. Dainty et al., 2017; Gottlieb and Frederiksen, 2020; Leiringer, 2020). This is the consequence of a production process, which is often project-organized and characterized by individual collaborations between many small to medium sized companies within a regulatory framework and operating on market conditions. This includes supply and contract forms but also market relations, where the various companies compete on a standardized basis, which may prevent them from taking advantage of innovative products and solutions (Winch, 1998). In a Danish context, the construction industry is often accused of being backward and locked-in (Kristiansen et al., 2005). This technological lock-in is partly attributed to the dominance of certain production technologies and materials that is maintained by the existence of strong manufacturers of e.g., concrete and insulation that historically have played an important role in the Danish economy and consequently have met strong political support (Klemmensen, 2001). Moreover, learning often takes place from project to project with limited opportunities to benefit from good experiences, as the next project is carried out in a new collaboration constellation and under new contractual terms (Winch, 1998; Chan et al., 2005; Eriksson et al., 2017). This counteracts incentives for using new technologies and materials (Giesekam et al., 2016) leading to incremental development and limited diffusion of innovations at industry level.

### 2.2. Socio-technical transition analysis

Theories on socio-technical transitions take a systemic perspective on the development and application of technologies, including the technology's relations to existing market structures, user practices, legislation, etc. In this perspective, innovations are seen as a process initiated by actors who are formally and informally bound together in the efforts to realize technological change (Ørstavik, 2014).

Geels (2004) and colleagues (e.g., Geels and Schot, 2007) have developed an analytical model to conceptualize how innovations develop in relation to broader societal dynamics, and thus how societal transformations take place in relation to the development of technological innovations. This model, which is known as the multi-level perspective (MLP), suggests that innovations that are developed locally in so-called 'technological niches' must interact with broader socio-technical systems at both industrial and societal levels to be accepted and diffused, thus contributing to a transition (see Fig. 1).

The MLP-model operates with three levels. At the micro-level, networks of innovative actors establish so-called niches that act as incubation spaces or protected environments for the development of new technologies, which are not immediately competitive or compatible with existing practices and processes at the regime-level. The regime, which constitutes the meso-level in the model, is seen as a socio-technical system that sets the framework for how a given societal function or activity is organized. Construction as an activity is not only conditioned by available production technologies, but also by legislation, user preferences, market mechanisms, industrial structure, etc. These elements are in mutual relationship with each other, which in turn creates a degree of stability and path dependency in relation to a specific technology that may prevent new technologies from becoming part of the regime. A transition to the use of a new technology thus requires

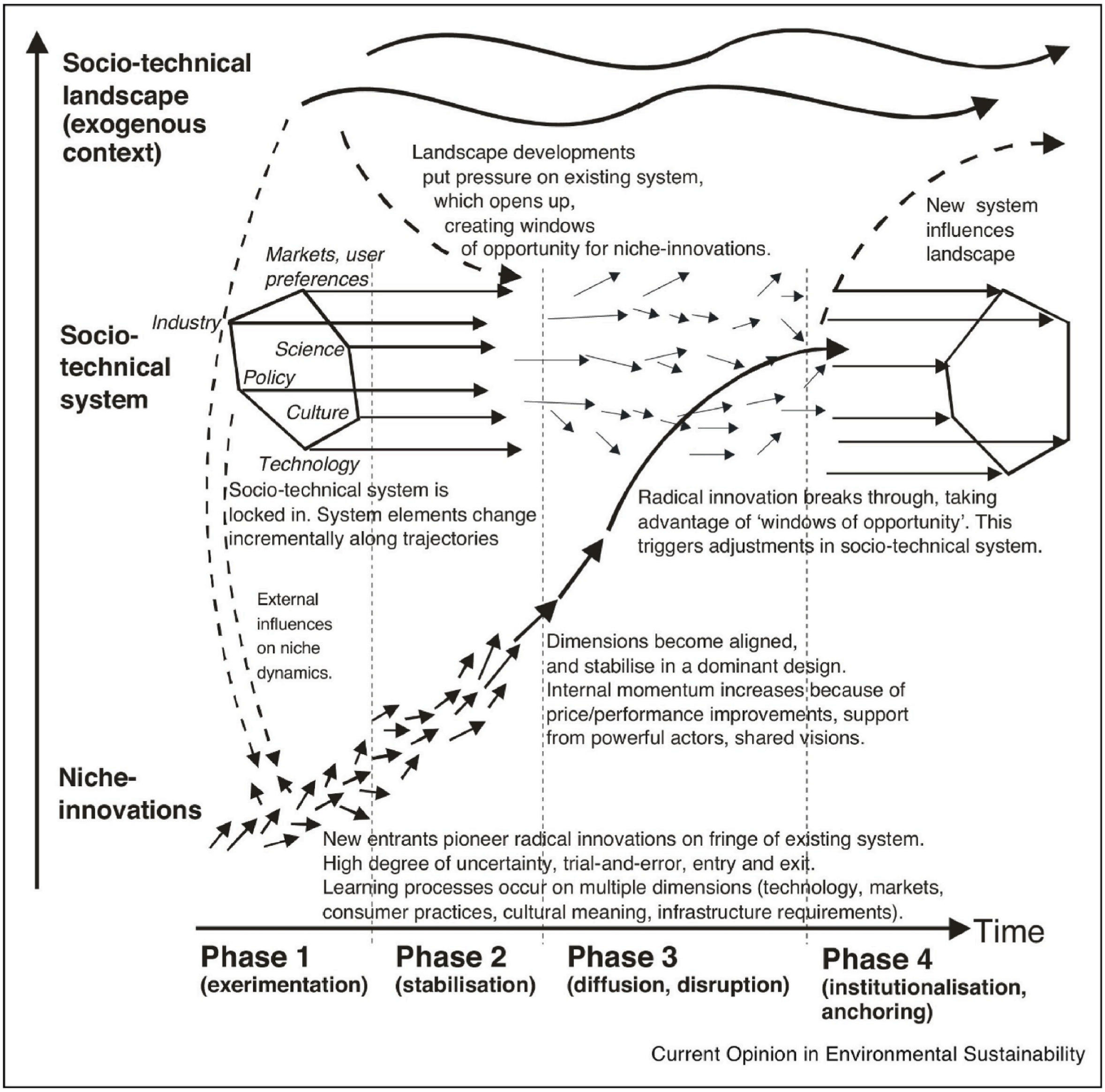


**Fig. 1.** Multi-level perspective on socio-technical transitions (Geels, 2019: 191).

basic reconfigurations of several dimensions in the regime. According to MLP, such changes require not only the presence of potentially mature niche technologies but also a window of opportunity that come as a result of so-called landscape pressure (Geels and Schot, 2007), i.e., long-term macro-structural conditions, which fundamentally challenge key societal dynamics and mechanisms.

### 2.2.1. *Elements and developments in socio-technical regimes*

Socio-technical regimes are often used to characterize a specific business sector or industry. In transition theory, a regime consists of several dimensions that are interdependent and configured around a prevailing technological development trajectory. Regimes thus function as selection environments, where development paths are built around a given technology. As technology diffuses, relationships between social and technological elements are established on many levels and dimensions. The development of regulation e.g., establishes relationships around the use of technology; and user practices, scientific knowledge, infrastructure, etc. help to maintain certain patterns of action and perceptions about the technology. This means that it is not only market mechanisms or regulations that determine whether a technology gains traction or not, but also the specific socio-technical relationships in the existing regime structure.

The interdependence between the various elements of the regime also means that the introduction of a new technology, or niche innovation, leads to extensive changes in a regime's structure. These changes may follow different so-called transition pathways (Geels et al., 2016b) that can be categorized based on the timing, respectively the nature, of interactions between developments at landscape, regime, and niche level. As for the timing of interactions, Geels and Schot (2007) argue that different timings of multi-level interactions have different outcomes. Landscape pressure may e.g., occur at a time when the niche technologies are not fully developed, the transition path will be different compared to when the technologies are fully developed. Analogously, transitions will follow different pathways, depending on whether niche innovations have a reinforcing or a disruptive relationship with existing regime structures.

Transitions can therefore both take the form of abrupt changes, resulting from exogenous crises that fundamentally upend current practices at the regime level, or gradual changes brought about as new technologies are introduced as an addition or substitute for existing components of the socio-technical regime which, over time, prompt changes in the relations between other elements of the regime.

### 2.3. Strategic niche management

While the MLP framework is useful to illustrate how existing socio-technical dynamics exert influence on the opportunities for introducing new innovations and thus the measures necessary to achieve a transition, it has been criticized for presenting an overtly structural framing of change, which lacks attention to how niche developments can be nurtured and governed (Jørgensen, 2012). To address this, the concept of strategic niche management (SNM) has emerged as a policy concept (Kemp et al., 1998; Schot and Geels, 2008) that has gained increasing importance in the efforts to induce more sustainable development. Caniels and Romijn (2008) thus argue that SNM advocates for the creation of socio-technical experiments where various actors are encouraged to embark on a learning process to facilitate the incubation of a new technology.

SNM offers a practice-policy-oriented perspective on how a technological change process can be organized and can be used as a tool to articulate necessary changes in technology and institutional context to ensure the continued development of the technologies in a given context. This deals with matters concerning the perceived value of the technology, how support groups around a technology can be built, and how to overcome structural and institutional barriers to innovation. In this context, SNM focuses on questions about how it is possible to create and lead development in technological niches. The assumption is that it is possible to design niche developments by setting up a series of experiments with a selection of new technologies. According to Kemp et al. (1998), such a process consists of five steps: (1) the choice of technology, (2) the selection of an experiment, (3) the set-up of the experiment, (4) scaling up the experiment, and (5) the breakdown of protection. These five steps are designed as a bottom-up process to transform a new technology from an unstable technological niche into a viable market niche, which can instigate a regime shift.

In this paper, we use socio-technical transition analysis and the MLP-model as tools for identifying barriers and drivers for the transition to biogenic materials in the construction industry. We then use the SNM perspective in the development of a roadmap for the transition.

## 3. Methods

The data consists of semi-structured single person interviews, with respondents from different positions in the industry. The data was generated following an abductive research design (Tavory and Timmermans, 2014) and consists of a ‘small-*n*’ interview sample (Small, 2009) drawing on eleven interviews with key actors in the Danish construction industry. Such a small-*n* approach has been published previously in this field (Hurlimann et al., 2018).

### 3.1. Selection of respondents

We utilized an information-based strategy (Flyvbjerg, 2006) to identify respondents (see Table 1) who had in-depth knowledge about the potential for biogenic materials and associated barriers and drivers. The respondents were sampled purposively (Patton, 2002) with the aim of including representatives who could disclose information on all aspects of the regime in the MLP-model, such as culture and user preferences, education, techno-scientific knowledge, policies and regulations, and market conditions. This included respondents from higher education institutions (n = 3), insurance companies (n = 1), manufacturers of conventional and biogenic materials (n = 2), industry associations (n = 2), practitioners (n = 1), and knowledge centers and standardization organizations (n = 2).

**Table 1**
Overview and details of interview respondents.

| No. | Title | Affiliation | Dimension represented | Duration (min) |
|---|---|---|---|---|
| 1. | Scientific employee | Higher education institution | Techno-scientific | 48 |
| 2. | Technical Case Manager | Insurance company | Political | 47 |
| 3. | CEO | Material manufacturer | Technological | 54 |
| 4. | Lecturer | Higher education institution | Infrastructural | 58 |
| 5. | Head of Information | Industry association | Industrial network/Political | 45 |
| 6. | Senior Researcher | Higher education institution | Techno-scientific | 41 |
| 7. | Technician | Practitioner | Market | 44 |
| 8. | Specialist | Knowledge center | Cultural | 42 |
| 9. | ESG Manager | Industry association | Industrial network/Political | 28 |
| 10. | CEO | Standardization organization | Culture | 45 |
| 11. | CEO | Material manufacturer | Technology | 44 |

### 3.2. Interview design and data collection

The interviews had an average duration of 45 min and utilized a semi-structured interview guide that focused on barriers, change measures and consequences related to the use of biogenic materials within the various dimensions of the socio-technical regime. For each dimension in the regime model, one to three hypotheses had been identified based on the theoretical framework and a preliminary integrative review (Snyder, 2019) on barriers to non-conventional building materials (see Table A1 in the appendix). The hypotheses formed the starting point for the interviews and were deliberately formulated with a critical angle to stimulate discussion with the respondents (cf. Lilleker, 2003; Van Audenhove and Donders, 2019).

The interviews were open-ended, meaning that even though the respondents were sampled to represent a specific dimension in the regime model, they had the opportunity to relate to other dimensions during the interviews. The interview guide was designed to allow for considerable dialogue and unexpected input from the respondents. Focus was, however, on getting the respondents' inputs in relation to the barriers, drivers, and consequences of biogenic materials in a short-term (1–2 years), medium-term (5 years), and long-term (10 years) perspective, as such datapoints are crucial for conceptualizing a roadmap for the transition to biogenic materials.

### 3.3. Data analysis

Notes were taken during the interviews. After the interviews, statements were categorized to fit the template that we constructed from our theoretical framework. The statements were thus summarized and mapped systematically for each respondent. Significant factors across the interviews were then summarized, so that they reflected concrete initiatives and barriers in relation to the given dimensions of the MLP framework. All statements used in the paper have been translated into English by the authors with a focus on retaining the original meaning.

## 4. Findings

The findings are structured in two sections. First, the identified barriers to the use of biogenic materials are presented according to the different dimensions of the socio-technical regime. Next, the measures identified to address the barriers and support the increased use of biogenic materials in a short, medium, and long-term perspective are presented.

### 4.1. Barriers to biogenic materials in the Danish construction industry

A total of 60 distinct barriers were identified by the respondents in the interviews. These have been analytically grouped into 13 main barriers at an aggregate level presented in Table A2 in the appendix.

#### 4.1.1. Cultural barriers

In transition analyses, culture designates the symbolic meaning that is attributed to a specific technology (Geels, 2002). A recurrent theme in the interviews centered on the notion that cultural changes were perceived as necessary if biogenic materials are to substitute conventional materials as the *de facto* standard in the industry. There are many myths and prejudices concerning 'alternative' and 'sustainable' materials, which act as deterrents for the use of biogenic materials. For example, a respondent explained that "*clients often associate biogenic materials with the notion of self-building*" (ESG Manager, industry association), which relates to a prejudice of an unprofessional approach to building. Even though biogenic materials may be seen as 'fit for purpose', these prejudices were nonetheless argued to suppress the use and wider diffusion of biogenic materials at an industrial level. Considerations and choice of materials, all too often, are taken at a time in the project when it is too late to make substantial changes to the project design. Moreover, biogenic materials were believed to only "*diffuse to the part of the industry that already has an interest in sustainable or green building*" (CEO, standardization organization). The limited knowledge of the application possibilities of biogenic materials related to the proliferation of different professional perceptions of how, and in which situations, biogenic materials can be utilized.

#### 4.1.2. Infrastructural barriers

In relation to infrastructural barriers, low interest in investing in research that can qualify the suitability of biogenic materials was highlighted as a major barrier by several of the respondents. Even though public funding is channeled into research on the technical properties of building materials, it is often only as a contribution to co-financed research projects that also depend on private participation. Manufacturers of biogenic materials are, however, said to be "*hesitant when it comes to making investments in research to document and qualify their products*" (Technical Case Manager, insurance company). The main reason for this is that many manufacturers of biogenic materials are small and may not have the financial capacity to engage in research activities. Moreover, biogenic materials are at odds with established practices, interests, and production methods in the industry meaning that an investment in research may not yield the desired return of investment due to the lack of market scale.

Another important barrier is a lack of teaching in biogenic materials at educational institutions. This barrier, which is intertwined with the techno-scientific barrier related to insufficient technical documentation, addresses the practical curriculum in vocational education programs. In this regard, a respondent elaborated that "*students are taught how to handle materials that traditionally belong to the trade*" (Lecturer, higher educational institution). This is a competence in demand in the industry, whereas knowledge of non-conventional materials and production methods does not constitute a prerequisite for the acceptance of newly qualified craftsperson's competences.

This is a situation that is well-known in highly stable and institutionalized social settings, where existing professional knowledge constitutes a source of conservatism. In the field of healthcare, Hall (2005), e.g., shows that educational experiences and the socialization process that occur during training reinforce common values and problem-solving approaches. Similarly, Hughes and Hughes (2013) show how professionalism preserves a body of knowledge and way of working that may constitute a challenge to sustainability in construction.

#### 4.1.3. Technological barriers

There are issues in relation to insufficient documentation of the technical properties of new biogenic materials. From a technological perspective, dealing with the practical aspects of knowledge (Flyvbjerg, 2004), it is the lack of *knowhow* in relation to how to build with biogenic materials and what specific application areas they have, which was identified as the main technological barriers.

This points to the issue of using biogenic materials in combination with traditional construction methods and solutions. Current practices in relation to specific conventional materials and products constitute a barrier, which, according to a respondent is "*rooted in a disagreement on whether the diffusion of knowledge on e.g., assembly methods, is left best in the hands of manufacturers, researchers or regulators, whose actions have a more direct impact on practice*" (Senior Researcher, higher education institution).

Following on from this, another respondent argued that "*a lack of predefined or pre-accepted solutions for using biogenic materials in different parts of the building inhibits their diffusion in favor of conventional solutions*" (CEO, material manufacturer). Contractors often deviate from the manufacturers' assembly specifications and use conventional methods when working with biogenic materials, which may potentially lead to defects. For example, as elaborated by a respondent, "*contractors typically install vapor barriers even though our [the manufacturer's] instructions do not specify this*" (CEO, material manufacturer). Pre-accepted solutions, which work as heuristics or templates, are thus helpful to practitioners as it allows them to design and construct specified solutions with which they have no prior knowledge. In practice, or for transmitting knowledge, pre-accepted solutions can according to Turnbull (1993) be seen as a representational technology with much of the power of a scientific theory.

#### 4.1.4. Market barriers

Biogenic materials have, as explained by a respondent, "*a poor image among clients, who associate them with products of sub-par performance compared to conventional materials*" (Technician, practitioner). Biogenic materials are moreover often more expensive compared to conventional solutions. Although there may be economic benefits of biogenic materials from a life-cycle perspective, the higher cost compared to conventional materials is nevertheless a substantial entry barrier. In addition, biogenic materials have "*a higher production conversion cost and additional costs associated with the need for changing construction methods*" (Research Assistant, higher education institution). New products may thus entail new production methods on-site, which must be included in the cost of construction, and existing machinery may necessarily be replaced, which may constitute a substantial investment for the contractor.

From the clients and the consultants' point of view, biogenic materials are "*typically associated with increased uncertainty and risk*" (Head of Information, industry association). This can be seen a consequence of the absence of market standards, which creates an imbalance between supply and demand, leading to higher costs (cf. Nußholz et al., 2019; Ghaffar et al., 2020).

#### 4.1.5. Political barriers

An important barrier is a lack of political interest. While many policy reports have highlighted the role of the construction industry in reducing $CO_2$ emissions (e.g., Ministry of Employment and the Economy, 2014; Boverket, 2020; UKGBC, 2021), the focus in these reports has been on either the operation phase of buildings or on reducing embodied $CO_2$ of conventional materials. Moreover, existing building regulations were identified as a barrier. The requirements in the national building code favor conventional materials and solutions which in the words of a respondent, "*makes it difficult for contractors and advisors to consider alternative, biogenic, materials due to the increased administrative documentation burden*" (ESG Manager, industry association). The documentation is perceived as both costly and difficult to conduct for particularly small and medium-sized companies that may not have the necessary in-house expertise or resources to handle all documentation requirements. Without political support, a 'sustainable divide' may occur in much the same way, as it has been documented that a digital exists due to political digital reform agendas not stimulating innovation on a wider scale, which results in small firm being disenfranchised (e.g., Dainty et al., 2017).

#### 4.1.6. Techno-scientific barriers

In contrast to the technological dimension in the socio-technical regime model, which deals with the practical aspects of knowledge, the techno-scientific dimension deals with scientific or theoretical knowledge.

In this regard, insufficient availability of technical documentation is a main barrier**.** This regards the performance and properties of biogenic materials in relation to "*issues of fire, acoustics, and moisture transport*" (Head of Information, industry association). Documentation for many non-conventional materials has been developed, but more research is needed. The lack of available information was reported as the main reason why consultants and contractors avoid using biogenic materials. Without research-based instructions, declarations of performance, and technical standards, consultants and contractors must document the performance and suitability of their choice of solutions and materials themselves, contributing to a so-called 'non-spread' (Ferlie et al., 2005) of innovative solutions.

The lack of scientific knowledge also involves insufficient availability of feedback from practice in the form of experience from completed projects. This type of knowledge is considered crucial in order to "*document standard solutions that may enable a rapid diffusion across the industry*" (Research Assistant, higher education institution). The structural characteristics of the construction industry, as presented in section 2.1, is however a barrier in this regard. Due to the project-based nature of production, learning is very thus rarely transferred from one project to another.

#### 4.1.7. Industrial network barriers

The final dimension in the socio-technical regime model deals with industrial networks. The main barrier identified is a lack of knowledge sharing between companies. This issue involves a dichotomy. On the one hand, a lack of knowledge sharing was argued to "*slow the rate of diffusion and weaken the competitiveness of the companies on a future market for sustainable building*" (Senior Researcher, higher education institution). On the other hand, it was argued that "*as long as sustainability remains a competitive parameter, companies will keep knowledge to themselves*" (Head of Information, industry association), which in turn inhibits diffusion of the new biogenic materials. In addition, strong vested interests of existing incumbents in the industry are considered a reason why it is so "*difficult to diffuse alternative practices and materials*" (Specialist, knowledge center). This illustrates the path dependency and lock-in to specific regime configurations that may prevent new technologies from becoming part of the regime (Geels et al., 2016a), which also Mahapatra and Gustavsson (2008) and Ørstavik (2014) have observed in context of construction innovation and the use of new construction materials.

### 4.2. Measures to support the use of biogenic materials

The interviews also focused on measures to overcome the identified barriers and promote an increased use of biogenic materials in a short, medium, and long term. These are presented in Table A3 in the appendix.

#### 4.2.1. Measures to promote biogenic material use in the short term

In the short term, defined as a time when biogenic materials are still considered immature technologies occupying a position as 'technological niche' in the mainstream regime, most measures identified deal with issues in relation to the availability of knowledge and how to ensure a gradual breakthrough growth on an industry level. The measures target the group of actors that are believed to be the ones that in the first instance can drive the development.

Clients and architects play a prominent role here, as sustainability to a great extent relies on decisions taken in the early phases of construction projects. There is a need for increased professionalization among clients, so they have the necessary competences to understand the environmental consequences of their choice of materials. In relation to architects, there is a perceived need for "*developing examples of good architectural solutions with biogenic materials*" (CEO, standardization organization). This is corroborated by research showing that architects often use examples of good architectural solutions, or pre-accepted solution as discussed later, as source of inspiration for their own designs (cf. Grangaard, 2021). It is also necessary to develop new calculation practices, where costs of material and design solutions are "*calculated according to more holistic considerations than only their monetary cost, e.g., $CO_2$ emissions and reuse value*" (Specialist, knowledge center).

Where clients and architects are identified as drivers of the choice of materials, contractors are on the receiving end of this development. Measures to ensure that contractors also consider non-conventional materials therefore encompass economic considerations to act as incentives. This includes, according to the manufacturers of conventional and biogenic materials, perceiving biogenic materials as constituting a competitive advantage, but also "*improving the availability of knowledge on materials and identification of relevant areas of application*" (Technical Case Manager, insurance company). This requires action on behalf of the industry's practitioners, who actively need to seek out knowledge about biogenic alternatives to conventional building materials. It is, however, also dependent on more and better documentation of the technical properties as well as the practical suitability of biogenic materials. If the potential for biogenic materials in the construction industry is to be realized, it is thus required that the industry commences in exchange of knowledge and experience in this regard.

Finally, on the availability of knowledge, more focus on biogenic materials in construction educations is necessary. In the short term, there are no identified regulatory measures that are deemed necessary, however, as discussed later, this is due to regulation being seen as playing a role in supporting and enforcing specific solutions and materials only their consequences have been documented.

#### 4.2.2. Measures to promote biogenic material use in the medium term

In the medium term, defined as the time when biogenic materials have undergone a transition from novel technological niche to emerging market niche that have gained a market share of more than 5% (cf. Geels and Schot, 2007; Schot and Geels, 2008), the supporting measures identified by the respondents change in character. Instead of issues related to awareness, availability, and dissemination of knowledge in general, a range of informational and economic policy instruments (cf. Vedung, 2017), in the form of e.g., technical standardization and market-driven developments, were identified.

There is a need for increased product differentiation. This is elaborated by a respondent who said that "*biogenic materials that cannot document a long life could beneficially be used in buildings with a short lifespan such as pavilions or other temporary types of housing*" (Scientific Employee, higher education institution). As such, instead of talking about a market for biogenic materials, it could be useful to distinguish between several markets, each with their own features and use-cases.

A central feature in the establishment of a market for biogenic materials, involves harnessing economies of scale in supply and demand. Standards play a prominent role in this respect. Examples of standardization in relation to biogenic materials involve the development of pre-accepted or typified solutions, as presented previously, that are widely accepted and can be used across professional boundaries (e.g., system deliveries) with little individual risk, as their performance have been tested and documented over time. Such solutions must be developed jointly, and the documentation of their suitability should be incorporated into common industry standards, which will contribute to their diffusion (cf. Allen and Sriram, 2000; Foucart and Li, 2021). This necessitates that industry organizations and professional associations must show increased interest in biogenic materials and setting up structures for knowledge exchange between companies.

The respondents also identified measures in the form of relying on public clients to exercise their buying power to place increased demands for more sustainable solutions and working to dis-associate biogenic materials with self-building. This was reported as a crucial middle-term step in mainstreaming biogenic materials as a viable market niche. The reason for this is that a regime functions as a selection and retention mechanism (Geels, 2002), where only technologies that 'fit' or align with predominant practices are prone to be accepted and diffused. Public clients play a role in this regard as a specific selection environment for experimenting further with the materials. Also, as biogenic materials must change status and be perceived on equal terms as conventional material, a symbolic detachment from the label of something used by ecologically oriented self-builders is needed.

#### 4.2.3. Measures to promote biogenic material use in the long term

In the long term, defined as a time where biogenic materials have evolved into a viable market niche, the measures identified include supply-side capabilities, supporting regulatory action and continued documentation and development of biogenic materials.

Companies should develop the necessary capabilities and practices to design and build with biogenic materials. This should be accompanied by a continued development and documentation of new products and solutions. In particular, knowledge on the lifecycle of biogenic materials should be documented as the first experiences with potential defects would begin to show. This includes documentation of how biogenic materials "*best are to be maintained, replaced, and disposed or reused*" (Technical Case Manager, insurance company).

There is also a need for making changes in building legislation and rules regarding building work. When biogenic materials and new technical solutions have proven their worth over a longer period, a "*full implementation can be* supported *through regulatory changes*" (CEO, standardization organization). This can be seen as a process of normalization (May and Finch, 2009) of biogenic materials supported by the establishment of formalized networks or professional associations for biogenic materials to ensure increased diffusion. Finally, biogenic materials should be embedded in the curricula of educational institutions, thus contributing to a bottom-up transformation of existing design and construction practices.

## 5. Strategic niche management as a framework for change processes

Based on the findings, we next develop a roadmap drawing on the transition analysis perspective of strategic niche management (SNM), as presented in section 2.3. In the following sections we review these steps and describe selected dilemmas in connection with the process.

### 5.1. The choice of technology

A potential niche manager, i.e., a coalition of actors assuming responsibility for designing a niche development, must first make considerations regarding which technologies are suitable for support through SNM. The theoretical starting point is that the technologies must exist outside the existing established regime but be relevant in relation to remedying a social problem at a cost that is not deterrent to the potential users of the technology. In addition, there must be a continued technological development potential present and the prospect of a future increasing return on its use. Furthermore, the technology must be consistent with current organizational forms and be compatible with user needs and values. Finally, it must be attractive as a substitute in specific situations where any disadvantages of the new technology are outweighed by its advantages (Kemp et al., 1998). These theoretical guidelines are congruent with the short-term measures identified in the findings, where the need for more pragmatic and market-oriented factors were identified.

Thus, based on the findings, we highlight three factors of particular importance for this first step. First, there is a need to map biogenic alternatives to traditional materials. This is not just a technical challenge. It is also necessary to uncover existing design and construction practices, as this is considered a significant barrier to use as illustrated by the repeated need identified in the findings for developing and diffusing pre-accepted solutions. Furthermore, niche managers should at this stage work to make economic conditions regarding biogenic materials visible, as the choices of including these to a large extent depend on considerations regarding their cost in relation to traditional materials. In this connection, economic conditions cover price as a whole, with $CO_2$ embedding, opportunities for recycling, etc. included in the inventories. This is consistent with Callon's (2017) observation that collective action on markets is dependent on so-called 'market devices' that enable bilateral commercial transactions to take place. Market devices include instruments to calculate prices and rules that organize competition or valuate goods and services (Muniesa et al., 2007). As such they are fundamental to the establishment of markets and are therefore crucial in this first step of gauging the potential of different biogenic alternatives.

### 5.2. The selection of an experiment

The next step in the SNM process is the selection of an experiment, i.e., selection of the setting in which the new technology is expected to be used and thus be tested. This involves considerations regarding the specific application of the technology (e.g., at building component level) or the market segment where the technology can be used (e.g., public housing, private properties, etc.). The idea in SNM is that the heterogeneity of selection environments means that there usually are many areas or types of application for which the new technology is relevant (Kemp et al., 1998). An example of this relates to the use of cross-laminated timber, which in a Danish context is primarily used for low-rise buildings, as opposed to multistorey buildings, where concrete still dominates.

There is a need to specify building components or specific areas of application for biogenic materials, as not all materials are necessarily useable in all contexts, yet still can be useful in other, more narrowly defined contexts. Furthermore, specific market segments must be specified. Respondents highlight a need for public and professional clients to take the lead, as they have the buying power and critical mass needed to scale the potential solutions from individual projects to a global niche, as we discuss further below. Finally, competence needs, risks, and insurance terms must be mapped. Technical documentation alone is not sufficient, as there also is a need for contractors and craftsmen to be equipped to work with biogenic materials.

### 5.3. The set-up of the experiment

The third step is setting up the experiment, where specific testing takes place. This is the most difficult step, as the right balance must be found between selection pressure and protection (Kemp et al., 1998). Protection deals with the measures that niche developers take to protect their technology from influences from the regime. Here, the challenge is to protect the technology to adequately explore its potential while still gathering experience and feedback from its users. Selection pressure deals with pressure from external stakeholders. Here, the challenge is to ensure that the technology is proven in relation to the requirements and conditions that exist at the regime level, without this leading niche developers to remove the potentially innovative element and fall into a conventional solution.

Our findings indicate that there is a need to launch several demonstration projects to test the use of biogenic materials. For this purpose, there is a need for collaboration with test cases and manufacturers of biogenic materials, so that both construction principles and material development mature at the same time. Implementation of knowledge from demonstration projects requires development of a standard for testing and gathering experience to ensure a uniformity. A key element in the testing is to ensure constructability and competence development among the different crafts and to focus on testing and determining risk and responsibility conditions.

### 5.4. Scaling up the experiment

According to Schot and Geels (2008), stand-alone projects or trials are not sufficient to ensure diffusion, so the fourth step is to scale up the experiment. It is necessary to develop a global niche in which actors across local projects exchange experiences and develop common perceptions, models, rules, etc. as illustrated in Fig. 2.

Global niches play a key role in establishing a technological trajectory or development path, where the technology is gradually adapted and refined through a series of successive technological design solutions, so that it is continuously perceived as more suitable for solving a given problem (Clausen, 2009: 71).

Policy instruments are central to the work of establishing a global niche. Even a successful experiment or technology often needs political backing to compete with other established technologies (Kemp et al., 1998). Vedung (2017) outlines three fundamentally different instruments: regulation (legislation, coercion, etc.), incentives (financial support, branding, etc.), and information (education, courses, etc.). Our findings indicate a need for informational instruments to document performance and design standard solutions. This may reduce uncertainty, and thus transaction costs when using biogenic materials. This has also been discussed by Qian et al. (2015) and Fan et al. (2018) who have documented that green building projects are associated with increased transaction costs compared to traditional projects. Another important instrument is the establishment of networks for the exchange of experience, to ensure the dissemination of information at industry level. Winch and Courtney (2007) have illustrated the importance of such networks, in the form of e.g., associations or public-private partnerships, as they assume a role of innovation brokers that effectively facilitate innovation by independently validating new ideas. Finally, the need for clear and visible requirements for $CO_2$ emissions and potential savings using biogenic materials was highlighted in this regard. Clear political visions and targets are thus important for companies when developing innovations, as it reduces uncertainties associated with resource investments (e.g., Wanzenböck et al., 2020). Moreover, clear visions are crucial for niche development as they provide direction for learning processes in the network (Schot and Geels, 2008) and thus to the establishment of a technological trajectory.

### 5.5. The breakdown of protection

The last step is to break down protection around the technology. This is typically a step taken either when (1) the new technology has gained ground as the dominant technology in the regime, (2) the specific results prove disappointing, or (3) the prospects for future use are unclear (Schot and Geels, 2008).

Here, the need to embed experiences in the teaching was pointed out, for example in construction engineering educations, as well as in the form of requirements in the building regulations. A critical element in this connection is also to have the necessary general technical common grounds (i.e., standards) to support the future use of biogenic materials. All these elements are part of a process of normalization (May and Finch, 2009), as mentioned previously, in which experiences and practice developed throughout the experiment become embedded in regime structures. In this process policies should be put in place not as top-down constraints (Göswein et al., 2022) but to coordinate the various developments in a coherent policy mix and provide the opportunities for an institutionalization of biogenic materials.

### 5.6. Roadmap for transition to increased use of biogenic materials

Based on the five steps, a roadmap for the construction industry's transition to biogenic materials is illustrated in Fig. 3.

In the roadmap, we have placed key initiatives from the interview study in the five steps, which Kemp et al. (1998) outline in their review of SNM. These can be taken progressively to create and organize the development of a technological niche. The proposed steps are to: (1) establish a maturity level for different biogenic materials and make economic conditions visible, (2) identify specific, differentiated application areas and associated risks, (3) establish demonstration projects to test materials and map competence requirements and risks, (4) document and disseminate performances and standard solutions, and (5) embed experiences and new requirements in building regulations and practices.

## 6. Conclusions

This paper has provided a socio-technical understanding of the transitions to increased use of biogenic materials in the Danish construction industry. We set out to answer the following research questions: (1) what are the main barriers and drivers that influence the uptake and diffusion of biogenic materials, and (2) how can measures to achieve a transition to increased use of biogenic construction materials be governed?

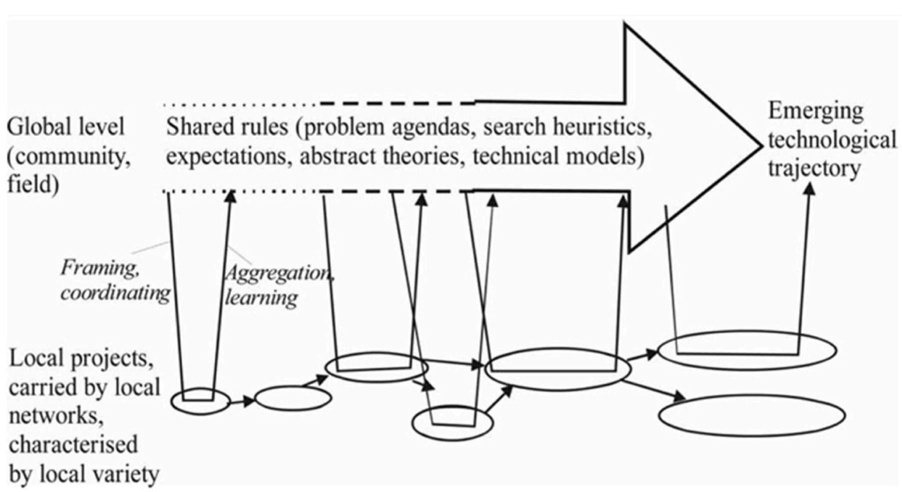


**Fig. 2.** Development of technological development path through local projects (Schot and Geels, 2008: 544).

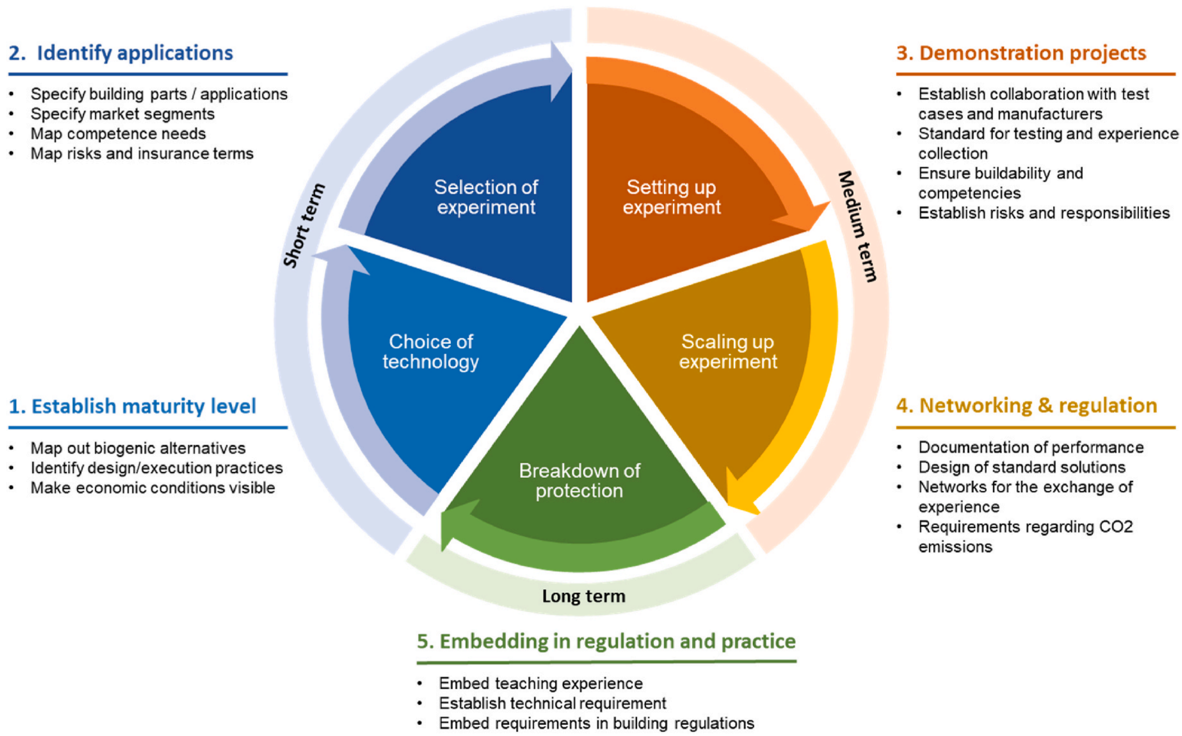


**Fig. 3.** A roadmap for the transition to biogenic materials in the construction industry (adapted from Rasmussen et al., 2022).

In answering the first research question, the study found 60 distinct barriers that were analytically grouped into 13 main barriers in seven different dimensions that constitute a socio-technical regime. All of these can be considered important or influential in explaining barriers to a transition due to their mutually constitutive and reinforcing nature. We also identified a series of measures that could contribute to increased use of biogenic materials. These measures address the different barriers identified and are grouped according to short-, medium-, and long-term relevance. As such, they should be seen as solutions progressively underpinning a development in the industry.

To address the second research question, theories on socio-technical transitions and strategic niche management were used to synthesize insights into a coherent whole in the development of a roadmap for the construction industry's transition to an increased use of biogenic materials. By articulating necessary changes in technology and institutional context to ensure the continued development of the given technology, this perspective offers a practice-policy-oriented description of how a technological change process can be organized as a part of the normalization of biogenic alternatives to conventional materials.

In doing so, the paper contributes to a topic of increasing interest in both policy, practice, and research (e.g., Sommerhuber et al., 2017; Nußholz et al., 2019) with an understanding of the interrelatedness of different institutional, structural, and cultural factors as drivers or barriers to the green transition using the Danish construction industry as a case. While different national construction industries may exhibit comparable structural conditions, it is the specific socio-technical configuration that influences the uptake and diffusion of new innovative practices and technologies, such as biogenic materials. Notwithstanding, the findings of the study can still be of relevance in other construction industries than the Danish. In particular, the roadmap based on insights from SNM provides a systemic approach to questions about how change towards more sustainable consumption and production practices in construction can be accomplished. Thus, while previous studies have examined barriers towards the increased use of biogenic materials in construction (e.g., Markström et al., 2016), and efforts also have been directed towards identifying broad pathways to change, it is also clear that less attention has been devoted to examining specific measures and actions necessary to achieve the transition. Few recent notable exceptions are provided by e.g., Cruz et al. (2019) and Petrescu et al. (2021) who have developed roadmaps providing good indicators of the variety of actions that may contribute to transforming the construction industry. These, nevertheless, offer goal-oriented analyses of the transition (Geels et al., 2016a), while downplaying the dependencies between factors and levels. By taking a socio-technical approach, we have contributed with a less deterministic and more constructivist perspective on changes necessary to support a green transition. This perspective has been instrumental in developing our roadmap, which illustrates how the governance of a transition towards increased use of biogenic materials requires coordination between many specialized actors as well as a translation of specific localized, professional understandings into a more coherent structural whole to succeed.

### *6.1. Limitations and future research*

The study has some limitations and implications for future research. First, the study is based on a small-*n* sample of respondents in only one country. To fully explore how different socio-technical configuration may influence the uptake and diffusion of biogenic materials, a comparative study of different national construction industries will be able to shed crucial light on different measures necessary to drive the development – and not least how transnational challenges, which the climate crisis is an exponent of, can be coordinated. Second, the study has focused on an industrial level. This means that questions about who is willing and able to assume the role of niche manager has not been addressed. While it often is the state or public client organizations that are mentioned as change agents in the construction industry (cf. Rasmussen et al., 2017), other types of actors may assume this role as well. In the context of the increasing neo-liberalization of industries across the globe, it is plausible that private companies will assume a role in promoting and managing various developments. However, as Flynn and Hacking (2019) have discussed in relation to the circular economy, the issues we face may be 'a challenge too far' for existing neoliberal environmental governance. This is corroborated by our findings that problematize the role of existing powerful incumbents in the industry that may prevent the uptake of new technologies. Future research looking into barriers and drivers of sustainable development and building materials could benefit from scrutinizing more closely the role existing corporations play in promoting or stifling innovation.

### CRediT authorship contribution statement

**Stefan Christoffer Gottlieb:** Conceptualization, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Nicolaj Frederiksen:** Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Lars Fjord Mølby:** Writing – original draft, Formal analysis, Writing – review & editing. **Lasse Fredslund:** Writing – original draft, Writing – review & editing. **Mikkel Bruun Primdahl:** Formal analysis, Investigation. **Torben Valdbjørn Rasmussen:** Conceptualization, Funding acquisition, Writing – review & editing.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Data availability

Data will be made available on request.

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## Appendix

**Table A1**
Hypotheses and issues as a starting point for the interviews.

| Dimension | Barriers identified |
|---|---|
| Culture | - There is no awareness of biogenic materials among consumers<br>- Biogenic materials are seen as less valuable than traditional materials |
| Infrastructure | - A full Danish production and use of biogenic materials will lead to significant industry shifts and new professions<br>- There will not be sufficient production capacity in the foreseeable future to cover the total potential need for biogenic materials<br>- The recent investments of companies in their production apparatus have locked them into their 'conventional' production |
| Technologies | - Although there are 'mature' biogenic solutions in markets, lack of knowledge about use, execution practices, etc. will constitute a barrier to their use |
| Markets and users | - There is a lack of standards to support the diffusion of biogenic materials<br>- There is no demand for biogenic materials that are perceived as less durable (and expensive) than traditional solutions and materials |
| Policies | - The building regulations directly or indirectly constitute a barrier to biogenic materials, as they exclude biogenic alternatives to existing materials through formulations and performance requirements (e.g., fire or energy requirements)<br>- Full use of biogenic materials can only be ensured through national or EU legislation that applies to the entire industry<br>- It calls for a broad 'policy mix' of requirements as well as subsidies if the potential for biogenic materials is to be fully exploited in relation to the climate accounts |
| Techno-scientific knowledge | - A lack of knowledge about service life, durability, and general technical joint ownership means that the risk of using biogenic materials will deter their use<br>- Existing decision-making tools (e.g., life cycle analysis and life cycle costing methodologies) counteract the diffusion of biogenic materials in the short and medium term, as their calculation assumptions are misleading or deficient |
| Industrial networks | - Manufacturers of biogenic materials are kept out of the market and their products are actively discouraged due to existing economic interests of existing players |

**Table A2**
Summary of identified barriers to biogenic materials.

| Dimension | Barriers identified |
|---|---|
| Culture | - Considerations to the use of biogenic materials are made too late in the project to be included in the design<br>- Different professional perceptions, myths, and prejudices regarding biogenic materials exist |
| Infrastructure | - Low interest in investing in research to establish the suitability of biogenic materials<br>- Lack of teaching in biogenic materials |
| Technologies | - Lack of technical understanding regarding how to build with biogenic materials<br>- Little knowledge of the application possibilities of biogenic materials |
| Markets and users | - Biogenic materials have a bad image being seen as inferior to conventional materials<br>- The responsibility for diffusing biogenic materials is unclear and risky<br>- Price is a barrier |
| Policies | - Building regulations promote the choice of conventional materials |
| Techno-scientific knowledge | - Lack of experience feedback with biogenic materials<br>- Insufficient documentation of the technical properties of biogenic materials |
| Industrial networks | - Company-specific experiences with biogenic materials are not shared across the industry |

**Table A3**
Identified measures to promote biogenic materials on short, medium, and long term.

| Dimension | Measures to promote biogenic materials | | |
|---|---|---|---|
| | Short term | Medium term | Long term |
| Culture | - Biogenic materials must be selected and considered at an earlier stage in construction projects<br>- Examples of good architectural solutions using biogenic materials | - Biogenic materials must be dis-associated with self-building | - Companies must acquire knowledge of and develop practices that enable them to design and build with biogenic materials |
| Infrastructures | - More focus on biogenic materials in construction educations | - Experiments with biogenic materials in construction education and securing construction skills | - Transformation of existing construction practices through the education institutions |
| Technologies | - Improved availability of knowledge on materials and identification of areas of application | - Need for product differentiation<br>- Pre-accepted solutions to be used across professional boundaries | - Continued development of new products and solutions |
| Markets and users | - Need for professionalization of clients<br>- Companies have to see biogenic materials as a competitive advantage<br>- Price must be calculated according to a holistic consideration | - Increased use of biogenic materials will lead to economies of scale | - Biogenic materials are competitive alternatives |
| Policies | - None identified | - Implementation of experimental buildings using biogenic materials<br>- Public clients must take the lead | - Changes in building legislation and rules regarding building work |
| Techno-scientific knowledge | - Consultants and contractors must seek out knowledge about biogenic alternatives to conventional building materials<br>- More and better documentation of biogenic materials | - Manufacturers must document the suitability of new biogenic materials<br>- Well-documented solutions must be incorporated into common industry standards | - Long-term documentation<br>- Collect knowledge on the lifecycle of biogenic materials |
| Industrial networks | - Ongoing collection of experience and documentation of the suitability of biogenic materials | - Industry organizations must show interest in biogenic materials<br>- Knowledge exchange between companies | - Establishment of networks/associations for biogenic materials |

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