Exploring Opportunities for Bio-Based Materials: Comparative Case Studies in Modular Housing Construction

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Student name : Arika Dhia Suryana
Student number : 5368901

in collaboration with Circular Building and Area Development graduation lab

at LDE Centre for Sustainability

Graduation committee

Chair:

Dr.ir. A. (Ad) Straub;

Department of Management in the Built Environment, Faculty of Architecture.

Supervisor:

Dr. Daniel Hall;

Department of Management in the Built Environment, Faculty of Architecture.

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TU Delft Delft University of Technology

Centre for Sustainability Leiden•Delft•Erasmus

Executive summary

The housing shortage remains a major concern in the Netherlands. The growing demand had been primarily stemmed from the positive foreign migration and the shift in household composition. With the constant escalation, 100.000 new dwellings including 15.000 flexible housing are targeted to be constructed annually from 2021 until 2030 (Ministerie van BZK, 2022).

However, the housing industry is not only suffering from low labour productivity and the pressing order to deliver affordable units, it is also struggling to reduce its resource consumption and waste production. The sector already accounts for 4% of global energy use and 9% of worldwide emissions. This highlights its alarming environmental impacts, especially after the declaration of Paris Agreement and Sustainable Development Goals that officially addressed the battle of global warming as a mutual goal and an international priority.

All of the above amplify the pressure on the Netherlands to actively look for future-proof housing solutions. This research is intended to expedite circular economy implementation as a promising solution by studying the combination of bio-based material and industrialized construction applications. The links between the adoption of bio-based construction materials and industrialized construction practices were investigated to help the development of practical, scalable, and cost-effective housing solutions.

Desk studies were carried out to gather relevant literature regarding bio-based construction materials and industrialized construction principles as the foundation of the research. Comparative case studies of three different modular construction companies were conducted afterward as exploratory research. The findings represent the current integration of bio-based material and industrialized construction in the Dutch construction companies, while the interpretation of the pattern from the cross-case analysis is valuable to identify the enablers and barriers as well as to formulate further strategies in improving the integration.

The use of bio-based or natural materials has been indicated to have prospective reductions in energy consumption, emissions, and costs. Their beneficial impacts have been particularly studied in walls, insulation, and façades applications. On the other hand, industrialized construction refers to the adoption of manufacturing methods in the construction industry with eight main principles: prefabrication, embedded technical systems, planning and control, integrated logistics, long-term relationships, ICT utilization, reuse of experience, and market-focused orientation. This way, houses are being produced instead of constructed which leads to better quality, shorter construction time, and less waste generation.

The case studies show that the integration of bio-based material is even more difficult in modular construction. It shows that the adoption revolves around wood products due to their proven quality and reliable supply. While acknowledging the potential and benefits of bio-based materials, construction companies perceive material replacement not as the most cost-effective option, making the adoption of bio-based materials to the existing system a formidable task. Additionally, the study also underlines the insufficiency of bio-based materials' performance and capacity to fulfill larger-scale modular building production.

Strategic pathways for IC companies encompass supply chain integration to scale up production capacity and joint R&D to speed up product development. Together with the regulatory bodies, companies can increase engagement in bio-based construction to attract more players and develop clear regulations to mitigate the potential misuse of IC applications.

Acknowledgement

This thesis research has been a deeply personal journey. I embarked on my research with embryonic provisions on bio-based materials, modular building, and the whole network in between. This period of exploration has been enchanting and I would like to my biggest gratitude to those who have taken part in the process.

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As I conclude this project, it becomes evident that our journey towards sustainable and circular living is far from over. I hope that we can spread the message and align us closer to our shared objectives. May you find this report engaging with valuable insight and can contribute to a bigger landscape.

Arika

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List of abbreviations

AGV	*: Automated Guided Vehicle*
AP	*: Acidification Potential*
BENG	*: Bijna Energieneutrale Gebouwen*
BIM	*: Building Information Modelling*
CE	*: Circular Economy*
CLT	*: Cross Laminated Timber*
CME	*: Construction Management and Engineering*
ETO	*: Engineer-to-Order*
EPD	*: Environmental Product Declarations*
EPS	*: Expanded Polystyrene*
FSC	*: Forest Stewardship Council*
GWP	*: Global Warming Potential*
HQ	*: Headquarter*
IC	*: Industrialized Construction*
LCA	*: Life Cycle Analysis*
MIA	*: Milieu-investeringsaftrek*
MPG	*: MilieuPrestatie Gebouwen*
NBS	*: Nature-based Solutions*
PO	*: Purchase Order*
SDG	*: Sustainable Development Goals*
SCC	*: Supply Chain Council*
SI	*: System Integrator*

1. Introduction

This chapter introduces the context of the research including the background, problem statement, research objective and scope, relevance to the study program, and report outline.

The accelerating effect of global warming in recent years has brought the discussion of climate change to the forefront. The effort to slow down the pace had been intensified following the 2015 Paris Agreement and the Sustainable Development Goals. The United Nations (2015) demands its members to come up with strategies and take action to reduce carbon emissions.

In response, the Netherlands committed to a national target of achieving carbon neutrality and circularity by 2050. The Dutch government has been actively investigating measures and their potential impacts to be integrated into the policy (Rijksoverheid, 2023; Rijksoverheid, 2019). Innovation programs had been launched to develop large-scale, rapid, and economic improvements. This includes short-term efforts to develop, demonstrate, and roll out potential solutions, as well as long-term efforts to ensure progressive research and development. Among the many measures being explored, the building sector become a critical concern given the significant carbon contribution from the materials and the long lifespan.

The housing industry in particular offers immense potential for transformation as 'future-proof' solutions that integrate energy-neutral, climate-adaptive, nature-inclusive, circular, and bio-based principles (United Nations Environment Programme, 2022; Abey & Anand, 2019; Provincie Zuid-Holland, 2023). Bio-based materials, specifically, have attracted attention as a potential solution to mitigate the environmental impact associated with building life cycles. Over the years, the government has actively promoted the adoption by incubating experts and practitioners to work on the applicability and scalability of bio-based materials in building construction. While research indicates that bio-based materials could reduce carbon footprints, their industrial-scale adoption remains very limited.

Bio-based material adoption is often associated with the enforcement of the circular economy (CE) model, addressing raw material availability and climate impact-related issues. It plays a crucial role in closing the loop as regenerative and biodegradable resource alternatives. The pursuit of CE in the building environment encompasses five principles of prolonging product lifespan, minimizing material consumption, selecting sustainable materials, and shifting the preference towards locally-based activities, as shown in Figure 1-1 (Dąbrowski, et al., 2023).

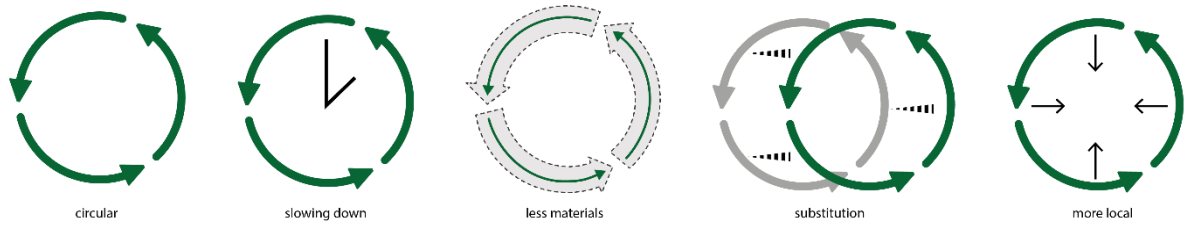


Figure 1-1. Circular economy principles (Dąbrowski, et al., 2023)

Furthermore, affordability was identified as a key driving force for CE implementation in the construction sector (Vermeulen & Willemse, 2021). This leads to the coupling with industrialized construction (IC) methods which not only enhance circular designs and practices but are also advantageous in terms of speed, cost-efficiency, lower failure costs, improved quality, and decreased inconveniences. The transition away from traditional construction methods will minimize on-site operations that generate significant amounts of residual materials and rely heavily on the usage of

construction equipment (Horman & Kenley, 2005; Sandanayake, et al., 2016). Besides being associated with CE, IC also presents viable solutions to prevailing housing shortages due to its rapidity and temporary nature. The local government has set the ambition to construct 50% of its housing stock industrially as part of its commitment to achieve the construction target (Provincie Zuid-Holland, 2023).

In addition, the selection of locally sourced materials as one of the CE principles holds immense potential for substantial reductions in both material consumption and emissions (Pomponi & Moncaster, 2017). Research indicates that the inclusion of local sources contributes significantly to the sociocultural landscape and serves as evidence of the impact of transportation on the total environmental performance of construction materials (Göswein, et al., 2018; Pomponi & Moncaster, 2017). Local material cultivation and production can conceivably release the Dutch dependency on importing raw materials which makes them vulnerable (Vermeulen & Willemse, 2021).

The deliberate integration of bio-based materials, industrialized construction, and the utilization of local resources, therefore, not only contributes to the achievement of circular and zero-emission targets but also plays a crucial role in improving the productivity of the construction sector itself and local communities.

1.1. Background

The Netherlands has been dealing with a severe housing shortage for years. This is majorly caused by residential choice that is reflected in domestic migration and changing household composition. Such an urban area attracts certain groups with technical capabilities. Highly educated, first-generation immigrants, and young singles have been proven to have big orientations toward the cities (Booi & Boterman, 2020). Therefore, the availability of housing stocks significantly influences regional labour supply and productivity (Thompson-Fawcett, 1997; OECD, 2007; Boelhouwer, 2017; Vermeulen & van Ommeren, 2009).

Besides the residential choice, there is also a constant population from international migration and natural population growth. According to statistical data, the number of households in 2021 was calculated at about 8.04 million and is expected to increase to approximately 8.66 million by the year 2030 (CBS, 2023). A significant proportion of 78% projected population growth is expected to be attributed to positive foreign migration, whereas only less than 25% is accounted from natural growth. This phenomenon is projected to result in the estimation of 7.4% population growth and a total of 8.9 million homes by the year 2035 (Gopal, et al., 2021).

Both factors, residential choice and population growth, lead to a deficit of around 279,000 housing units. This makes up for around 3.5% of the total housing stock. It is anticipated that the shortage will reach its highest point at 3.9% in the upcoming year 2024. The ultimate goal of the regulators is to attain a housing shortage of 0%, aiming to always have available housing stock for the coming households and lowering the current immense effect of housing stock on the housing price (Gopal, et al., 2021; Boelhouwer, 2017).

70,000 new dwellings were previously targeted to be constructed annually (CBS, 2023). However, the growth in the number of households outpaces construction, prompting a total target of building 900,000 new dwellings by 2030, 100.000 units including 15.000 units of specific flexible housings annually (Ministerie van BZK, 2022). These efforts aim to not only increase the quantity of housing units but also to create future-proof housing that prioritizes sustainability, quality of life, and safety. While progress has been made, there are doubts about the current trajectory's adequacy to achieve climate neutrality by 2050. Given the highly ambitious target, European Commission (2023) had issued

country-specific recommendations for the Netherlands to speed up the construction process, take into account fast housing, and large-scale construction.

1.2. Problem statement

Construction had been running on a take-make-dispose system, which relies heavily on virgin raw materials and generates substantial waste (Ellen MacArthur Foundation, 2015). Construction sector notably stands as a prominent contributor to global material intensity (OECD, 2019). European Commission reported that construction and demolition waste was the largest waste stream in the EU, with 450-500 million tonnes produced annually taking one-third of the total waste (Embureau, 2022; Bilsen, et al., 2018). According to the Global Alliance for Building and Construction (2016), the building and construction industry accounted for 31% of the overall energy consumption, equivalent to 122 exajoules, and around 40% of the total energy and process emissions on a global scale in the year 2014. In spite of the introduction of the Sustainable Development Goals in 2015, the sector has no significant improvement, accounting for 34% of total energy consumption (135 exajoules (EJ)) and 37% of global energy process emissions ($10GtCO_2$) (United Nations, 2015). Housing construction operations alone were responsible for 4% of global energy consumption and 9% of emissions, establishing the housing industry as the second-largest global emitter (United Nations Environment Programme, 2022; Circle Economy, 2022).

In addition to the high energy consumption and waste generation, the construction sector struggling to provide affordable housing and has low labour productivity, which is ranked as one of the lowest labor productivity among all economic sectors (European Construction Sector Observatory, 2019; McKinsey Global Institute, 2017). The upward trend in construction costs is heavily affected by the increasing labor cost, followed by the more rigorous building standards and regulations and the rising material prices (Pittini, et al., 2017). While digital innovations slowly allow productivity enhancements, factors such as skills shortages, indigenous material depletion, stringent quality requirements, rapid economic growth, and urbanization continue to hinder the sector's productivity (European Construction Sector Observatory, 2019; Pittini, et al., 2017; Gann, 1996).

Furthermore, in order to prioritize the preservation as much as possible green spaces, the government desires to concentrate housing construction efforts in urban areas. However, as urban areas in general host 56% of the global population and 80% of the global GDP, this approach exacerbates existing challenges that urban areas have already responsible for 60% of resource consumption and 70% of waste globally (Circle Economy, 2022; The World Bank, 2020). Urban areas are also responsible for 70% of global CO_2 emissions due to high dependency on fossil fuels and carbon-intensive materials, makes it crucial to minimize carbon footprints during construction work (Dasgupta, et al., 2022). Although rapid urbanization poses threats to housing stocks, it also presents an opportunity, as a study shows that larger cities tend to produce lower emissions per capita (Cheng, et al., 2022). Population agglomeration demonstrates potential for more efficient climate change mitigation and wider transition in energy efficiency improvement and carbon intensity reduction.

Amidst these challenges, global demand for raw materials has been tripled since 1971, with construction materials consuming nearly half of global resources in 2019 (Hanemaaijer, et al., 2023). According to the OECD (2013), there was an 80% growth in the extraction of construction minerals from 1980 to 2008. With the current production chain, the security of supplies are highly depend on the volatile external conditions such as political influence. The urgency of overcoming the crisis is also because of the rapid environmental impact of raw material extraction and process.

Circular economy (CE) emerges as one solution to address multiple societal problems including climate change, loss in biodiversity, environmental pollution and supply risk (Hanemaaijer, et al., 2023).

However, Circularity Gap reports a decline in the global circularity rate from 9.1% in 2018 to 8.6% in 2020 and 7.2% in the latest 2023 report (Circle Economy, 2023). Although the number of circularity rate of each year is hardly comparable, this decline can be attributed to the rise in global material extraction for durable product which lack of material cycling.

1.3. Research objective and scope

As an integral part of the CE vision, the Netherlands has proactively translated international agreements into tangible action in a top-down manner. The Dutch government has developed transition agendas and policy frameworks, which encompass a complete roadmap including in the construction sector. The Circular Economy Implementation Programme has brought together government institutions, companies, and organizations in a collaborative effort to accelerate the transition (Rijksoverheid, 2018). The goal is to present a conducive and supporting ecosystem that accommodates the transition toward CE.

On the other side, there are bottom-up approaches focusing on scaling up innovations and practices at the product level (Dąbrowski, et al., 2023). Various examples of circular construction products have emerged across the value chain, encompassing construction material producers, building system manufacturers, and construction companies by incorporating bio-based resources and industrialized construction (IC) concepts. Despite their dispersion along the value chain, the interconnectedness of these movements holds the potential to amplify their collective impact through efficient integration. More research to create an environment that not only optimizes bio-based material use, but also fosters a conducive landscape for new entrants to thrive in the sustainable construction business, therefore, will be valuable.

The urgencies stated above drive an immediate implementation of bio-based material adoption in the industrialized construction sector. Despite this urgency, research and practical integration at the intersection of these two fields remain limited. This research aims to understand the relationship between bio-based materials and industrialized construction. The purpose of the research is to help filling in the gap between research and commercialization of bio-based materials in the industrialized construction sector. To accelerate the implementation, the study will identify barriers that impede the acceptance of bio-based resources and utilize these insights to formulate strategic recommendations to integrate bio-based materials and industrialized construction. The research focuses on the available bio-based materials and IC methods in the market, observing existing housing manufacturers in the Netherlands.

1.4. Research question

Based on the objective of the research, the research was designed to answer the main research question as follows

> “How to integrate more bio-based materials in industrialized construction systems?”

To answer the main question, five sub-research questions are formulated:

1. What are the applications of bio-based materials and industrialized construction in the building industry domain that has been identified in academic literatures?
2. How do Dutch industrialized construction companies incorporate bio-based materials in their systems?
3. What are the enablers and barriers to adopt bio-based materials in the Dutch industrialized construction systems?
4. How can industrialized construction companies enhance the performance of their supply chains?

5. What are strategies to adopt bio-based materials in the Dutch industrialized construction systems?

1.5. Relevance to construction management and engineering

Construction is there to fulfil human need for infrastructure that has evolved over time, transitioning from basic methods to complex systems and structures, shaping the built environment, and enriching quality of life. Its complexity makes it possible to create larger and more aesthetically pleasing infrastructure with advanced functionalities. Infrastructure construction interconnects people and provides the foundation for societal advancement in other sectors. Construction Management and Engineering (CME) program is structured to prepare students with the ability to design clever construction projects with effective coordination by using smart tools and models.

The advance development of IC can be a pivotal point in the construction sector, representing the future that could potentially supplant traditional approaches. IC emphasizes transformative changes in key areas of design and engineering processes, procurement and supply-chain management, on-site execution, digital technology, advanced automation, and the workforce. It brings innovations to reform the industry dynamics and regulation in a wider sense. According to the McKinsey Global Institute (2017), the adoption of IC oriented upon innovation that has the capacity to greatly augment both productivity and quality within the construction industry.

One of the CME focus points is the integration of the construction sector in a broader economic, societal and environmental context with a specific emphasis on the sector's adaptability to the emerging challenges. With collaborative and iterative process, CME has the effort and design research that interplay between interdisciplinary process and technological innovations. It is important for CME academic research to act as the circular initiatives in infrastructure within the Dutch and global context. Similarly, this research engages with an interdisciplinary study of bio-based materials and IC, serving as a strategic approach to align construction practices with the transitioning CE landscape. Its initiation form requires collaboration between parties to rethink about the design and procurement in the sector which guarantees their suitability for both governmental and market adaptations.

Moreover, not only must construction practices minimize environmental footprints, but they should also enhance durability and recyclability to align with the extended lifespan of buildings (European Commission, 2015). The assessment of the life cycle performance of new construction is of utmost importance, as it enables the data availability, efficient material transfer, and the raise the awareness of sustainable building market (European Commission, 2014). The European Commission (2015) has given priority to the construction and demolition industry, as well as the biomass and bio-based products sector. This prioritization is based on considerations such as the value chains, environmental footprint, and material dependency of these sectors. This strategy highlights the importance of both sectors in promoting sustainability, prompting current stakeholders and new entrants to proactively adjust their practices in accordance with the sustainable and circular goals.

1.6. Report outline

Chapter 2: Methodology

Chapter 2 outlines the approach of the research, including literature review and case studies. Followed by the elaboration of data collection, data processing, and data analysis in the subsequent sections.

Chapter 3: Theoretical Background

Chapter 3 answers the first sub-question of the research. It presents the literature findings regarding the benefit of bio-based material and its application in wall, insulation and façade building system. IC

principles are elaborated in adapting the manufacturing concepts to the construction sector. It also gives the basic knowledge for further research in the following chapters.

Chapter 4: Case-study result

Chapter 4 presents the findings of the research. The findings are organized to provide an overview of the modular construction companies, followed by their roles as system integrators and their target markets. Subsequently, their adoption of bio-based materials and industrialized construction methods are explained. Lastly, an exploration of their future prospects are described.

Chapter 5: Cross-case analysis

Chapter 5 presents a cross-case analysis of three cases that look into the adoption of bio-based materials in modular building systems, the implementation of industrialized construction principles within their manufacturing process, and the performance of their respective systems and supply chains.

Chapter 6: Discussion

Chapter 6 elaborates on the implications derived from the cross-case analysis conducted in the previous chapter, particularly focusing on bio-based material adoption in modular construction, adding bio-based variance in modular construction, the inclusion of bio-based material in modular construction planning, and future strategies to nurture a bio-based industrialized construction ecosystem. The limitations of the research are also presented.

Chapter 7: Conclusion and recommendations

Chapter 7 concludes the research by elaborating the research findings in accordance with the research question along with recommendations and further research.

2. Methodology

As the research aims to address the question “How to integrate more bio-based materials in industrialized construction systems?”. The objective, to understand how industrialization in the construction industry can facilitate the adoption of bio-based material, is suitable for exploratory type of research. Exploratory research enables a comprehensive investigation of the topic, discovering underlying connections between bio-based materials and industrialized construction domains. This type of research does not only seek the connections but also serves as a foundation for hypothesis formulation (Verschuren, et al., 2010).

In the pursuit of comprehensive learning, a qualitative approach is ideal for exploratory research in order to grasp the actual meaning of the collected data. Qualitative approach is better in capturing and interpreting verbal data than quantitatively. This approach also gives reflective and descriptive results in a societal context.

By using the combination of desk and empirical study, it serves as extensive previews of the potential association between these two concepts and increases the overall accuracy of the research. The desk study will gather related information from existing literature and be used as the basis of the empirical research from reputable sources to achieve the research objective. By integrating relevant perspectives, this methodology not only guarantees an in-depth understanding but also establishes the foundation for a thorough examination of the interconnections between the two concepts.

2.1. Literature review

The literature review was conducted to gather information regarding the applications of bio-based materials and industrialized construction in the building industry domains. It focuses on the research findings of potential implementation to answer the first sub-research question “What are the applications of bio-based materials and industrialized construction in the building industry domain that has been identified in academic literature?”. As the foundation of the research, existing academic literature presents the investigations within each domain that are not connected yet in their practical construction industry.

Because both bio-based material and industrialized construction research are common in a variety of industries, a collection of papers was chosen based on their availability and relevancy. The availability was subjected to the accessibility to their full version, while relevancy is subjected to the relation to the topic of interest. The literature collection was gathered from relevant academic papers, scientific reports, institutional databases, and official documents. The snowballing technique expands the scope of the search by extending beyond a single reference or author. The literature review was conducted in the following order:

- Verifying the availability of the defined topic using keywords.
- Screening findings based on their relevancy to the research.
- Gathered more sources from the selected document citations and authors.

In order to find useful articles, certain keywords that reflect the concepts are used. The keywords include general criteria, specific characteristics, or synonyms. Individuals or combination searches were screened to provide a broader range of scholarly sources. Adding ‘interdisciplinary’ keyword can curate the selection from various fields of study.

2.2. Case studies

In this research, a case study was formulated to address the second through fifth sub-research questions based on industrialized construction systems in practice. Multiple case studies help to

provide insights into the practical incorporation of bio-based materials and industrialized construction, the barriers and enablers influencing the adoption of more bio-based solutions, supply chain performance, and strategies for broader adoption.

The case study method, particularly an exploratory case study, is employed to examine novel landscapes in which there are information about the phenomenon, but the problem has not yet defined (Yin, 2017). It reflects the same situation with what hinder the implementation of bio-based material in construction industry. Even if there are prospective aspects such as cultural, economic, technical, political, or combinations that might cause the phenomenon, the real cause is still unclear because the context is multidimensional. This method is appropriate for acquiring the prevailing behaviours of IC firms towards bio-based material alternatives. Furthermore, due to the emerging state of the topic and non-standardized industrialized construction system, single case study is considered not to be representative. Conducting multiple case studies with various systems and settings are preferable for better generalizability and validity.

The target group in this research are industrialized construction companies in the Netherlands. More specific the study targets existing industrialized construction firms that have integrated bio-based material into their building systems. In this case, the two possible groups are modular construction companies or panelized construction companies. The similarity within the cases is that they are members of the bio-based construction networks that are facilitated by local governments. The interview participants, representing their respective companies, were not confined to specific roles, allowing for the inclusion of multiple standpoints. The diversity in cases and roles can enhance the thoroughness of the findings. Finally, modular builders are selected to be the cases as they have sufficient degrees of both bio-based materials adoption and industrialized construction methods.

Individual case studies were conducted separately and analysed to get a cross-case conclusion. The cross-cased analysis was done to recognize patterns across the individual cases to deliver the findings in a report. Ten other sources were also interviewed, comprising four material providers, three component manufacturers, a modular builder, and a consultant, to gather more insights for a broader range of perspectives.

The case studies are conducted following the steps suggested by Goodrick (2014).

- Clarifying the research question that need to be addressed.
- Identifying the case criteria.
- Selecting the cases.
- Defining data collection and processing.
- Considering alternatives explanations.
- Writing the findings.

2.3. Data collection

Semi-structured interviews were conducted with representatives of each case as data collection method to acquire primary data. With a designated guidance based on the subsequent research questions and theoretical findings, a list of open-ended questions were given to the participants. This enable the interviewer to provoke further explanation and allows the participant to elaborate their answers based on their experiences and concerns. Participants were asked to give a brief explanation about the company as the opening question of the interview to get the idea of what they want people to know about their company as its core value. Follow-up questions were given to explore how and why they chose to integrate bio-based materials into their production.

The semi-structured interview has the advantage of finding out unforeseen interests which fit the exploratory purpose of the research. Data collection must be maintained to keep the independent thoughts of the participants while also covering topics that are difficult to be written in official documentation or in the presence of other peers (Adams, 2015). Semi-structured interview is crucial in discovering new insight on the topic where very limited information about the bio-based implementation is not shown in official documents.

Ethical guidelines concerning were followed in regards of the interview confidentiality. Participants had been given informed consent prior to the interview and had given their consent to record the interview and the content are being used for research purpose. This is to ensure that their voluntariness and prevent any harm to the participants personal information. Personal data including name of the interviewee and email address are not revealed in the transcription and only anonymized quotes are presented.

The interviews are conducted via Microsoft Teams, a platform chosen for its convenience with regard to recording purposes. The data collection process unfolds as follows:

- Formulating interview protocol and interview questions based on research questions and academic literature findings (Appendix A: Interview protocol).
- Preparing Human Resource Ethics Committee (HREC) forms, Informed Consent, and Data Management Plan (DMP) to ensure data protection and provide data processing information (Appendix B: Research ethics).
- Sending interview requests to potential participants.
- Sending informed consent and research information to the participant prior to the interviews.
- Conducting and recording the interviews.
- Using the interview recording for analysis.

2.4. Data processing

Interviews are the main source of data in this research. The interview recording were auto transcribed and manually edited to correct misinterpretation. Reassessment of the transcripts were done by repeatedly run through the file to understand the real meaning of the conversation and denote the true content of the interview. Using Atlas.ti software, codes are assigned to label notable quotes in the transcription file. The codes present patterns to be categorized into more general themes for thematic analysis. Thematic analysis method is used to identify and analyse the themes with flexibility of its interpretation. It aggregates the raw interview data and organize the data set (Braun & Clarke, 2006). Inductive or bottom-up coding process used the contents of the interview to determine the codes. The data set forms the themes without preconceptions that is appropriate for explorative study. Thematic analysis helps to summarize the key aspects, giving structure and description to the data set. Frequent review and check of the theme are to ensure that the themes content are internally coherent and unique between one and the other. It also suit the purpose of the research to interpret societal and psychological aspect, perceive unforeseen feedback, and has the flexibility to work on multiple frameworks. Data processing were done based on thematic analysis (Braun & Clarke, 2006) as below:

- Getting acquainted with the data by transcribing, reading, and re-reading.
- Coding notable quotes across the data set.
- Finding themes from the coding patterns.
- Verifying themes in accordance to the quotes.
- Defining themes to turn descriptive empiric to theory.

Validity of the research is considered as how well the findings can be generalized to other contexts and settings (Sekaran & Bougie, 2016). Interview protocol can be reused to replicate the study in the same context and case criteria with different and population samples. Reliability of the research refers to the data interpretation consistency when analysis is done by other researcher (Sekaran & Bougie, 2016). Some direct quotes are presented to highlight the key findings instead of interpreted summaries. Comprehensive elaborations are also provided to let the reader get better perspective of the participants.

2.5. Data analysis

2.5.1. Cross-case analysis

A cross-case analysis is an assessment method that compare multiple cases as the subject of the study. The cases are compared to one another to identify the similar patterns among them, as well as the distinct features. The description of the similarities and differences observed between each case are used to generate holistic views and explanatory propositions of how bio-based material adoption differ in different industrialized construction system (Goodrick, 2014). Propositions may as well be strengthen from external sources and literature findings. The assessment must be maintained sensitive to new evident, which may arise along the analysis period.

Bio-based materials adoption

The cross-case analysis was conducted to compare the adoption of bio-based materials across building systems. This analysis encompassed the materials used for the foundation, structure, wall, ceiling, insulation, facade, floor, and roof, aiming to unravel the 'why' and 'how' behind their adoption. The exploration is pivotal for understanding the practicality and feasibility of integrating bio-based materials in modular construction systems. By identifying the challenges and bottlenecks, this analysis sets the groundwork to create implementation strategies that can accelerate the transition towards the implementation of bio-based material construction.

Industrialized construction methods

The analysis was then carried out to compare the implementation of industrialized construction methods among the cases based on the eight principles of industrialized construction. These principles include prefabrication, technical system, planning and control process, logistic integration into the building process, long-term relationships with actors, use of ICT tools, measurement and re-use of experiences, and customer and market focus. The analysis focuses on how these principles play a pivotal role in facilitating the adoption of bio-based materials. It is critical to understand what has to be done to accelerate the integration of bio-based materials in their construction system.

SCOR model

SCOR model is utilized to evaluate supply chains, providing frameworks for best practices (Huan, et al., 2014). As construction companies delve deeper into manufacturing processes, they encounter challenges such as fluctuating commodity prices, rising customer expectations, and volatile economic conditions within the manufacturing settings. For those reasons, firms unify their own competencies with the capabilities of their suppliers in supply chain arrangements, forming coordination of material, information, and cash flow (Alomar & Pasek, 2014). This arrangement enlarges the competition from the manufacturer level to the supply chain level. Timely re-evaluation therefore is necessary in order to improve performance, compete, and survive in the long-term. Performance measurement does not only help to avoid unbalances and enable effective coordination, but also in decision-making. It is as important to adjust operations and strategies in order to meet rapid and various business environment changes.

The Supply Chain Council (SCC) is an international non-profit organization established in 1996 with the objective of developing a standardized industry process reference model for the supply chain. The SCC has developed the Supply Chain Operations Reference (SCOR) model as a framework for assessing and comparing supply chain operations and their associated performance. In the SCOR model, processes are divided into plan, source, make, deliver, and return for the firm to fulfil customer's demand. SCOR analysis is used to assess the overall performance of the supply chain process at multiple levels from the strategic level (level 1) to the implementation level (level 4) (APICS, 2017).

Level 1	:	Defines the scope, content, and target of the supply chain.
Level 2	:	Configures the operation process in the supply chain.
Level 3	:	Break down level 2 processes into individual activity and task.
Level 4	:	Implement workflow to Level 3 processes for a specific organization.

This performance assessment is measured by various attributes in order to plan the strategic actions. Performance attributes are used to identify generic supply chain characteristics and to outline supply chain strategy in particular (Palma-Mendoza, 2014). The main supply chain performance attributes are examined by comparing organizations and their strategic choices. According to the SCOR model in 1996, there are five performance attributes: reliability, responsiveness, agility, costs, and asset management efficiency (assets) as seen in Figure 2-1.

Reliability	:	The capability to execute task as expected. Reliability represents the predictability of the goods being delivered in the correct quantity, quality, and period.
Responsiveness	:	The ability to efficiently carry out a task. Responsiveness is reflected on the speed to deliver the goods.
Agility	:	The ability to successfully adjust the market fluctuation. Agility shows how company maintain the competitive position by quickly and accurately modify production based on request or resource availability.
Costs	:	The capacity to efficiently and effectively proceed the task. Cost portrays the profitability by managing the expense to deliver the goods that include labour, material, management, and transportation costs.
Assets	:	The ability to efficiently utilize its assets. Asset management efficiency management through inventory reduction and decision to insourcing or outsourcing.

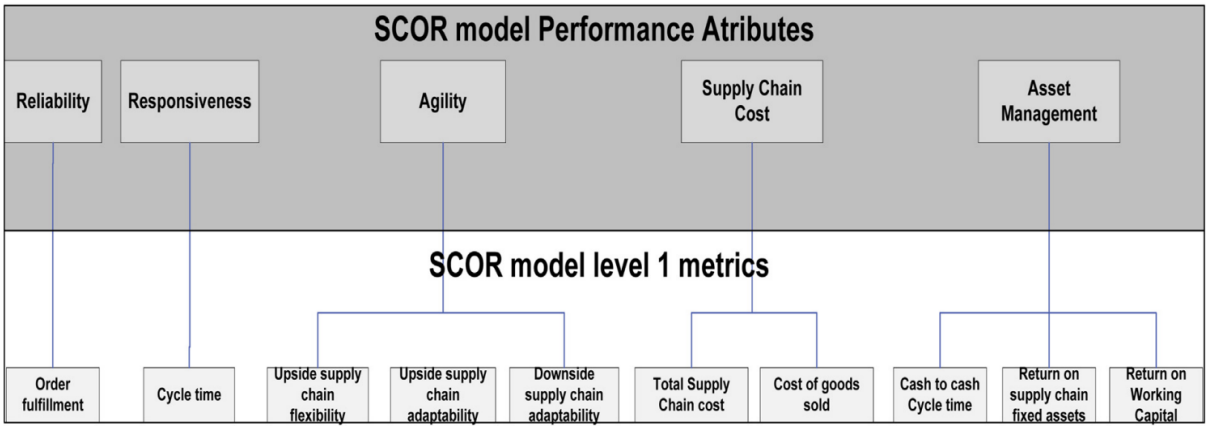


Figure 2-1. SCOR model performance attributes and 1st level metrics (Palma-Mendoza, 2014)

Supply chain performance attribute will be reviewed using SCOR Level 1 analysis. The output of the analysis is combined with SWOT analysis to define desired improvements on the supply chain.

2.5.2. SWOT analysis

SWOT analysis is utilized for strategic planning by analysing both the current situation and anticipated future conditions (Weihrich, 1982). Strengths, weaknesses, opportunities, and threats are organizational factors known as SWOT. SWOT analysis is a procedure performed to assess internal and external factors that may impact future decision-making. It involves identifying both inhibitors and enhancers of performance, analysing these factors in terms of their potential contributions to overall value, and making estimations regarding their controllability (Capon, 2004). Internal performance enhancers are labelled as strengths and internal performance inhibitors as weaknesses. Strength refers to internal competencies, beneficial resource, or characteristic that enhances an organization's position or performance. Weakness refers to the internal limitation to the abilities, assets, or qualities required for good performance or advantages. External impulses are categorized as opportunities, whereas external restraints are known as threats. Opportunity is an external aspect or circumstance that, if leveraged or actively pursued, has the potential to enhance performance and confer a competitive advantage. Threat is the external factor or barrier that could hinder performance and potentially lead to reduced success or unfavourable outcomes.

In a 2-by-2 table or matrix, strategic planning can be designed by highlighting the major setbacks, identifying the options, and focusing on the opportunities as seen in Table 2-1 (Weihrich, 1982). The cross-section between weakness and threat indicates the precarious position that firms want to evade, preventing the weakness to cause the emergence of the threat. The cross-section between weakness and opportunity as well as between strength and threat reflects the firm position. These options include minimizing weakness and the chance of threat occurrence, maximizing strength and opportunity probability, or taking no action, leaving the strength exploited by and opportunity in the hand of the competitor. The cross-section between strength and opportunity emphasizes the strength in exerting the advantage of the opportunity. SWOT depicts the current condition of the company with the expectations and concrete action for further improvement.

Table 2-1. SWOT matrix adapted from Weihrich (1982)

	Opportunity	Threat
Strength	Maximize advantage	Identify options
Weakness	Identify options	Avoid major setback

The interpretation of the pattern from the cross-case analysis coupled with the assessment of supply chain analysis is valuable in deciding whether the efforts to increase the adoption of bio-based materials in industrialized construction settings are in the right direction or to reconsider the current approach.

3. Theoretical background

The initial national climate ambition, which targeted a 49% reduction in carbon emissions by the year 2030, had been raised to a target of 60% (Ministerie van EZK, 2019; Rijksoverheid, 2022). To achieve this goal, the Dutch government is seeking energy-saving solutions that are practically scalable and cost-effective. This chapter presents the theoretical background of the potential of bio-based materials and industrialized construction in the building sector as the basis for further research.

3.1. Bio-based materials

As a widely recognized relationship exists between climate and nature, the government is actively pursuing the implementation of nature-based solutions (NBS) in the fight against climate change (Rijksoverheid, 2022). For building and construction sectors, implementing smart and efficient way of using materials seems as a viable approach that can be done by the substitution of conventional carbon-intensive construction materials with bio-based materials. The shifting towards bio-based material will transform buildings into carbon sinks, not only resulting in far less emission compared to mineral-based material but also positively impacting social well-being (Yadav & Agarwal, 2021).

3.1.1. Conventional construction materials versus bio-based materials

Bio-based materials refer to all natural materials from renewable biological resources (Krasny, et al., 2017). Multiple studies have demonstrated the advantageous characteristics of bio-based materials in comparison with conventional construction materials.

Energy

Energy consumption for a building can be categorized into two main types, the first one is embodied energy and the second one is operating energy. Embodied energy represents the total energy used to manufacture building materials. This includes energy used for production, transportation, and disposal. Bio-based material has significantly lower embodied energy in comparison with conventional construction materials (Garas, et al., 2009; Atkinson, 2008; Jones & Brischke, 2017). The extraction of conventional construction materials requires a substantial amount of energy. According to the comparative research done by Brojan & Clouston (2013), brick walls require 9.4 times more embodied energy than straw bale walls. Given that embodied energy in typical houses in Northern and Central European regions accounts for 10% to 20% of total energy consumption, the choice of material has an important impact on the total energy consumption (Kotaji, et al., 2003).

On the other side, operating energy refers to the energy consumed for operational purposes including heating, cooling, lighting, and other appliances. Bio-based materials have notable insulation properties that can significantly reduce the energy for air conditioning (Garas, et al., 2009). Krasny et al. (2017) demonstrated straw insulation material reduces up to 60% of the peak heating loads in comparison with expanded polystyrene (EPS) insulation, decreasing the overall energy demand by half. Moreover, this substitution is calculated to waste 10 times less energy during day-to-day use.

Emission

Conventional construction materials are mostly derived from fossil fuels. Not only do they consume a lot of non-renewable resources, but their production process also heavily contributes to pollution, ozone depletion, and greenhouse gas emissions. In contrast, bio-based material does not reduce carbon emissions by requiring less energy for its production, it is also capable of capturing carbon during its cultivation period. For comparison, EPS as a conventional insulation material has a significantly higher global warming potential (GWP) with a value of 5, while straw insulation has a negative GWP value of -1.2. in addition to 4 times lower acidification potential (AP). According to Guy-Quint (2006), every cubic meter of wood, that substitutes conventional construction material, results

in the reduction of 2 tons of carbon being released into the atmosphere. With the studies, bio-based materials for building applications have the opportunity to reduce approximately 50% of the total CO_2 emission (Jones & Brischke, 2017; Krasny, et al., 2017; Alcorn & Donn, 2010). It was calculated that building with bio-based material is even more effective in reducing carbon emissions than the combination of using solar hot water, photovoltaics, efficient electrical appliances, and lighting (Alcorn & Donn, 2010).

Recyclability

Bio-based materials offer a remarkable recycling potential of up to 97%, a significantly higher percentage than conventional construction materials. Conventional construction materials have been through long and complex processes, making retrieving the material is difficult task (Garas, et al., 2009; Krasny, et al., 2017; Atkinson, 2008). When recycling bio-based material is not feasible, the inherent biodegradability possesses the ability to naturally degrade down to compose over time. This means they can break down and be used for fertilizer or biomethane production, leaving minimal residual waste for landfills (Jones & Brischke, 2017). Meanwhile, conventional construction material, such as concrete and steel, degrades slowly, taking several decades to hundreds of years to cause waste accumulation.

Financial

On the financial part, multiple studies have modeled the full bio-based house in comparison to their conventional counterparts. The comparative studies highlight an appealing claim that using bio-based material can save about 40% of the total direct cost. The major factor contributing to the decrease in costs is attributed to the reduction in energy consumption to manufacture the materials (Garas, et al., 2009). Studies show that substituting cement bricks with a strawbale wall system can reduce 10% to 14% direct cost and switching concrete slab with wooden-based roof can reduce a substantial 50% of direct cost reduction (Garas, et al., 2009; Brojan & Clouston, 2013).

Indirect cost savings are also achieved by reducing energy consumption from given thermal comfort. Constructing with bio-based materials has the potential to decrease operational costs by reducing the energy demands for heating equipment, air-conditioning units, and lighting, resulting in potential savings up to one-third of overall utility bills (Krasny, et al., 2017; Garas, et al., 2009).

Material performance

Bio-based material has been observed to have a good performance for building systems. In general, the application of wood and vegetal piths as bio-based material has proved to have good thermal performance with low thermal diffusivity and high specific heat capacity, making it an excellent thermal insulation in keeping the temperature stable and comfortable. Additionally, the thermal expansion coefficient is almost zero, which is reliable for building design (Jones & Brischke, 2017). It also performs well in moisture performance. With high vapor diffusivity and high vapor dispersal, the application is suitable for the European climate. The material is able to control moisture, prevent mold, and regulate humidity for a comfortable and healthy indoor environment. Other fine features of straw bale as a bio-based material include excellent performance-to-weight ratios, dimensional and shape stability, and up to 81% acoustic protection (Garas, et al., 2009). The material is qualified for its fire performance, although many studies suggest the need for additional fire retardants (Yang, et al., 2022).

Bio-based material is not only a propitious option with aesthetic appearance and durable quality but also great for the inhabitant's well-being. This is important since conventional construction materials contain carcinogens and neurotoxins, posing significant health hazards to humans. The numerous adverse environmental and health impacts make it harmful to the building environment (Krasny, et al., 2017).

Concluding this section, the adoption of bio-based material in construction industry will help to significantly reduce fossil-based energy demand, carbon dioxide emission and non-degradable waste generation. It also has positive environmental impact from biogenic carbon storage and negative GWP (Sierra-Pérez, et al., 2018). Although it is arguable that both conventional and bio-based material can be equally designed for low operating energy, the impact from material production, construction, and decommissioning of conventional construction material is irreversible (Brojan & Clouston, 2013).

3.1.2. Bio-based materials in building systems

Presently, wood and its processed derivatives have been the primary bio-based alternatives for construction materials. However, a broad range of bio-based materials has been studied. This section explains the application of bio-based material in building systems.

Walls

For the application in wall systems, comparative studies between straw and brick or lime sand were found in many researches. Straw is a type of crop that is cultivated as a byproduct of various crops. This makes the material widely available and requires relatively low energy to produce. Straw evidently shows environmental and financial benefits to improving Global Warming Potential (GWP) by 15% and reducing construction costs by up to 40% (Gonthier-Gignac & Jensen, 2007; Garas, et al., 2009; Jones & Brischke, 2017). Even though straw is lightweight, its application in the wall doubles the wall thickness. It has the impact of using more internal lighting, but at the same time, it is better for noise transfer reduction as well as temperature and humidity control (Jones & Brischke, 2017; Garas, et al., 2009). Performance-wise, straw has comparable thermal performance, fire resistance, and durability. Straw can be a safer substitution for brick and lime sand as they were exposed to radioactive substances from blast furnaces (Krasny, et al., 2017).

Insulation

As the government intends to have natural gas-free buildings for new construction (Ministerie van EZK, 2019), biobased raw materials are expected to be the primary large-scale source of sustainable heat (Ministerie van BZK, 2022). This concept resembles the idea of a passive house, where the building requires no active heating system and is built from local materials. Passive house represents easy access to natural building materials, independent from air-conditioning, and as an easier technique to build and maintain (Krasny, et al., 2017). By incorporating thermal insulation material in building construction, the demand for energy resources is reduced (Adamczyka & Dylewski, 2017). As a result, the initial expenses are offset by substantial energy savings over the years. Economic benefits are most pronounced in regions with cold climates, as well as in buildings with expensive heat sources and affordable insulation materials (Adamczyka & Dylewski, 2017). The optimal thickness can be calculated with regard to power consumption and environmental constraints (Sagbansua & Balo , 2017). As the insulation thickness increases, the emissions and power consumption will decrease. However, the investment for initial installation also rises proportionally with the rising thickness. Calculation can be done for the optimal insulation thickness where the minimal thickness meets the maximal power saving. The energy saving differs between different heating sources.

Façade

Bio-based material façade applications are commonly made from wood, wood derivative, and biocomposite, giving natural appearances to the buildings. As façade, these materials are not form-free. It is important, however, to use a bio-based façade as a complementary when using bio-based material walls. Bio-based materials characteristic that is breathable possess moisture management properties, enabling moisture evaporation from their surfaces. This attribute enhances their durability

by preventing moisture-related decay, mold growth and ensuring better indoor air quality (Krasny, et al., 2017; Exposito, et al., 2023).

Furthermore, Kriegh et al. (2021) came up with twelve criteria for material selection that can be considered to evaluate the potential of bio-based material; development stage, mock-up and prototype potential, state of compliance testing, construction assemblies and prefabrication/modularization potential, carbon-storing potential, data on carbon-storing capacity, potential locations and availability for raw materials, potential for community impact, high impact reward, high risk, reference paper and/or case study exists potential development partners.

3.2. Industrialized construction

To incorporate bio-based materials into IC, the concept of IC first must be explored. In this subchapter, a literature review of the IC concept and principle will be presented in order to gain an understanding and relation to the use of bio-based materials.

The term industrialized construction refers to the switch in the construction sector from a traditional method to a more manufacturing system in which construction takes place in a controlled environment with minimum site works (Fathi, et al., 2012). It had different motives from time to time, to redevelop destructed areas after a major disruption, increase competitiveness in the market, or serve as a solution in various crisis from housing to labor shortages (Amin, et al., 2017; Hashemi, 2013).

Industrialized buildings majorly emerged in the 1960s as large-scale industrialization attempts in the construction sector (CIB, 1966). It introduced a new way of building construction by fabrication and standardized technology. The shift from construction work to manufacturing processes was highly influenced by the effectivity of automobile industry; fragmenting the unit into components, made by machines in the factory, for later assembly (Gann, 1996; Russell, 1981). This way, it can take away up to 33% of the site work, cut the labour cost by up to 50%, improve speed and quality, as well as reduce material waste (Kendall & Sewada, 1987; Gann, 1996). However, the transition could not be significantly executed as the ‘temporary’ project-based nature was not able to recover the required investment and the limitation in manufacturing principles and techniques that evidently could not strive the growing complexity of craft-based construction nature in the construction sector (Garas & Hunter, 1998; Miller, et al., 1995).

Manufacturing works on three main principles; standardization, prefabrication, and systems building (Gann, 1996). Fixed capital is required to establish a factory of machinery to prefabricate standardized designs and ensure control over the structure, tolerance, performance, and installation. The interchangeability allows parts to be mass-produced with faster and more integrated processes, resulting in higher quantity and quality buildings at a reduced cost (Gann, 1996; Crowley, 1998). The process can also be precisely measured, thus efficient calculation of labour and material can be allocated for higher profitability of the companies.

The problem with implementing the principles, unlike manufacturing, construction industry end-product is a large and immobile building, which is harder and more costly to transport (Gann, 1996). Building is highly dependent on site conditions, making each product unique and assembly can only take place at the point of construction makes it hard to control (Gann, 1996). Lack of governmental regulation and experts are leading to difficulties in financing schemes, IC companies struggle with getting adequate and timely capital as it requires high initial cost (Amin, et al., 2017). The gap in technological advance and the fluctuation in raw material price also makes it difficult to maintain a steady cash flow and profitability (Saberi, et al., 2022). Due to the high price and durability of a building, the adoption is subjected to limited market stability and size as it requires a big and stable

housing market to justify the investment and ecosystem reorganization to establish the business model (Gann, 1996).

The adoption of manufacturing principles in construction sector is a trade between economies of scale and economies of scope (Gann, 1996; Robertson & Ulrich, 1998). The aim to scale up the economy and productivity shall not override the customer individual satisfaction (Thuesen & Hvam, 2011). Uniqueness of each product shall be maintained while taking the advantage of mass production efficiency (Pine, 1993). The balance between repetitiveness and distinctiveness only can be achieved by improving and managing the design efficiency in which point the standard production is decoupled with the customization as shown in **Error! Reference source not found.** (Barlow, 1999; Thuesen & H vam, 2011). Technology integration and standardization remain to be the challenges in this matter. At component level, parts changes shall be managed to a minimum to keep the investment in machinery low and to design the part completely and consistently interchangeable in which pushing the assembly cost (Womack, et al., 1990). Strategic stock should be kept at a minimum reasonable level to minimise stock and obsolescence costs while maximising service levels (Naim & Barlow, 2003).

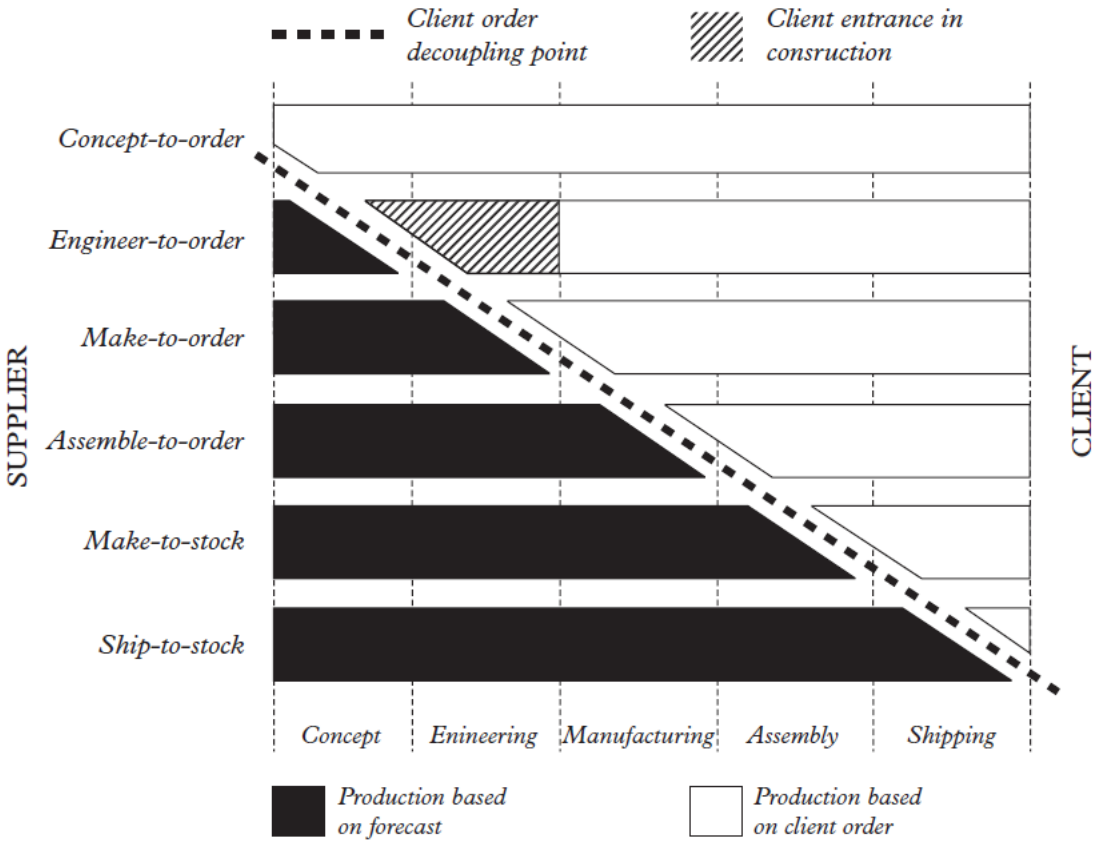


Figure 3-1. Decoupling point between supplier and client (Jansson, et al., 2014)

The perception of industrialised house-building during the first years of the 2000s was partly based on such historical descriptions, with mass production still at the core of the concept (Goodier & Gibb, 2007). “offsite construction”, “preassembly”, “prefabrication”, “system building”, “modern methods of construction” and “industrialized building” are terms that interchangeably refer to IC (Pan & Goodier, 2012). However, the term IC is not limited to manufacturing and prefabrication building system, but continues improvement in its principles. Industrialized construction is now recognized as a complex concept to achieve the highest value by having efficient management with controlled activities, flows, and resources (Lessing, 2006). It enables resource consumption and waste reduction while keeping the value as long as possible by mindful material selection and lifetime extension in an optimized

system throughout the lifecycle (Kedir & Hall, 2021; Adams & Hobbs, 2017; Rahla, et al., 2021). More importantly, IC can be the catalyst for the transition toward a circular economy (Berglund-Brown, et al., 2022).

The advantage of IC is improved safety, weather independence, quality improvement, shorter execution time, higher cost predictability by continuously improve the eight principles of industrialized construction; planning and control process, technical system, prefabrication of building part, logistic integrated into building process, long-term relationship with actors, measurement and re-use of experience, used of ICT tools, and Customer and market focus (Lessing, 2006).

3.2.1. Prefabrication of building parts

With the increasing complexity in the construction project, site-based construction activities were experienced to be inefficient. Moving toward prefabrication method to perform the work in a controlled environment with minimum interference is done to achieve a lean production process (Tykkä, et al., 2010). Taking of the process from site is also increasing the standardization that boosts effectiveness and quality, allowing great deal in cost saving (Ågren & Wing, 2014). It comes to managing the proper balance between integrity and modularity in shifting the conventional on-site construction to off-site prefabrication.

Transforming on-site construction to off-site prefabrication is done by adopting manufacturing nature of making the product in a more standardized way. To get the advantage of the prefabrication while still accommodating customer preference, finding the optimal trade-off between distinctiveness and commonality in product architectures is necessary. Mikkola & Skjøtt-Larsen (2004) strategically approached this with postponement and mass customization strategies. Postponement strategy goes back to the system separation of customization from standardization. The longer manufacture is kept at the standard design, the later the customization of each product. This way, the modularization to higher level as seen in Figure 3-2 (van Hoek, et al., 1999). Mass customization marks the completeness of the postponement strategy. It denotes the implementation of modularity while keeping autonomous innovation and customer focus. The key challenge of implementing mass customization is the variety dilemma caused by frequent design changes and process variations (Jiao, et al., 2007). Receiving as much external input as possible from suppliers can have a significant effect on the ability to mass customize.

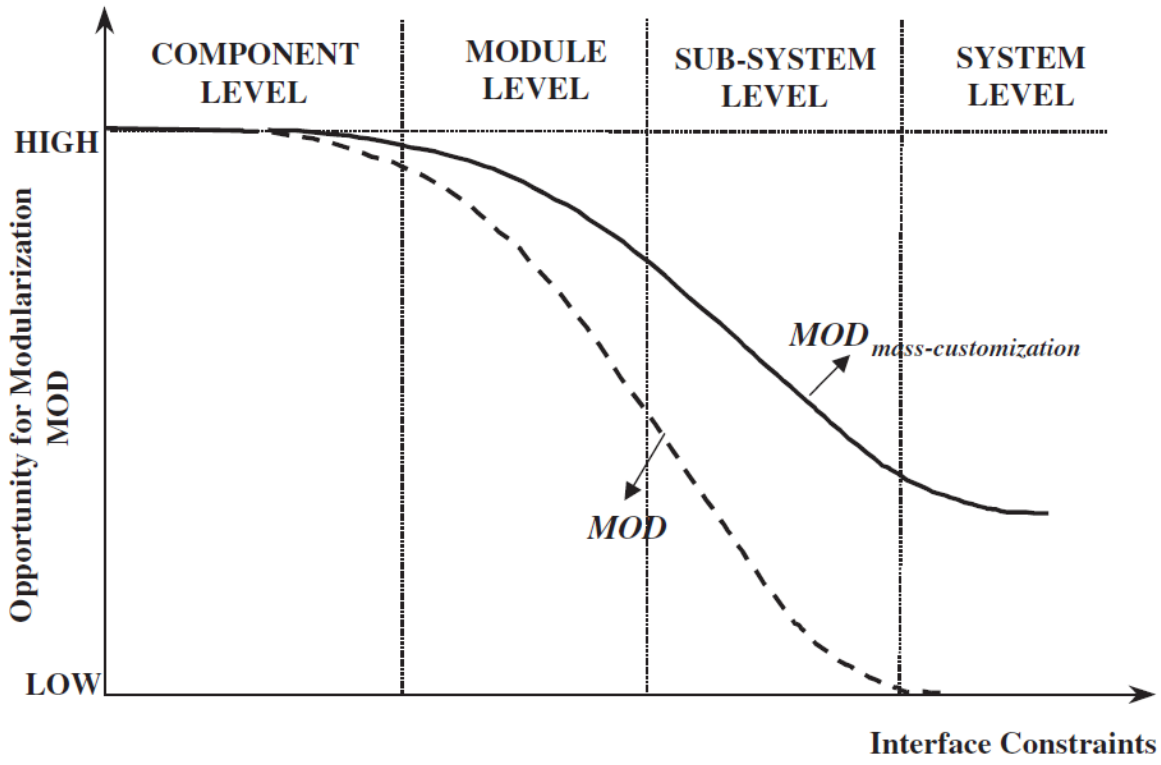


Figure 3-2. The effect of mass customization (Mikkola & Skjøtt-Larsen, 2004)

3.2.2. Technical system

Technical systems refer to the development of technical solutions in the system (Lessing, 2006). Modularity is the approach that construction wants to pursue when adopting manufacturing. The concept is to separate a system into independent parts or modules that can be treated as independent units (Jiao, et al., 2007; Ågren & Wing, 2014). A module refers to a physical or conceptual grouping with common characteristics such as functional commonality, technical commonality, and physical commonality. Functional commonality classifies the modules based on the component functionality, technical commonality categorizes the modules based in their final configuration, and physical commonality sorts the modules based on the interface between components (Salvador, et al., 2002).

Structure-wise, product elements are put together to construct components, families, design, and variety (Salvador, et al., 2002; Jiao, et al., 2007). A component is a group of elements. The task in this level is to determine the configuration between the component interfaces. A family refers to a set of similar components that possess specific functionality, which requires the alignment of customer, product, process and supply chain preferences. Product design is the layout, configuration, or topology of functions and their embodiment that focus on standardization mapping the component functions and focus on component swapping, component sharing, fabricate-to-fit, and sectional modularity.. While a variety is the functional or technical diversity that is offered in the market that further concern in the manufacturability and costs. A modular design displays dominance in product family or higher (Jiao, et al., 2007).

Modularity is also a way to mitigate the risk from having complex architecture to the availability of suppliers. A range of modularity that can be applied in the product architecture. Different type of modularity implies the different ways to achieve product variant, in the variety level, that is offered to the customers. Salvador et al. (2022) had investigated different kinds of modularity from component swapping modularity, fabricate-to-fit modularity, bus modularity, to sectional modularity. Component

swapping modularity refers to swapping a particular component on a bigger product body. Fabricate-to-fit modularity refers to changing variable in a particular component. Bus modularity refers to putting one component as the main connector of the other components. Sectional modularity refers to having the common connection for all components.

3.2.3. Planning and control of process

Planning and control of process refers to well-defined, structured, documented, and communicated process in the system (Lessing, 2006).

Process planning as a part of house-building can be interpreted as a pre-definition phase (Jansson, et al., 2014). Process planning is essential in the beginning to set terms and conditions for the rest of the production phases. It is to minimize unnecessary conflict in such high complexity product and complex production process that leads to more predictable and stable processes (Jansson, et al., 2014; Bertrand & Muntslag, 1993). The higher the number of physical component and process knowledge, the more complex the system gets (Sackett, et al., 1997). The typical characteristics in manufacturing, as adopted in IC, are dynamic, uncertain, and complex (Bertrand & Muntslag, 1993). Dynamic refers to the constant changing in situations that can be predicted, but are hard to anticipate. Therefore, multiple solutions may be required. Uncertainty refers to the gap between required and available. While complex refers to a broad range of characteristics from the structure of the goods flow, multi-project character, composite to assembly factor. To handle complexity, incremental innovation, and balance between cost and value proposition.

To control the process better, the process shall be segmented so that emerging problems can be worked on particular. The four control principles including decision structure, goods flow control, aggregate production planning, and setting boundaries between production and sales are considered (Bertrand & Muntslag, 1993). Decision structure suggest that delegating is preferable than centralized decision making. Goods flow control suggest to start the control over logistic chain then orderly passing through resource capacity. Aggregate production planning is to match the available resource capacity to the capacity requirements or the other way around. Finally, the interface between production team and sales need to be clear. While production is responsible for providing production capacity and ensuring that the customer order is completed on schedule, sales are responsible for ensuring sufficient product demand and for accepting customer orders.

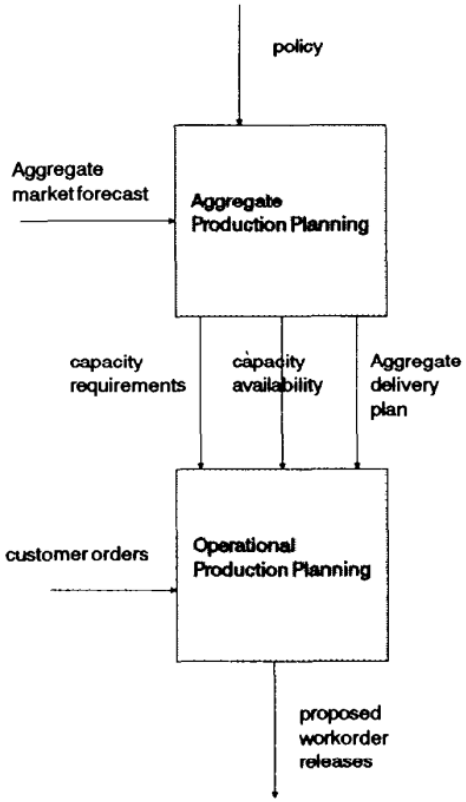


Figure 3-3. Good flow control as described by Bertrand & Muntslag (1993)

3.2.4. Logistic integrated into building process

Logistics refers to the flow of material and information throughout the processes (Lessing, 2006). Conventional construction has a complex structure with multi layered supply chain and tends to be inconsistent between projects with unpredictable delivery time expectation (Sackett, et al., 1997; Bertrand & Muntslag, 1993). More demanding requirements for reduced lead times, customized buildings, and delivery quality force construction companies to implement systematic approaches inside their supply chain and logistic operations. The establishment of a reliable supply chain facilitates the implementation of design management techniques. These strategies aim to standardize technology and work procedures (Jansson, et al., 2014; Jiao, et al., 2007).

In manufacturing supply chain, physical goods production or service delivery are more structured (Sackett, et al., 1997). The configuration of a supply chain has an essential influence on how a manufacturer of complex products organizes and coordinates the stream of innovative products through platform and architectural design strategies in relation to sourcing, production, and distribution methods (Mikkola & Skjøtt-Larsen, 2004). The absence of supply chain integration results in limited feedback information to the supplier (Naim & Barlow, 2003). The geographical distance with suppliers also the impacts in reducing sourcing lead-time, uncertainty in material planning, and component inventory risk (Salvador, et al., 2002). For all the scenario, the closer the companies with the suppliers, the more benefit can overcome operational disadvantage. The strategy is to have the company located relatively closer to the supplier for the component with the longest throughput time.

Internal logistic arrangement is also important. As the connectivity and accessibility are not properly engineered into the site layout it increased the chance of excessive waste and losses. Due to confusion, more material gets dumped, misplaced, and damaged. Material sorting and transporting is highly

affected by poor material identification, leading to unsynchronised information, wasted time, and delivery error including wrong point, time, and quantity (Naim & Barlow, 2003).

Furthermore, opened type supply chain, as in typical construction firm, with short term relationship, higher cost and heavier product where suppliers offer their standardized component. Closed type supply chain, on the other hand, typically has longer term and co-coordination with supplier that integrated into the manufacturing process (Mikkola & Skjøtt-Larsen, 2004).

3.2.5. Long-term relationship with actors

The project-based in conventional industries was originally intended to bring organizational dynamics in responding to the increasing requirement complexity. However, this approach including risk transfer down the upstream chain, reducing the incentive to collaborate and co-develop between actors (Barlow, 1999; Di Vincenzo & Mascia, 2012). This arrangement led to the fragmented process with independent and sequential phases. The fragmented value in also means that the components have different economic characteristics making it weak at coordinating processes, resources, capabilities, and keeping learning curve and innovation (Hobday, 2000; Barlow, 1999).

Innovations depends on the industry and its collective ability to gather knowledge and establish productive interactions with customers. The firms which are most adaptable and best able to develop an organizational culture that prioritizes learning and innovation, rendering them high survival. One who adhere to conventional competitive strategies are at risk of exiting the market or becoming vulnerable to acquisition (Barlow, 1999).

Long-term relationship in this context refers to the collaborative supplier involvement that is not only transactional but in a continuous interactional scheme (Sackett, et al., 1997). With the gained market feedback, suppliers have a clearer vision of upcoming trends and are capable of anticipating short-notice requests. Supply management that is transactional-based increase the suppliers' tendency to simultaneously engaged in multiple projects, making them incapable to respond and re-configure on a short call. Suppliers have strategic roles through early involvement or even have the leverage in product development (Mikkola & Skjøtt-Larsen, 2004; Naim & Barlow, 2003).

3.2.6. Use of ICT tools

Information Communication Technology tools are digital infrastructures that can be used in a broad range of application that can support technical system and processes. In construction project, ICT tools can be handy to store and update information in a real-time. It provide reliable and accurate information as well as facilitate the sharing among the authorized users. According to Thuesen & Hvam (2011), there is no requirement for any specific technology or high-specification tools to be utilized on the platform. It can be effectively utilized with any available tools and skills.

3.2.7. Measurement and re-use of experience

To be able to improve, technical and process performance is timely evaluated. Robertson and Ulrich (1998) studied the planning of platforms for market purpose. Relevant information about component, process, knowledge, people, and relationship is used to understand the market better and improve accordingly. The platform focuses on tailoring product to targeted segment with less risk. The improvement itself, is emphasizing on incremental improvement rather than drastic changes, to be flexible for producing many different, and decentralised production. To ensure effective implementation, it is important that the platform is clearly defined, transparent, communicative, and involving management level (Jansson, et al., 2014; Thuesen & Hvam, 2011). Using an orderly process structure with all process variants; derivation of specific process variants from the common structure; and correspondence between product and process variety, variety coordination as correlation

between product and process platforms (Jiao, et al., 2007). Platform thinking is handy to produce high variety while maintaining economy of scale. It is important to have a clear distinction between the continuous development of the platform and the whole system (Thuesen & Hvam, 2011).

3.2.8. Customer and market focus

Customer and market focus are developing products that are based on market demand. Specific customer focus is actually the core value of mass production (Thuesen & Hvam, 2011). So it is important that the product to meet the desired quality at price customer willing to pay.

The role of customer in construction, however, does increase the level of uncertainty. Customer-specific requirement, variety, and demand are naturally unpredictable (Bertrand & Muntslag, 1993; Sackett, et al., 1997). Specific requirement does not necessary mean custom built. Customers seek products that align with their specific requirements, without placing significant emphasis on whether those offers are custom-built or standard product. Personalizing the shopping experience but not the products itself (Salvador, et al., 2009). This relevant flexibility can be adapted by increasing functional variety. To hit the right target, a market-oriented perspective need to be embedded in the technical platform by developing in product line structure, equilibrium pricing, and product positioning (Thuesen & Hvam, 2011; Jiao, et al., 2007).

4. Case studies results

This section presents the findings of the research. The findings are organized to provide an overview of the modular construction companies, followed by their roles as system integrators and their target markets. Subsequently, their adoption of bio-based materials and industrialized construction methods are explained. Lastly, an exploration of their future prospects is described.

4.1. Company A

Company A emerged with a mission to redefine the construction industry. The co-founders had a very strong urge to tangibly address sustainability after years of witnessing the wastefulness and lack of critical thought in the construction industry. Recognizing that plenty of improvements can still be made, Company A was founded in 2020 with the aspiration to transform construction practices. Company A aims to be a catalyst for change, committing to the reduction of carbon emissions as a measure to mitigate global warming. The team believes that this can be achieved through the adoption of renewable materials and the minimization of energy consumption throughout the construction process.

"So that's also one of our missions to be an example of sustainability or create an example of sustainable construction."

To ensure the company's commitment is realized, the co-founders are directly hands-on throughout the entire process from the design phase up to project execution. Sustainable housings are executed by a bio-based modular approach. The maximized integration of bio-based materials ensures material circularity and carbon-neutral building. Modular design and construction methods reduce material usage and enable rapid realization. Consequently, the products are simply in accordance with sustainability-related standards.

The concept adapts the 19th-century neighbourhoods, with natural materials that can be long-term CO_2 storage. With maximized integration, Company A has successfully achieved 90% bio-based construction with wood, spruce, flax, and bamboo. These materials are lightweight and provide a healthy living environment with pleasant looks for the inhabitants. The design complies with permanent building codes to avoid noise, darkness, and hygiene issues in traditional wood construction. The construction also uses dry method, which means that all connections are screwed or nailed. This way, the component can easily be dismantled and reused. Additionally, the company places a strong emphasis on sourcing local materials to shorten supply chains, with multiple suppliers of cross-laminated wood based in Germany and Austria.

With a grand vision, Company A aims to demonstrate that sustainable housing is possible and affordable at the same time. Company A utilizes a factory-made production that turns site construction struggle with energy-intensive resources into timber constructions in a clean factory hall. This way, construction activity can be more stable because of its independence from weather and external influence. The employees can work indoors conveniently which better ensures the work safety. This lowers the risk and enhances the control of material supply. By doing most of the work inside the factory, Company A manages to produce in an efficient way with the lease transportation coming to and departing from the construction site. This also benefits the site's neighbourhood as it experiences less nuisance from construction work. The choice of natural materials Construction technique that is coupled with a high degree of standardization, ensures shorter construction time, constant product quality, and fewer complaints resulting in lower construction costs and competitive prices. Modular construction enables impactful, affordable, and comfortable green spaces to deliver future-proof buildings for its clients and the inhabitants.

In an effort to further optimize sustainability and reduce environmental impact, less transportation is arranged by transporting the product in one go. The teams are also living in the nearby area which is within close proximity to the factory. This minimize the emissions associated with transport logistic and daily commute by reducing the travel number and distance.



Figure 4-1. Company A's location: factory

4.1.1. Company A as system integrator

Company A began its early projects to construct non-residential buildings with 2D construction, before settling their factory for modular housing production. With panelized method, Company A managed to complete most of the work in the factory with minimum loads and jointing works at the construction site. In less than three years, Company A had delivered its first complete package of modular wooden housings. The modules are produced in a standard size, and through the combination of these modules, multiple variations can be created for customers. To keep the impacts and the affordability at scale, Company A does not sell its product to individuals, rather only in series for housing associations and project developers. Company A put its product in a purchase-based with the smallest unit can last for fifty years and costs about 95,000 euros. Tender submissions show that Company A is able to offer cheaper offers than traditional construction companies whose works are done at construction sites. However, the prices remain more expensive in comparison to other modular construction companies that use conventional construction materials and have bigger production capacities.

Company A production had met all the criteria for MIA (Milieu-Investeringsaftrek or Environmental Investment Allowance) which requires an MPG score to be less than 0.6 and 50% biobased materials at minimum. The modules now already had an MPG score of -0.5 and more than 90% biobased material in terms of volume. As a result, Company A is eligible for a 5% to 10% tax reduction depending on the current EU regulation. It makes using bio-based material is not only great for environment and social wellbeing, but also financially advantageous. This rate further indicates invulnerability to the changing standards and regulations in the foreseen future. Company A’s performance has garnered considerable interest from the officials and housing corporations that often come for consultancy to get broader perspectives in tackling the housing problems in the midst of Sustainable Development Goals (SDG) narration.

"What we really see is that there's a lot of attention into biobased building. We have a lot of housing cooperations that are now coming to us, for at least more information, and they also have signed some agreements with the government, also the Paris Agreements, to lower the carbon before 2030, or minimal with 50% bio-based, so they also need to do something and they are now looking into broader perspectives."

4.1.2. Creating the market

Bio-based material currently is still more expensive than conventional construction materials, making bio-based materials less attractive in the market. Despite that, Company A sees the supplies are adequate to accommodate the housing industry. The strategy of delivering bio-based housing, therefore, lies in the decision to make a modular construction factory that helps to keep the competitive price for the clients.

"The price of bio-based materials is still higher than the traditional materials like concrete, iron, and metal. So in order to lower that gap, we decided to construct in the factory. So you have a very efficient production process. So we gained a lot of efficiencies and such also lower the costs on labour, so we are competitive to the traditional construction companies."

From time to time, Company A has been involved in housing challenges and networks. Company A made it to the finals and won multiple prizes for its product designs. These events connected the company with its prospective clients that aim for energy-neutral, natural, flexible housings. Company A emphasizes permanent quality homes, that comply with the BENG rules and the Building Decree, while inevitably being able to be relocated without any problem.

Company A has been selected by a housing corporation to be one of the construction companies jointly delivering a minimum of 8,000 flex homes in 2023, followed by 10,000 homes each year for the subsequent two years. The selection was based on flex home providers with energy-efficient houses that can be quickly delivered. The housing corporation engages in joint purchasing with construction companies through framework agreements that cover quality, security of supply, lead times, and costs. With the temporary location, a financial relocation guarantee is provided by the government to facilitate the relocation of the units.

Furthermore, Company A was able to sign a climate-neutral commitment with a sustainable construction network, as its design has been aligned with the 2050 carbon budget objectives. This alignment is primarily achievable through the careful selection of materials, enabling the products to sequester more CO^2 than they emit. Besides having low carbon production processes, the absorbed CO^2 remains stored within the materials throughout the units' lifetime. In addition, the company also had a chance to sign the agreement to use locally produced bio-based insulation in the coming year. At present, the company sources wood fiber insulation from Germany. This development presents an opportunity for farmers in the region who have expressed a long-standing interest in cultivating fiber crops for construction purposes. The intention is to grow crops in 100 hectares for 500 homes initially and 1,000 hectares by 2030. The deals can be mutually beneficial for farmers and the company, as the company gains access to purchase local bio-based materials.

4.1.3. Bio-based approach

Company A has achieved a remarkable 90% bio-based material composition. This percentage refers to the volume of the product and is not represented in terms of the weight. Cross-laminated wood (CLT) is mainly used to construct the house from floor, wall, up to ceiling. Although CLT is not produced in the Netherlands, it is significantly lighter in weight, and its processing and transportation require less energy compared to concrete and stone. 180-200 millimeters wooden plate for flooring and 60

millimeters wooden plate for ceiling are sturdy enough that to be lifted without deformation. Company A also proves that wooden construction can have precise clearance in a matter of millimeters. Not only convenient for construction, it is also good at regulating heat and moisture for a pleasant indoor climate all year round. Each home can store up to 40 tons of CO^2 and the trees essentially grow back every twenty seconds.

The primary material utilized for insulation is wood fiber, derived from compressed sawdust as a byproduct of sawmills. In addition to wood fiber, other crop-based insulation materials such as hemp, flax, and straw may also be utilized. These fiber insulation boards are placed at the timber framing, within the seams between modules, and atop underfloor heating. Furthermore, Company A is in the process of exploring additional insulation techniques, such as blow-in to incorporate more bio-based insulation material. For external finishes, pine planks serve as the material of choice for cladding, while façades are predominantly constructed using wood or bamboo. Additionally, solar panels are placed on the roof to provide green energy.

With the design, Company A has achieved MilieuPrestatie Gebouwen (MPG) score -0.5. The MPG is a standardized tool used to objectively assess the environmental performance of a building, wherein a lower score indicates greater sustainability. It should be noted that the environmental benefits of wood are most pronounced when the material is utilized in its natural form like construction rather than heavily processed such as paper products. However, there is still a misconception about bio-based housing in the public eye. It is often associated with irresponsible deforestation in order to get materials. This false perception raises doubt in the adoption and willingness to go on full bio-based. Therefore, Company A requires Forest Stewardship Council (FSC) certified suppliers that ensure its sustainable sourcing to the client. The FSC certification guarantees sustainable forestry that at least one tree is planted as a replacement for every tree harvested, thereby maintaining or potentially expanding the size of the forest and enhancing its biodiversity.

At the moment, Company A's design still uses a concrete foundation, metal screws for installation, and glass for windows and roofs that remain non bio-based material. When it is not possible to use bio-based material, recycled materials such as reusable steel screw piles are utilized. All materials are provided with a materials passport, so it is possible to be reused after demolition. Ultimately, Company A aims for 100 percent biobased.

The emerging bio-based construction trend has yet to be adequately regulated by authorities. Current environmental calculation methods still favour conventional materials, thereby not assigning a fair score to bio-based materials for their actual impact. The prevailing calculation is based on the assumption that bio-based material will be burned after 50 years, despite the longer life span and the reusability at end-of-life scenarios. This assumption has long been speculated to be influenced by the concrete industry. Furthermore, many potential bio-based materials have not yet been registered or are simply in progress to be acknowledged by the national environmental database. This serves as a challenge in bio-based material construction that needs to be seriously addressed.

"Municipalities that come to us want to know what's already possible, in order to change the legislation. Because What a moment, it's not in the bouwbesluit, in the legislation, that you need to use a certain percentage of biobased or recycled material."

4.1.4. Company A as a modular builder

Company A established a factory specifically tailored for the production of ground-level housing, with a range of options including free-standing, blocks, back-to-back, up to four-story apartment buildings. The focus is on lower-rise constructions as higher constructions introduce increased complexity in the

design. Three main housing categories are offered. Firstly, flex type is well designed so that the unit can be relocated, available in forms ranging from a single-story house to an apartment building. Smaller ground-level units of 65m^2 are more standardized, while larger units ranging from 78m^2 to 140m^2 offer greater flexibility for customization. The larger units can be personalized with varying roof and window styles. Customers can choose between a two or three-layer facade, and select a module width ranging from 3.5 to 6.5 meters, although the length is fixed at 9 meters for all units. Despite the degree of standardization, meticulous detailing is required during the design phase, as certain modifications, such as adding additional electrical points, cannot be accommodated post-design.

There is a basic module in the unit with a number of options that can be chosen. These designs are in fact fixed with relatively small adjustments that can be made. For instance, modifications can be made to the roof and façade, and the cladding color and texture can be varied. Client preferences are accommodated more through module configuration rather than unique designs for each project. The modules are arranged back and forth with the length side of the modules connected to each other and the width sides are bracketed to the ground. By sequentially mounting the modules, the overall width can be expanded in increments of 3.5 meters. This arrangement ensures that the units retain a balanced proportion, avoiding the typical narrow and elongated appearance of container structures.

To validate the design in a practical setting, a model or test house was constructed prior to actual production. This model house underwent various tests including an acoustic test and a lower door test. Besides verifying the specification, the test results are used to further quality improvement. Foundation works including digging, grounding, and setting the foundation still need to be done at the construction site.

In the factory, the builders prepare the elements before assembling them into modules. Everything from wood fiber insulation to wooden and bamboo cladding, windows, and utilities are put together. Once the modules are delivered at the construction site, they are placed atop each other with wood fiber insulation inserted for acoustic damping before façade installation and water and wind-proofing. Although there's a claim of producing one unit per day, the overall module production and installation process takes considerably longer. Company A has managed to deliver products within 28 weeks post-agreement signing. There's an annual production target of 150 units, with an ambitious goal of doubling this capacity each year.

Company A does not purchase prefabricated building systems from suppliers, instead, it purchases pre-processed materials to suit the production line in the factory. The element had been sawn out according to the design from the supplier resulting in less residual from the sawing loss, lighter material transportation, and allowing faster assembly process. The company found no actual difficulties in getting the materials and does not feel the urge to secure the supply to specific suppliers. It maintains the flexibility to choose the supplier and believes when the demand increases, the supply will naturally follow.

As Company A prefers to find a closer supplier to its factory, it sources the CLT from Germany and Austria. The modules will be temporarily stored at the factory and only after finishing the complete set, the modules will be transported to the construction site all at once. As the typical family house is constructed from 4 to 6 modules, four movements from the factory to the site are required to transfer each unit. Company A manages its product not to be limited to certain transportation dimension, so still maintain an advantage. Transporting modules, even with substantial empty space, is preferable rather than shipping every material and performing more work on site.

4.1.5. Into the future

As Company A has emerged as a notable entity in the domain of bio-based construction, it had failed to secure multiple flex homes tenders. While most projects only mandate a 20% utilization of bio-based materials, which is fulfilled by the company, the inability of Company A to adhere to the rapid construction timelines has resulted in lost opportunities. One significant contribution of Company A to the broader industry is its validation of bio-based materials for construction purposes. The company's experiences serve as a tangible proof-of-concept demonstrating the feasibility and practicality of adhering to eco-friendly guidelines without compromising economic viability. This realization opens the doors for more companies to explore bio-based materials in construction, thereby fostering a more sustainable industry landscape.

"You need to start from somewhere. So, start with the pilots and don't stop after that pilot. It's also in the beginning. It's an investment that you do, so maybe the 1st house or the first thing that you built might not be profitable, but the next one or the one thereafter is so. It's a more long-term perspective than, only the short-term profit."

Flexible homes are garnering increasing attention in the construction sector, presenting both opportunities and challenges related to the incorporation of bio-based materials. Despite their temporary nature, flexible homes should not be regarded as disposable. The financing of flex homes can appear complex due to their transient placement for around 10 to 15 years and the uncertainty surrounding relocation. Given their actual lifespan of at least 50 years, government intervention through project support, incentive schemes, and guarantee plans for potential relocation is necessary. Furthermore, Company A sees the underlying barrier to the adoption is in the mindset. The common thinking that using bio-based material is hard, rests in the unfamiliarity of using new material and the comfort with the usual practice. It is a matter of replacing the difficult mindset with an easy mindset, bio-based material can be worked as easily with less effort as conventional construction material. Company A embraces its extreme approach and encourages other modular builders to adopt a similar innovative mindset. Thus far, Company A has not encountered substantial challenges in working with bio-based materials.

The adoption of flexible homes and bio-based materials in the construction sector often encounters misconceptions and mindset barriers. Therefore, the government schemes and a shift in industry mindset are crucial. Company A's experience shows that bio-based materials are feasible options, reinforcing that the issues at hand are largely perceptual.

"There you see that the traditional construction company does not use to think in a different way than they used to do. So it's also kind of a mindset and a different way of thinking, but the construction itself, I think even easier because it's all with wood."

Company A highlights several significant aspects pertaining to the implications of bio-based material integration in modular housing construction.

- **Economic Factors**
  The current dynamics in the construction industry reflect a notable shift in material preferences and pricing. As conventional building materials like steel and rock wool become more expensive, natural, bio-based alternatives are reaching maturity and affordability.
- **Public Awareness**
  With the misconception of wooden housing about the feasibility of bio-based housing, the effort to broadcast the real bio-based building's benefits is important to straighten the false understandings on the demand side and gain broader acceptance of bio-based construction.

- **Network**
  Recognizing the need for market expansion in this sector, the company has proactively engaged in bio-based construction ecosystems. Knowledge sharing is a way to broaden the application of bio-based materials in construction. The network is essential to reach stakeholders both the material suppliers and clients, keeping the exploration of a broader range of bio-based material.
- **Regulatory Implications**
  Beside consumer preference, definitive regulations in the bio-based construction had been long awaited. The absence of such regulations represents an existential challenge to the large-scale adoption of bio-based construction material.

"And in order to make people make companies use this kind of bio-based materials and to speed up that whole process, I think the government needs to put that in legislation and same with the electrical car they've set in 2035. On the top of my head, they don't want to have any regular cars anymore. So only electrical cars can be sold. So if they do the same with the materials for construction."

4.2. Company B

In 2020, Company B emerged as a collective vision between the two visionary founders. With the founders' expertise in concrete harvesting and modular house construction, Company B aims to address the housing shortage in a climate-friendly manner. The founders decided to create Company B that 'produces' factory-made housing using sustainable and circular materials. Sustainable refers to the use of cross-laminated timber (CLT) as a renewable source and circular refers to the use of recycled concrete that replaces primary raw material.

By using factory construction method, the company's commitment extends beyond supplying large quantities in a short period of time. Company B particularly focuses on delivering affordable housing that fits with the social housing segment and prioritizes the inhabitants' well-being. Not only to build cheap and fast, Company B strives for high-quality housing that is nice to live in.

"You must have seen in the Netherlands, like building projects from the 60s, 70s. Really ugly social housing. Building blocks really small and that's something that the Netherlands want to change."

Furthermore, the modules that construct the units are specifically designed to be demountable and transportable, extending the life span of the material and making them well-suited for temporary housing. Therefore, Company B offers purchase-base units with a take-back guarantee to its client, promising to pay some portion of the price, which is called restwaarde (rest value), to be able to use the modules in different locations. Even so, the company maintains its permanent building permit to ensure the quality of the dwelling is at the highest standard.

"So our goal is always to achieve the permanent building permits. Competitors of ours, they mostly go for the temporary building permit, but trust if you do temporary, the quality will go down on stuff like the internal staircase of the building. And that's mandatory with the permanent building permit. Also, the daylight entrance and the square meters and somebody can get the whole list and we always aim for the highest quality."

4.2.1. Company B as system integrator

To provide adequate quality and affordable prices for social housing, Company B arranges a fixed floor plan in a Partner Ecosystem. With this structure, the limitation of a maximum of 1,700 euros per square meter gross is set to keep the competitive price.

Company B, with a small team of commercial directors, architects, and project managers, acts as the **system integrator** that connects and delivers the end product to the clients as well as coordinates the building permit and technical design. The company is responsible for the management and coordination of the assembly process, whereas the partners are tasked with prefabricating the components, delivering them to the assembly hall, and installation works.

Partner ecosystem refers to the collaboration in delivering the product. Every partner is an expert in their domain and responsible for their part in the production. Together, all the partners work on their parts on the same modules. With high ambitions, company B finds partners that match its DNA. These partners are carefully picked that are really connected to sustainable and circular visions and bound to long-term partnerships. With the partners, company B shares the goals and works side-by-side in accordance with Building Information Modelling (BIM) guidance. The agreement to put the responsibility on each partner is intended to enhance the development of the products. While keeping the floor plan as it is, Company B always encourages each partner to innovate. R&D and innovation lists that they want to pursue are a staple in their weekly discussions held every Thursday.

"We have long-term relations with our partners, we don't want to look like the traditional way of building. Some builders have contracts with some parties, but most of the time it's just putting it open and see who gets who comes with the best price and the best time. Uh, we don't do that. We use the same partners for a long time."

With long-term collaboration with its partners, Company B intends to have continuous production with a high degree of standardization in its production processes. It is to ensure the scalability in design, production capacity, and control over the assembly hall. Repetitive actions improve the speed and reduce the cost of production. While optimizing operations, standardization does affect the innovation and adaptability of the modules by making them less flexible.

"What Company B offers to all our partners is that they are all experts on their own product, they have their old factories running, running their own projects. But we said to them whenever your factory is running low, then you can make your products for our houses. So we keep their factories running all the time. Uh, so the for them is super interesting because it saves them a lot of money and they can offer us a bigger price, but we try to, fill up their capacity as you may because our modules, that's where we work into now are going to be the same."

The headquarters (HQ) of the company is a workspace for the team members and partners and a representative office for marketing purposes. The HQ has a model home used for demonstrations and testing. The **Assembly Hall**, on the other hand, is located separately. It is where the prefabricated components are delivered and assembled to be constructed into modules. It is possible to use any unused hall to be an assembly location. This is how the company can be less capital-intensive compared to other modular builders with typically expensive production facilities. The assembly hall can be chosen to be in close proximity to one of the partner factories or to the construction site. This is also the reason that drives the company to have more assembly halls, shortening the transportation from the assembly hall to the construction sites in the upcoming years and projects. Figure 4-2shows the office location in red pin and the separated location for the assemble hall as marked in blue pin.

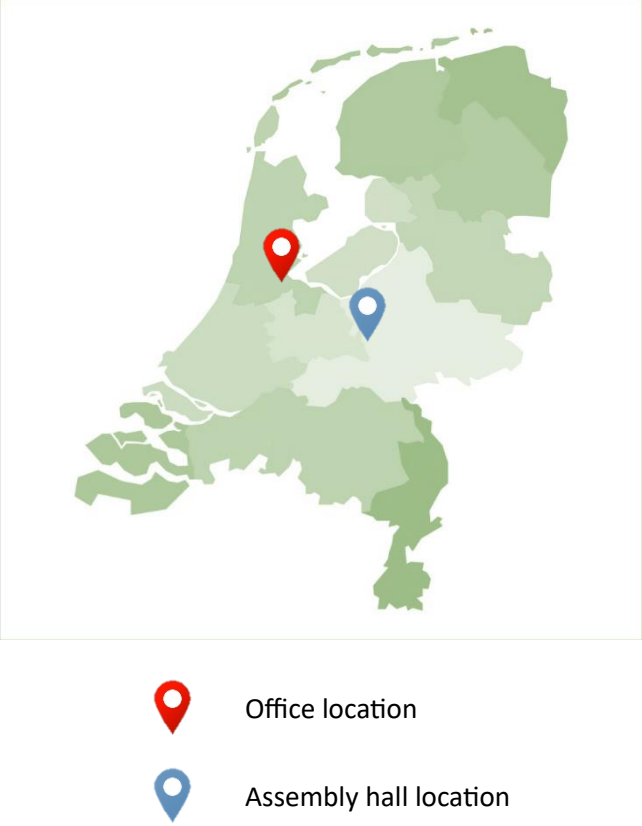


Figure 4-2. Company B's location: office and assembly hall

4.2.2. Creating the market

As the housing demand is always high in the Netherlands, financial constraints are often encountered due to the limited budgets allotted to social housing developers. Fortunately, a cultural shift has been observed over time among social housing agencies, manifesting in enhanced requirements. Not only demanding rapid and low-cost housings, the housing association had started to look future ahead, improving the quality and taking into account the sustainability and circularity of the product at end-of-contract scenarios. Although some adaptations can be negotiated to meet client specifications, it is hard to compromise on the quality for cost reductions because it poses a significant dilemma as it contradicts the company's core values. Company B aims to maintain the good quality of its product as a feature to distinguish itself from the competitors. In many cases, this results in higher offerings to the client in comparison to the competitors, a reflection of the diverse materials and suppliers involved in the submissions.

"They have some budget, but they're limited because they only can ask for a certain amount of rent every month and that's kept in the Netherlands. And so, that's to make income source and of course other investments. But so you need to offer a good price to them, also as they need to be cheaper. So I know that also struggle with the quality and the price you offer."

In 2022, the company joined the **local housing association partnership** that aims to centralize the purchasing, standardize the construction process, and build modularly and circularly in a factory without compromising on quality, affordability, and appearance. The corporation intends to build 750 dwellings annually by a total of six modular builders. Company B was assigned to cover the flexible home section and worked on 30 units of 10-year temporary ground-level homes for their first project.

This membership portrays the certainty in demand that strengthens the company's internal partnership in developing and delivering the modules together.

4.2.3. Bio-based approach

Company B implements a production strategy that relies on the utilization of **hybrid materialization**. The company uses biobased material, if possible, and circular material if that is not possible. CLT and timber frames have been used in structure, wall, and ceiling systems. Even when bio-based material takes most of the module composition, it is limited to certain types of wood products that have stable performances. When less sustainable material is unavoidable, second-use material is chosen. The floor is reusing the concrete from construction demolition. Recycled concrete is used for flooring, internal staircases, and elevator construction as it acts as the stability core of the building. The roof uses recycled bitumen which is more acknowledged as citumen. This hybrid materialization uses common material that enables company B to construct higher stories and get higher benefits from economies of scale.

"With just woods, you cannot go to certain heights, yet, so that's why we would focus on the combination of the two materials."

The design philosophy of the housing units underscores a strong commitment to sustainability and longevity. As a manifestation, while the inside frames feature wood as preferred by the inhabitant, the outer frames are still made from aluminium. Furthermore, abundant triple glazing is used not only to natural light but also as an avenue to achieve Bijna Energieneutrale Gebouwen (BENG) standards. In the kitchen, a natural stone countertop can be sanded and varnished as new every two decades, ensuring its continued utility and minimizing waste. These deliberate choices collectively underscore the dedication to sustainable practices and the maximization of each component's lifespan.

It is hard to adjust to changes due to joint coordination and responsible shares between company B and the partners. It is also meaning that it will be difficult to integrate more bio-based materials into the system. The slightest change can impact all the other components. Thus, the changes must be fit to the existing system for a smooth transition. The continuous production also implies that the material used needs to have a relatively stable stream and price. Hence, it requires big partners that are experts in bio-based material for this matter. With the partner and material settled, the company actively looks for new ways to use natural materials for further improvement to achieve cheaper, more bio-based, and less environment impact construction.

4.2.4. Company B as a modular builder

Company B offers three kinds of products including ground-level house, apartment, and residential tower. The units vary in size, ranging from 30m^2 to 130m^2 with the same floor plans and hybrid materialization of concrete floor and wooden walls. The basic module is 3 meters times 10 meters on the inside and 3.4 meters externally with the façade. The size variety spans a range from extra-small to extra-large, with the addition of half a module for each subsequent increase in size. As an illustration, the extra-small unit is comprised of one module, the small unit is comprised of one and a half modules, the medium unit is comprised of two modules, and so forth. The combination of floor plans can create numerous possibilities in the design.

The product is designed to be detached by using the click method instead of gluing and screwing the joints between the wall, ceiling, and roof that come as different prefabricated components. The aim to reduce the cost requires the production to be in scale and standard, thus the customization is limited to different types of façade and roofs that come in square or triangle forms.

Before mass production, modules are tested to verify the design. The testing is performed communally with the partners. The first test is for the material, the second test is for the actual building process, and the final test is for the product itself including accessibility assessment, daylight assessment, fire safety assessment, and others. For wooden materials, partners are required to have FSC certification.

With the arrangements, the process is definitely faster than the conventional construction method. For big projects, it may completed within a year from the start to the completion of the project. After receiving the purchase order (PO) from the client, partners are going to manufacture the prefabricated components in their own facilities. Within 14 weeks after the PO issue, partners have to deliver their semi-finished products as prefabricated components to the assembly hall. In the assembly hall, partners continue working to integrate their part of the module together, which produces at the rate of 5 modules per week. All the modules are designed to fit into a truck, so when it is ready to ship, it can always go by regular trucks and does not require any special transportation, which can be very expensive. The modules will be put on top of each other at the construction site before the façade and roof installation.

"It's all based on the modular building and all the partners making their own products. And it's all about making the assembly hall run. So we want to be like how a car factory does. That's the resemblance we want to do in the building world."

As mentioned multiple times, the partners are responsible for the procurement, transportation, and assembly works of the components. The production involves all the partners as the following:

- a ground preparation construction company,
- a site construction company,
- a foundation construction company,
- a crane and heavy lifting rental,
- a concrete urban mining company,
- a prefabricated concrete company,
- a structural engineering company,
- a wood construction company,
- a wall and ceiling producer,
- a roof producer,
- a prefabricated kitchen producer,
- a prefabricated toilet and bathroom producer,
- a wood façade/frame producer,
- a steel fence producer,
- a sustainability engineering company,
- an installation engineering company,
- an energy engineering company,
- an electrical installation company, and
- a law firm.

The partners possess a high level of knowledge in their respective components, indicating that they are prominent entities within their respective professions. Some of the partners are family-running businesses with short-line communication. This type of company strives for long-term partnerships with clients and contractors. While others are considered major players who share the same views towards circular and sustainable practices.

Ground preparation and foundation works are carried out at the construction site including paving, sewing, earthing, and piping works. The prefabricated components from concrete, wall and ceiling, roof, kitchen, toilet and bathroom, wood façade, to steel fence are manufactured at each partner factory, packed, and delivered to the assembly hall. The components are designed to be interconnected and compatible with each other for seamless integration. This also allows the component to be detached and reused for subsequent usage periods. The modules then will be constructed in an orderly manner where assembly of the components, utility installation, and finishing works happen. As wood is the major construction material, the assembly hall currently is conveniently located near the wood construction partner. The module design and execution also involve consultancy firms specializing in high stories of wooden structures, sustainability, and energy.

The partners responsible for managing the digital environment include developers of 3D programs and the digital building marketplace. The IT support covers the entire lifecycle from building configuration at the design phase to the digital library at the operational and end-of-life periods. The digital environment is developed to facilitate rapid calculations and measurements. Not only for internal use, the 3D building configurator enables clients and partners to quickly review the financial and spatial feasibility of the unit on a specific plot.

In collaboration with a law firm that serves as an in-house legal partner, this partner engages in collaboration at a predetermined rate that is reassessed at every project milestone. It is important to note that the price remains contingent upon prevailing conditions that cannot be fixed over extended durations. With a high level of coordination, Company B is consistently looking for prospective actors to be involved in the partnership. For instance, the company found a façade company that is using recycled PVC and is currently undergoing a trial period before potentially become the partners.

4.2.5. Into the future

Looking into the future, some critical points from company B are notable for future production and the supply chain.

- **Ensuring a stable supply of materials**
  Guaranteeing the availability of the material is essential for both short-term operational efficiency and long-term strategic planning. Choosing a consistent and reliable source can mitigate risks associated with material shortages and production delays.
- **Diversifying the supply chain**
  Stable supply can be anticipated by either expanding relationships with existing partners or engaging with new ones. A diversified supply chain can provide a more resilient material stream, which can come from either refurbishment processes or regular sourcing mechanisms.
- **The balance between supply and demand**
  It is always bound to the complex chicken and egg problem to decide whether the supply or demand is to lead the other. The availability of the supply can influence the demand as well as the increasing demand can influence the supply. The risk of wasted production from the supplier and inadequate supply to the client are still uncertain for the actors.
- **The equilibrium between price and quality**
  The importance of the pricing strategy remains a pervasive challenge. Even big contractors have difficulties giving the correct offers that require accurate market analysis.

“Price and quality are always battling against each other and you need to find the sweet spot of that and it depends on every aspect of the house.”

The equilibrium between price and quality remains the highest concern for Company B. The persistent pressure faced by the housing sector can be indicated by rising demand, insufficient supply, and escalating prices. This can result in short-term solutions that fail to address the underlying systemic issues and lead to suboptimal results that will continue in the long term. A prevalent emphasis on delivering higher numbers, by both the government and housing associations as the market, might compromise the quality of the housing units produced, leading to the development of units that are not only aesthetically unpleasing but also potentially less durable and sustainable. The tendency to prioritize quantity may result in less quality units that are poorly designed and constructed leading to future costs related to maintenance, renovation, or demolition. Hence, the apparent emphasis on quantity, as a short-term response to market pressure, raises significant concerns about the long-term sustainability and quality of housing stock.

"I'm worried that the focus is going to be too much on the speed like how fast we build houses, to produce houses, than offer the right quality that a human being wants. So my worry is that too many people going to live in a very bad house. I want to give them the best house you can offer and so I want the government to see that they should prioritize quality instead of quantity."

Finally, Company B highly encourages the utilization of bio-based construction materials, if not implementing them already. The adoption of bio-based material is presented not only as a promising construction material alternative but also as a favourable option to promote the long overdue transition of the cattle farmland. The conversion from cattle farmland to crop farmland is beneficial for a safe and healthy environment from the reduced emissions and waste associated with cattle farming. Conversely, crops like flax and hemp have a lower ecological footprint, requiring fewer inputs such as water and fertilizers and offering carbon sequestration benefits. It also serves as a catalyst in sustainable construction, creating a win-win situation for the environment, the economy, and the governance.

"Agricultural materials that you grow, can be used for the building sector. So we need to use the lands to grow the materials, we need places where we can manufacture products like half products, and then use those for the building worlds. That's also getting more attention in the Netherlands and the minister, Hugo de Jonge, is really enthusiastic about this idea and those are great ways to lower or tackle other problems."

4.3. Company C

Company C is a Dutch-origin construction company that was established in 1960. The company specializes in the production and refurbishment of modular construction, presenting a sustainable and cost-effective alternative to traditional construction methods. Company C closely controls its carbon emissions and maximizes the reusability of its module, positioning itself as a strong player for addressing urgent housing needs with scalable solutions. The company has significantly grown and has expanded its market presence internationally to Belgium, Germany, and the UK. In the year 2020, the company underwent an acquisition by a giant industrialized construction company that wanted to enter the European market. The mother company, whose expertise in 2D prefabrication, by nature has a different focus on panel installation and attachment. With the implementation of a new organizational structure, Company C maintains its dedication to replaceable and demountable modules.

Company C had established multiple factories within the Netherlands and abroad. The HQ has the biggest facility to manufacture new modules and module storage. In close proximity to the HQ, there is one facility dedicated to refurbishment. There is one factory in the south and another in the north part of the country whose modules are designed for earthquakes. There is the newest factory in

Germany to make special projects. And, all these facilities are based on the same construction way. As for refurbishment, minimal work is done. Most of them are only to repair the visual or external touch-up, whereas some others might need to replace some parts. In total, there are no fewer than 22 factory halls in the Netherlands alone. The company has also offices and production facilities in Belgium, Germany, and UK.



Figure 4-3. Company C's location: headquarters and production hall

Over decades of experience, the company has refined its modular housing solutions with consumer demands for comfort, safety, sustainability, and flexibility. It provides permanently flexible housing with HR++ double glazing, insulated walls and roof, modern sanitary and utilities, solar panels, and energy-efficient installations such as heat pumps. With permanent quality and appearance, the final product is indistinguishable from conventional construction.

The production facilities are claimed to have smarter, faster, cleaner, and more cost-efficient construction. The construction process reduces 30% to 50% of construction time in comparison with conventional on-site construction. Financially, the modules can be easily relocated which is more cost-effective than producing or constructing new units. Environmentally, Company C has carbon-controlled installations that produce around 50% less carbon emission. 92% of the modules are going to refurbishment, and 87% of the materials will be eventually reused. In total, 80% of building materials are repurposed, with a mere 8% not immediately reusable, minimizing the need for new materials and thus reducing the carbon footprint of each project. Therefore, this method ought to be financially and environmentally beneficial for consumers, making it an attractive option.

Temporary modular buildings have emerged as a quick and flexible solution to a myriad of market-driven demands. Company C, as a major player in the market, not only addresses the immediate needs

for such structures but also emphasizes sustainability and circularity in its approach. Due to their temporary status, these constructions are subject to fewer procedures and regulations, allowing for expedited construction processes for the growing housing crisis and the uncertainty of political dynamics.

4.3.1. Company C as system integrator

As a modular builder, Company C stands out in this market with its broad designs for various segments and durations of use. In accordance with the purposes, the modules are meant in the span of daily, weekly, monthly, yearly, or even permanent structures. The multiple purposes of the modules underline the company's ability to meet market demands across a wide spectrum. These include but are not limited to:

- **Housing**
  from urgent housing for refugees and asylum seekers to permanent units.
- **Public**
  fire stations, sports halls, schools, and daycare centers for vital and long-term applications.
- **Commercial**
  ATMs, shops, and festivals for short-term use.
- **Business**
  office spaces for various sectors.
- **Industries**
  industrial plant and temporary office for construction sites.
- **Specialized uses**
  floating structures that showcase the modules' innovative potential.

This adaptability is a significant advantage for Company C, allowing it to cater to a variety of market demands. As an old play in the Dutch market, Company C holds a significant share. Despite the rising number of players in the modular housing sector, Company C accounts for at least 25% of flexible homes in the country.

Furthermore, the company's ability to rapidly produce new modules and fully refurbish existing ones still has misconceptions about its applicability and longevity. Company C actively works to correct prevalent misconceptions about modular housing saying modular construction is only suitable for temporary use. The company contributes to a more accurate and nuanced understanding of this stereotype by producing durable units and demonstrating the financial implications that extend beyond a cheaper option. Not only found to be 10% to 15% cheaper when considering the entire life cycle of the building. It also has a significant increase in value due to the rising costs of construction materials. In addition, modular construction enables quicker returns on investment for both clients and developers. Faster construction times lead to lower interest costs for clients, reducing the total cost of capital for the project. Similarly, the quicker turnaround time for modular construction provides financial advantages for developers by allowing them to complete projects faster, thus freeing up capital for other ventures. This surge in value presents as an investment over time.

“It was built for around 30 million in 2012. In 2026, the building will be dismantled. So in two years or three years, the value the estimated at about 50 or 60 million at this moment.”

4.3.2. Creating the market

The success of any company in the construction sector is not solely based on its ability to deliver high-quality homes efficiently. It is also significantly influenced by its relationships with key stakeholders, such as government agencies and housing associations. The company maintains a strong relationship

with governmental bodies by maintaining frequent participation and constructive discussion in the networks. In the commitment to deliver 900.000 flexible housing, the government ordered 2,000 flexible from Company C out of 37,500 units that must be delivered by the end of 2024. The purchase includes a relocation guarantee that the financial risks are divided into three parties: 60% to the central government, 25% to the municipality, and the remaining 15% is deductible for the company. The company also works together with the housing associations. Through a competitive tender process, the company made deals to supply based on standardized procedures with other modular construction companies.

However, bio-based construction material remains more expensive in the market with a 10% higher price for bio-based alternatives. While on the demand side, it had been asked from time to time. However, there has been no urgency to immediately incorporate more bio-based materials in the units.

"They say OK, I want the highest requirements, most sustainable, etcetera, etcetera. But then, most of the time, sustainability is a part, but it's like for the most of it, it's just a cost."

4.3.3. Bio-based approach

Currently, the average modules contain approximately 12% of bio-based material. It mostly consists of wooden walls and additional wooden façades when requested. Concrete is used for a special floor which is only 5cm thick. The steel frame is also used for framing. Despite steel frames and concrete floors forming significant components of the units, Company C maintains the design as it is, acknowledging the units are not made with the most sustainable material and the need for more sustainable alternatives.

"Steel is the biggest impact of our materials in total. So it's about 50 or 40% of the CO^2 impact of our building system. But it's, for us, at this moment, the best way to build because it's what we're doing for many years already."

Company C has not remained complacent and has continually explored numerous options to find more sustainable bio-based alternatives. For concrete floor, additional biochar alternatives is considered to make the floor carbon-contained. More CLT integration is another long shot. As for the insulation, Company C is still observing the odds of finding bio-based material with similar characteristics. The most likely scenario is either to replace bit by bit of the system with bio-based materials or to create an entirely new bio-based production line. Company C has also piloted a fully circular, wooden project but has not yet integrated this into its mainstream offerings.

"We also have made another project for ourselves which was wood, really circular as well. Everything was demountable. So the units, everything was in there as well. But we are not using it yet in our mainstream project product."

It is likely that bio-based material will become cheaper while conventional construction material become more expensive due to the scarcity in the foreseeable future. However, the underlying reluctancy, here, is the compatibility with the existing system. With thousands of modules coming back to the factory each year, the system need to maintain the same. Thus, it is really difficult to change the material as it might not only be suitable substitution for the system but also not technically comparable with the current conventional material. It is complicated to find bio-based replacement that has the same fire proofing, sound proofing, and Rc values qualities. Notably, emerging materials that have not long been proven. Bio-based material in modular building tends to be more suitable for longer term or permanent building due to the minimal movement. For temporary building that have quiet mobility, with all the movement, strong and resilient like metal is necessary.

"So, I think, for the longer temporary or permanent building, it's perfect to use. But for short-term temporary modules, I think it's really hard to use it for a long time as well, because when it's damaged you can't use it anymore."

Legislation-wise, there has not been clear regulation regarding bio-based materials, yet. Consequently, there is no obligation to use bio-based materials, and not many people are willing to make such a risky investment. Logically, building standards for taller buildings are likely to become stricter as well, making the adoption of bio-based materials even more questionable. The situation boils down to environmental impact calculations such as MPG and Paris proof. The issue of a gelijk speelveld (level playing field) is also tricky for the industry, as companies practicing sustainable construction are subject to the same tax as those employing less sustainable methods. For every module that comes back to the factory, Company C gets the advantage in its life cycle analysis (LCA). This then later improves the environmental performance in terms of MPG score and Paris proof. For sustainability reasons, Company C made its own carbon calculation, in which carbon design and environmental impacts from each material are known, and issued a carbon performance letter from the calculations. Sustainable sourcing is also ensured by using only FSC or PFC-certified wood.

"So we only buy sustainable wood. So when you only buy sustainable, you only sell sustainable. So that's at least part we committed to when we are using wood, which is plenty still."

4.3.4. Company C as a modular builder

Company C relatively has long-term relationships with its material suppliers as preferable vendors, even though it always remains open for new suppliers. Big distributors such as Jongeneel or BMN have been a good choice for Company C because they can easily be found all over the country. While having automated machines to manufacture the elements, utilities like bathroom and kitchen are procured as prefabricated modules. The transportation from the factory can be varied. To ship 3x6 meters modules by regular low loader vehicle. However, bigger modules, such as 5x10 meters modules, need special transportation and are only allowed to depart at night time. Although it might be easier to ship three small modules rather than one big module, it requires more assembly work at the construction site. This arrangement always depends on each project.

Company C has developed and produced modules in highly standardized processes. The standard module measures 3 x 6 meters. These modules can be stacked up to 12 stories in Germany, whilst only 6 stories in the Netherlands. Company C allows customization in their housing units for the selection of windows and façades to offer clients the opportunity to align with their aesthetic or functional needs. Differences in period of use vary in the selection of windows, air tightness, and weight of the modules. Rc value, a measure of thermal resistance, for temporary use is only 1.5, indicating lower insulation levels suitable for short-term applications. Whereas for permanent use, the Rc value ranges between 4.5 to 5.3, ensuring a higher degree of thermal resistance, ideal for long-term applications. Ventilation requirements also differ based on the usage duration. Temporary units only require windows for ventilation, whereas modules intended for more than 15 years of use need to be either energy-neutral or at least comply with BENG requirements as stipulated by local regulations.

Previously, Company C relied on external vendors to prefabricate components such as steel frames. To support the production, Company C invested in industrialization and robotization for complete in-house production. This allows increased process efficiency which robots can cheaply and quickly execute. Utilizing robots not only enhances speed and efficiency but also reduces the margin of error and waste. Thus, leading to higher production quality and lower environmental impact. The company uses drilling machines and pairs of welding robots for greater accuracy. Better precision optimizes the use of material, leaving minimum waste. The company had also purchased a series of automated

guided vehicle (AVG) for its new production halls. Simultaneously, the company integrates digitalization to further refine its operations. Latest updates are easily documented and displayed on the screen at every workstation, ensuring real-time access to information. BIM technologies are also employed to transform information into three-dimensional geometries, aiding in the efficient design and documentation of the building modules.

To further ease production, the company dedicates each production hall to certain processes. This assigns one area for specific and limited tasks to eliminate distractions and better asset management. Each module starts with a 5cm-thick concrete floor, which is designed to harden quickly due to the inclusion of a specialized mixer. The steel frame is then erected atop the hardened floor, which is then encompassed by wood skeletons, walls, and ceilings to form the basic structure for the modules. Parallelly, the production sequence includes creating manufacturing components such as floors, roofs, and structures. These modules are then assembled and stored before being transported to the construction site and subsequently put into their final building form.

Being mature in the technical system, the company successfully produced 5,000 new modules and refurbished 4,500 modules in 2022. The company has unveiled a strategic roadmap to further escalate its production capabilities over the next two years from 10,000 to 15,000 modules. To facilitate this significant upscaling, Company C is investing in new production lines and expanding its manufacturing capacity through the construction of additional factories. Company C demonstrates its commitment to project delivery timelines within a 30-week timeframe from the start of groundwork.

4.3.5. Into the future

Company C demonstrates a long journey of modular construction practice. The case study highlights the operational strengths of modular construction methods, which are proving to be increasingly suitable for quick and cost-effective building projects. However, the study also reveals some systemic shortcomings that need to be addressed for the sector to evolve. One such concern is the market-centric orientation of Company C, a phenomenon that seems to be pervasive across the modular construction industry. This orientation often results in a lack of innovations, largely due to the substantial financial commitments involved in developing new materials. Given that the current operational paradigm is largely seen as satisfactory, there seems to be limited impetus within the industry to explore alternative, possibly more efficient or sustainable, solutions. Another critical point to consider is the challenges associated with implementing sustainable, bio-based materials in construction projects. As per internal commentary from Company C, there is a considerable demand-side deficiency, as clients are either unaware or unwilling to invest in more sustainable options. This creates a situation for companies who have the expertise but find it financially or practically unfeasible to push forward extensive research and development in sustainable materials. Hence, it is imperative to enhance awareness on the demand side in order to foster greater adherence to the desired direction.

“I know a lot about bio-based materials and build with it. I think we should do a little bit more with it, but when the clients don't want to, they don't ask for it enough or they don't want to pay for it. It's really hard for us to start our research more intensively.”

Company A also indicates its commitment to carbon budgeting by implementing an allowable carbon budget for each project. This pertains to the upper limit of permissible CO_2 emissions that will challenge the innovation in construction methodologies and practices. Carbon budgeting focuses on material transition, which can be done in several ways. Firstly, preventing the use of material. Secondly, implementing environmentally responsible practices. It implies that constructing buildings in a manner that enables easy deconstruction and reuse of building elements. Thirdly, leveraging sustainable

alternatives such as bio-based materials and promoting the idea of giving building elements a second life. Company A is heading toward more sustainable practice every day and see even better opportunity in the future.

"So I really understand the reason that we are not going into the full on biobased materials because the situation on the regulation part isn't that hard yet. So it started a little bit more and it's finally getting a little bit interesting after a few years. But I still think there is a lot of a lot more to be achieved."

5. Cross-case analysis

This chapter presents a cross-case analysis of three cases that look into the adoption of bio-based materials in modular building systems, the implementation of industrialized construction principles within their manufacturing process, and the performance of their respective systems and supply chains.

Cross-case analysis was done to gain comprehensive insights and a deeper understanding of bio-based material adoption in IC firms. By thorough comparison of the three cases, this analysis aims to uncover common patterns, distinct variations, and unique nuances that might otherwise remain obscured when studying individual cases independently. The comprehensive cross-case analysis is extracted from Company A, Company B, and Company C to provide an organized structure for synthesizing the findings and drawing meaningful conclusions by assessing the bio-based material in the building component, industrialized construction implementation, supply chain performance, and opportunities.

5.1. Bio-based material adoption

It is evident across all three cases that the construction companies have acknowledged the benefit of bio-based material alternatives. Each case has integrated bio-based materials into its building system in a varying degree of adoption. As explained in Chapter 3, bio-based material can be adopted in various building systems. Table 5-1 shows the bio-based material utility in each case study.

Table 5-1. Adopted bio-based materials in three case studies

	Company A	**Company B**	**Company C**
Foundation	Concrete	Concrete	Concrete
Structure	Wood	Wood	Steel
Wall	Wood	Wood	Wood
Ceiling	Wood	Wood	Wood
Insulation	Wood fiber	Glass wool	Glass wool
Façade	Wood	Wooden façade upon request	Wooden façade upon request
Floor	Wood	Concrete	Concrete
Roof	Wood	Bitumen	Bitumen

Commonalities

For **wall and ceiling applications**, a similarity across all three companies is their utilization of wood-based products. The wooden materials include timber, CLT, and OSB plate. These types of applications are commonly used in conventional construction systems as an alternative to brick wall and concrete ceiling, therefore having proven performances over decades. This is supported due it its lightweight characteristic that is convenient for module construction, transportation, and assembly. Wooden products are also seen to serve vapor control purposes. The wood applications in wall and ceiling systems, combined, play a major part in the overall building. In addition, all of them had managed to use only FSC certified to prove their responsible resourcing and maintaining sustainable practices.

Moreover, there are similar possibilities in having wood products as material for **façades**. All three cases offer wood-finished façade for its products. This possibility is not necessarily related to the construction technicality nor performance, but aesthetic preference that gives an effect of natural material. Even it is not an existential matter, as the building skin, wood-finishing provides a tactile and visual warmth, enhancing the building's integration into its natural surroundings. While the façade is

not structurally integral, its aesthetic appeal plays a significant role in shaping public perception and could potentially increase societal acceptance of sustainable and circular buildings.

However, it's critical to acknowledge the limitations and challenges in the adoption of bio-based materials. Besides the similarities in using bio-based material, there is correspondence in having no applicative replacement yet for the **foundation**. At present, concrete remains irreplaceable as a foundation material, owing to its structural integrity and durability. The concrete foundation has not been designed for dismantling, even for temporary buildings, it stays forever at the building site as it is not actually part of the modular building system.

While the companies are knowledgeable and actively looking for more possibilities to adopt bio-based material, the adoption of bio-based material in IC systems is found to be very limited. The primary goal of implementing IC is to improve efficiency and scalability, however, IC is unnecessary to be more effective in adopting bio-based material. Thus, IC show no better ability to implement new approach or accept intervention, such as in utilizing bio-based material. Instead, IC systems tend to adhere to established and proven concepts. It is underpinned by the need to ensure consistent quality standards and stable supply, especially when it comes to mass production. With that being said, IC firms have the tendency to use only the materials that have been already used and **proven in more traditional construction practices**.

The aforementioned statement, of course, excludes **the involvement in the development of materials** and components. The companies in different ways participate in the material development by integrating the material into the building system at least on a trial basis. Company A willing to use new insulation material in collaboration with the supplier for a specific number of units. Company B is testing out a new material to be applied for its façade. Company C participated in and sponsored a fully bio-based house project in collaboration with an educational institution. This way, the IC firm can better learn about the possibilities, while the material supplier can save some costs associated with testing, which is usually a financial constraint for emerging companies. Additionally, IC firms can better customize the material development to their system.

There are also convincing testimony that there is a **height limitation** in constructing with bio-based material. Company A revealed that its commitment to fully bio-based construction methods restricts its projects to a maximum of four stories. This limitation is primarily attributed to complexities in design. Similarly, Company B adopts a hybrid materialization strategy, combining bio-based materials with recycled concrete to construct taller structures. In contrast, Company C, which does not incorporate bio-based materials into its structures, has relatively no height restriction. This highlights a shared industry perception that bio-based materials in IC are currently not viewed as suitable for high-rise construction.

While successfully adopting bio-based construction material, Company A, B, and C have another similar consensus that bio-based material is **more expensive** than conventional construction material. This leads to the variation in bio-based material adoption in their building systems.

Distinction

Company A, among the three cases, stands out for its **extensive integration** of bio-based materials into almost every facet of its building systems. The **availability of bio-based material suppliers** in the market adequately supports Company A's ambition to integrate a substantial amount of bio-based materials, and this process is eased by its self-developed system, which allows for direct sourcing and integration of bio-based materials without external dependencies. Beyond just wall and ceiling applications, where wood-based products are commonly utilized, Company A goes steps further to

achieve 90% incorporation of bio-based materials into its units. The exceptions to that are the concrete foundations, glass in windows and roofs, and metallic fixtures for jointing and electricity installations. Impressively, Company A had incorporated bio-based insulation, floor, and roof in its modular system which is not been adopted in the other two cases. The wood fiber insulation material is even interchangeable with flax which is in board insulation form. This flexibility enables the company to collaborate with emerging local material producers, adding hemp to the bio-based materials adoption. It is obvious that bio-based became not only the principal but also the identity of Company A.

Company B, in contrast, adopts a **hybrid approach**. While similarly utilizing wood-based materials in its load-bearing structures, it combines these with recycled concrete floors. Besides being able to construct higher, concrete is essential for ensuring both stable supply and proven performance, thereby assuring the ability to a long-lasting production. The extent of bio-based material integration is further influenced by its partnership model. The core of this model lies in aligning with partners who are not only experts and experienced in their field but are also available to join the collaboration. This approach poses certain challenges when it comes to incorporating bio-based materials in the products. The realm of **bio-based construction material suppliers, which are mostly under development, aren't as established as that of conventional material suppliers in the market**. Making bio-based materials integration somewhat reliant on the availability and readiness of potential partners in this niche domain. Bio-based construction material **suppliers need to exhibit strength in terms of consistent supply chains and maturity in their product offerings**, as well as to be available to engage in long-term partnerships to make the production economically viable. Company B underscores the interplay of market dynamics, partner availability, and economic feasibility in steering the course toward more sustainable and bio-based construction solutions.

Company C lags in terms of integrating bio-based materials, restricting their use to wall and ceiling applications, which constitute approximately 12% of their overall building materials. Bio-based material has not been put in priority to replace the long-standing materials due to **incompatibility with the existing system**. Incorporating new materials requires exploring new supply chains and making adjustments to existing production facilities, all with the risk of potentially not achieving the same performance or cost-effectiveness. For instance, Company C has not found a bio-based alternative that can match the thermal resistance of the glass wool insulation currently in use. If bio-based insulations were to be employed to maintain the same thermal resistance, it might necessitate a larger dimension, which would be incompatible with the existing system. This makes bio-based materials integration a less favorable option, given the investments already made in the established system. The company leans more towards **modifying existing materials** to ensure reusability and durability, especially for relocation purposes. Hence contributing to sustainability and circularity in a different manner. For example, the floor had been modified over time to be thinner to minimize concrete use while maintaining system compatibility. Despite steel and concrete accounting for a significant proportion of 63% of the total carbon emission, they have the longest lifespan and still be seen as the most optimal way of construction.

Furthermore, the integration of bio-based materials into the construction industry is driven by the aim to promote more sustainable and circular practices. However, the effort to pursue it is not exclusively and practically confined to the adoption of bio-based materials. Multiple approaches are taken to achieve sustainable and circular goals. Drawing the silver lining from a comprehensive analysis of three distinct case studies, each case implements a different strategy to fulfill its environmental and societal responsibilities. While companies A and B prioritize sustainability and circularity by using sustainable materials in their building systems, Company C has proven their conventional material modules can be reused over decades of operation and therefore emphasizes reusability as its key sustainability and

circularity strategy. There remains a fundamental difference between the adoption of sustainable materials in companies A and B. When Company A solely emphasizes sustainable sourcing through the use of bio-based materials, Company B adopts a hybrid materialization that not only uses bio-based materials but also recycled material. This highlights the **diverse approaches to implement sustainability and circularity within industrialized construction systems.** In summary, while all three companies acknowledge the potential of bio-based materials, their strategies for integration differ by their individual operational and financial considerations. Company A champions the use of bio-based materials as a core part of its identity, Company B adopts the combination of bio-based and recycled material as its sustainable material selection, and Company C focuses on optimizing existing materials for reusability and longevity. The chosen strategies represent each company's perception of the most economical and pragmatic pathway to infuse sustainability into their operations. The variances in their strategies highlight the **equilibrium between environmental responsibility, operational practicality, and financial viability**.

5.2. IC methods

Bio-based adoption in the three cases has been reviewed in the previous chapter. Cross-case analysis on the IC firms itself will elaborate more on the relations between IC principles and the adoption of bio-based material. Table 5-2 shows the eight IC principles in each case study.

Table 5-2. Industrialized construction principles application in three case studies

IC Principles	Company A	Company B	Company C
Prefabrication of building part	Modular construction	Modular construction	Modular construction
Technical system	Standardized module production	Standardized module production	Standardized module production
Planning and control of process	In-house module production	Project management (as coordinator)	In-house module production
Logistic integrated into building process	Strategic factory location	Strategic factory location	Strategic factory location
Long-term relationship with actor	Flexible supplies	Suppliers as partners	Preferred suppliers
Use of ICT tools	For internal sharing only	For sharing with partners and clients	For real-time sharing between multiple offices and production halls
Measurement and re-use of experience	Iterative learning process	Iterative learning process	Iterative learning process
Customer and market focus	Bio-based-oriented	Quality-oriented	Market-oriented

Commonalities

All three companies share a core focus on **modular construction**, epitomizing an industry trend toward off-site construction. While these firms specialize in creating modules intended for temporary use, their quality standards are commensurate with those expected in permanent construction. A notable shared feature across all three cases is the reusability. They engineer their modules not only for durability but also for the ability to be reused with minimal degradation. Therefore, the utilization of

durable materials that can uphold their structural integrity in operational periods as well as during disassembly, relocation, and reassembly processes is essential.

Shifting toward manufacturing methods in the building sector, every case had implemented a **standardized module production**. A module is a self-contained unit that individually or collectively constructs a building. A standardized production of these modules will increase the speed of the production in an optimized way and therefore enable a scalable production. By having the least amount of site work together with a standardized process, modular builders in the case studies significantly reduce the overall construction cost, giving the advantage to the more traditional type of construction firms. To still be able to accommodate customer preferences, the companies combine their standard module to make variations of size and building type. The companies also allow clients to choose their facades, letting the appearance of their building be based on their preferences. This approach allows companies to keep their standard module designs relevant to client preferences.

Furthermore, as stated in the previous analysis, the main bio-based materials used in the building system are wood products. All the firms in the case studies had managed to source the material from nearby suppliers which positively impacts supply assurance, and therefore, operational performance as well. This refers to the wood sourced from European regions, as opposed to purchasing tropical wood from distant countries. In addition, a **strategic factory location** in the middle region of the Netherlands provides convenient proximity to not only the supplier but also construction sites.

With the similarities in modular construction nature, one commonality that emerges is all three companies apply an **iterative learning process**. Although each company standardizes its construction methods, they have platforms for collecting and integrating both technical and process-related feedback to be later developed as future improvements. This standardized yet flexible approach allows each company to continually refine its operational practices. In essence, the standardization serves not as an endpoint but as a catalyst for ongoing improvements and optimizations tailored to each company's unique operational framework. By iterating on these standards, all three companies are better positioned to adapt to new challenges, integrate innovations, and ultimately enhance their construction quality and efficiency.

Distinction

Company A, for starter, invests in **in-house production** lines, where components and modules are meticulously fabricated at its factory. The proprietary production system of Company A facilitates the procurement of pre-processed materials, customized precisely to align with its technical requirements. These investments play a pivotal role in not merely expanding the operational bandwidth of Company A, but also in amplifying its capability to effectively integrate bio-based materials into its production line. In addition, Company A's transactional approach fosters **flexibility in the supplier**, allowing the company to source bio-based materials from a diverse range of available suppliers in the market. This flexibility embraces a bio-based material strategy without being constrained by supplier limitations.

Company B, contrarily, performs its role **as a project coordinator without having any production facility of its own**, except for providing an assembly hall. Company B manages its supply chain and operations through collaborative partnerships, which not only ensure a secure and consistent material supply but also put the production responsibilities to suppliers. It relies on its partners to manufacture prefabricated components, conduct assembly, and execute installation. This arrangement facilitates well-organized feedback together the suppliers, leading to more effective product improvements. Its supplier has greater involvement in the process, the relationship becomes internal coordination with so much leverage in the product development. Furthermore, the partnership also means that Company B commits to maintain a consistent and ongoing transaction on a regular charge basis. This

means that the partnership scheme might emerge as a challenge, particularly during business downturn periods. To balance this cost and coordination challenges, the firm set its module standardization in stone This entails preserving technical designs for extended periods to minimize frequent modifications and adjustments, which could lead to overcharging by partners. The module is also to be kept at a standard size that can always be transported by regular vehicle rather than convenient bigger modules that require special transportation and incur substantial costs. Adding to the matter, changes can only proceed with the approval from all the partners due to the interconnected. Therefore, a radical change is also hardly possible to be implemented and might require a long process of readjusting the whole partnership. By striving for this degree of standardization, Company B manages to optimize the benefits derived from its collaborative partnerships while mitigating potential downsides. Thus, to be able to incorporate bio-based material in a partnership model, it is necessary to have robust and mature **bio-based material suppliers that are available for collaboration**.

Company C, on the other hand, has invested significantly in the **improvement and expansion of its in-house production facilities** over decades. This keeps its material selection to be aligned with existing technical capabilities and production systems. Company C focuses on ensuring compatibility and efficiency of the supply capacity to uphold a steady production flow. Despite this, Company C maintains its suppliers on a transactional basis, opting for widely available materials to mitigate risks tied to material and supplier dependencies. Only after a substantial number of transactions, Company C identifies and shortlists preferred suppliers. The selection of these preferred suppliers is based on their recurrent transactions, to verify the consistency and reliability. This is important to reduce procurement costs incurred for each transaction. This strategy is considered appropriate as the company **does not perceive any urgency to secure material supplies on a long-term basis given the availability of materials in the market**. Thus, even when these companies adopt similar modular production, their **material control and planning are highly influenced by technical systems and relations with their suppliers**.

Moreover, the analysis looked into the use of technology and digitalization are varied in **how the digital platforms are deployed**. While the scope of this research does not delve deeply into the intricacies of BIM application, it is evident that each company adopts these digital tools for distinct operational objectives. Company A and C primarily employ BIM and related technologies for internal organizational purposes, limiting the scope of these tools to in-house activities. Company C further leverages these digital tools for real-time data and information exchange across its multiple offices and factories, enhancing coordination and efficiency. In contrast, Company B adopts a more collaborative approach by allowing access to its partners and clients, thereby promoting a more open and inclusive environment for data sharing.

The cross-case analysis finally highlights distinct orientations among the three companies, revealing **disparate objectives** in their approach to construction and material utilization. Company A appears to be squarely oriented towards the emerging bio-based market, with an aim to capitalize on escalating environmental concerns and the accompanying demand for sustainable building solutions. This orientation manifests itself in the company's commitment to maximizing the use of bio-based materials in construction. In contrast, Company B places a dual emphasis on delivering high product quality and rapid construction. While sustainability remains a priority for Company B, its approach aims to strike a balance by also addressing the urgent societal need for housing. This suggests an integrated strategy designed to serve multiple, sometimes competing, demands. Conversely, Company C operates within a framework that is primarily market-driven, responding to a consumer base that is particularly price-sensitive. This company's material choices reflect an operational strategy geared

toward maintaining cost-effectiveness, largely due to its customer's apprehensions regarding the perceived extra costs tied to sustainable or bio-based materials. Therefore, each company's orientation serves as a lens through which to view their differing priorities and approaches to sustainability, quality, and market responsiveness.

5.3. Supply chain performance analysis

To The shift towards more manufacturing processes emerges different complexities in fluctuating commodity prices, rising customer expectations, and unstable economic conditions, which are commonplace in traditional manufacturing settings. This elevate the competition from company level to the supply chain level. To assess the current status of the supply chain, Supply Chain Operation Reference (SCOR) model is used. This report provides insight into companies through SCOR model level 1 by looking at five different attributes. The SCOR will give an overview of company's supply chain performance in comparison with each other as seen in Table 5-3.

Table 5-3. SCOR analysis

Performance attribute	Company A	Company B	Company C
Reliability	Inferior	Inferior	Superior
	3 years experience	3 years experience	63 years experience
Responsiveness	Inferior	Inferior	Superior
	5 modules/week	5 modules/week	>100 modules/week
Agility	Inferior	Advantageous	Superior
	Small-scale resources	In collaboration with big partners	Big-scale resources
Costs	Inferior	Inferior	Superior
	Bio-based material	Sustainable material	Conventional material
Asset management efficiency	Inferior	Superior	Superior
	Small scale in-house production facilities	Managing working capital	Large scale in-house production facilities

Reliability

Reliability, a crucial attribute in the context of both manufacturing and construction, pertains to the predictability and accuracy of fulfilling orders. Company C, with its longstanding operational history, exemplifies reliability in product delivery. Over the course of more than six decades, Company C boasts a diverse portfolio, extending beyond housing to encompass a wide array of modular construction projects. Perhaps the most telling evidence of Company C's reliability is its substantial market share capturing a promising 25% in the housing sector alone. This market presence is indicative of its capability to meet customer expectations consistently and a sign of trust, thereby solidifying its reputation for reliability. This seasoned expertise affords Company C a competitive edge, positioning it as a reliable player in the field of industrialized construction.

Contrastingly, Companies A and B, which were founded in 2020, are still in their infancy as startup companies that are working their way to enter the emerging sustainable construction market. Their experience is limited to a single project being completed in the summer of 2023 for each housing corporation they have collaborated with, highlighting their nascent stage in terms of reliability. While these startups may demonstrate promise, their track record is insufficient to ascertain a level of reliability comparable to Company C.

Responsiveness

Responsiveness is a critical dimension that encapsulates a company's work efficiency and its ability to meet deliver the product on schedule. Here, the factor of production capacity serves as a linchpin for

gauging responsiveness, with higher capacity often correlating to shorter lead times in order fulfilment. Within this parameter, Company C stands out for its advanced operational maturity. Company C has not only harnessed its extensive operational history but also consistently invested in progressive strategies aimed at process improvement and workflow optimization. This commitment to continuous improvement has reaped tangible benefits. For instance, Company C has successfully scaled its production capacity from an initial 5,000 modules in 2022 to an ambitious target of 15,000 units annually in the following year, thereby accentuating its responsiveness to urgent housing demands.

In contrast, Companies A and B operate at a smaller scale, churning out approximately five modules per week. In comparison, Company C has the capability to produce around 100 new modules and refurbish approximately another 100 units on a weekly basis. The comparison is revealing Company C's heightened level of responsiveness.

Agility

Agility signifies the capacity to swiftly adapt and navigate changing market dynamics. It possesses expansive production facilities, including technologically-advanced robotic appliances and ready stock material resources. These features enable Company C to scale production up swiftly in response to increased demand. Furthermore, its stock of returned modules provides a quick solution for urgent requests, enhancing its flexibility. Additionally, Company C has the benefit of extensive storage spaces across multiple factories, allowing it to manage excess inventory effectively when there is a need to scale down production.

Despite its smaller production, Company B leverages supply chain adaptability through strategic partnerships with large suppliers. These collaborations offer the dual advantage of boosting production capacity and augmenting material and labour resources during periods of rising demand. Moreover, the assembly hall is flexible, primarily used for the assembly of prefabricated components by partners that can be reconfigured without own substantial investment in machinery. This feature adds another layer of flexibility to its operations.

In contrast, Company A struggles with both flexibility and adaptability due to its confined operational scale. While it shares a similar current production capacity with Company B, its limited space and in-house resources make rapid adjustments to production more challenging. Despite ambitions to double production capacity annually, executing such aggressive scaling in a short time frame appears to be a significant hurdle with limited resources and space.

Cost

In terms of cost, Company C possesses a distinct advantage. Not only does Company C benefit from the competitive pricing of more conventional construction materials, but it also reduces transportation costs due to the widely spread suppliers all over the country. Furthermore, the utilization of in-house resources contributes to cost efficiency.

While Company A also utilizing in-house resources, it faces higher costs due to its commitment to bio-based materials. These materials are not only more expensive, but their nonexistence of local sources also incurs additional transportation expenses in the material price.

Company B, on the other hand, opts for sustainable materials, which inherently come at a higher price. Although long collaborations with partners might offer some cost adjustment, the relations are still on a fee-for-service basis. These service charges can be particularly impactful on profitability because it is more expensive than in-house resources on a regular operation. Therefore, in terms of cost,

Companies A and B face challenges in cost-efficiency, unlike Company C, which leverages its scale and resource integration for cost advantages.

Assets management efficiency

Although no specific data about the return of investment, in general, the return on cash is shorter for IC products because of the shorter lead time. It can be assumed that Company C, with its larger production capacity, gains a faster return on a transactional base, allowing for quicker reinvestment of its capital. Its advanced facilities in the newly expanded production hall, however, will take time to regain the investment. But with faster project realization, Company C can get the cashback more quickly as well.

The return of investment for Company A, which also has in-house production facilities, will be contingent on both the volume and the speed of project completion. These factors collectively influence the project duration thus affecting the speed at which cash returns are realized.

On the other side, Company B has made a relatively lower investment in fixed assets, particularly for production facilities. Therefore, its profitability and long-term survival are closely tied to the number and scale of projects it can undertake with its partners. Therefore, Company B might be more focused on the working capital.

6. Discussion

This chapter elaborates on the implications derived from the cross-case analysis conducted in the previous chapter, particularly focusing on bio-based material adoption in modular construction, adding bio-based variance in modular construction, the inclusion of bio-based material in modular construction planning, and future strategies to nurture a bio-based industrialized construction ecosystem. The limitations of the research are also presented.

The cross-case analysis is used to identify key trends, challenges, and opportunities that emerge across different cases, clarifying the factors that influence the adoption of bio-based materials in industrialized construction systems along with the strategies and necessary actions for further development. This section reviews the analysis in previous Chapter 0 to extract valuable lessons, best practices, critical implications, and recommendations that can contribute to both theory and practice.

6.1. Bio-based material adoption in modular construction

The case studies indicate that the integration of bio-based materials into modular construction systems tends to be limited to the materials that are already been proven in traditional construction methods. Among all materials, the adoption of bio-based material is dominated by wood products. The wood products such as timber and CLT essentially meet all material selection criteria outlined (Kriegh, et al., 2021). These criteria were made to compare the prospective bio-based material during exploration, encompassing various parameters from the development stage, available mock-up, and prototype, established testing requirements and protocols, suitable for construction assemblies and prefabrication or modularization, having high carbon-storing, verified Environmental Product Declarations (EPD) as data on carbon-storing capacity, available raw materials worldwide, high community impact, high impact reward, low-risk adoption, available reference researches, up to available partners for development in the market. Fundamentally, materials that can meet the majority of these criteria are most likely those that have already been long-established in the industry. **The modular construction sector appears not to be very adaptive to new bio-based materials**, a complexity arising from the manufacturing settings demanding a consistent and stable supply of materials.

The limited precedent for emerging bio-based materials in traditional construction methods requires a strategic approach for these emerging materials to gain market traction. Suppliers need to present a robust product specification and supply chain. As materials become pivotal for achieving green building accreditation, obtaining sustainable bio-based material certifications has become increasingly significant. Various certifications pertaining to materials and resources are available to serve as credible attestations of environmental performance and conformity with sustainability standards (Jones & Brischke, 2017). The **availability of certifications from the material supplier can lower entry barriers for the integration**, fostering a conducive environment for the growth of a bio-based material supply chain that aligns with the requisites of modular construction.

Moreover, the approaches undertaken in each case underscore **the most feasible sustainability strategies for individual operational contexts**. While Company A had optimized the integration of bio-based material use in their production, Company B stands with hybrid materialization due to the market availability of the partners, and Company C emphasizes on its reusability features that comply with its existing systems. This diversification reflects the most economic pathways that align with each company's distinct circumstances.

Company A is able to demonstrate the full-scale bio-based material adoption strategically by configuring its entire production line to be compatible in working with bio-based material. Although it

is widely recognized that bio-based materials tend to be more costly, this alignment with bio-based materials is the fundamental precondition of its operational structure, therefore the production is actually optimized when using bio-based material.

Company B, which based its operations on collaboration with its partners, discovered that these collaborations are not without limitations. There are not many options for suppliers of bio-based materials to begin with. It is possible to integrate more bio-based materials by collaborating in the development phase, which takes time before it is ready to be implemented in the building systems. Hence, finding alternative sources of sustainable materials is necessary for immediate application. The most viable approach at present time is to implement a hybrid materialization strategy that combines bio-based materials with recycled materials. This is primarily due to the presence of existing supply chains and the availability of suppliers for partnership.

Company C implements sustainable and circular practices by placing a higher emphasis on reusability rather than immediately adopting bio-based materials. Unlike Company A and B, Company C has established production lines that were not initially designed to integrate more bio-based material. To accommodate the increasing demand for bio-based material in the building systems, Company C needs to make a new production line that is specifically accustomed to the new requirements. As a result, opting for maximized reusability is the most technically and financially viable option.

Besides working on their environmental performance, material suppliers need to demonstrate an **adequate supply chain performance that ensures short lead times, customizability, and adherence to the quality standards** set by modular construction companies (Jansson, et al., 2014).

6.2. Adding bio-based variance in modular construction

As the housing crisis in the Netherlands intensifies, the issuance of building permits has notably declined, and the lead time for obtaining new building permits has extended, now requiring a significant number of years to allocate land and construct new housing. Given these circumstances, the modular construction method has gained increased attention, especially for temporary housing solutions. Modular construction allows for quicker construction processes, and when utilized for temporary structures, it may be subject to fewer regulations and procedures due to the urgent need for housing, less permanent impact on the local environment, simpler design standards, easy post-usage removal, special permitting pathways, and the use of pre-fabricated modules that have complied with building codes and standards. Consequently, temporary modular housing emerges as a convenient and faster solution to address the urgent need for housing, offering a viable alternative to alleviate the housing shortage in the Netherlands. Policy initiatives by local or national governments also encourage the use of temporary or modular constructions by reducing the bureaucratic hurdles associated with their approval and joint relocation guarantee with the housing association (Rijksoverheid, 2019).

However, modular construction has preconditions for production such as dimension and material that are determined during the design phase. **The design phase is a critical part of modular construction as the decision on how to standardize is set**. The foundation to build the company's ability to cater to high demands within a short time span will be then prioritized (Jansson, et al., 2014). By combining the standard module, the companies in the case studies manage to deliver the product in various forms. Balancing the standard design and the flexibility in offering space for personal preference is necessary. To give more comfort to the habitant, removing the temporary, cheap, and low-quality stigma when it comes to modular building.

All three study cases show the typical construction step with a similar variance in their standardized product that resembles the sectional modularity and component swapping modularity (3.2.2.Technical system). The sectional modularity is the main self-contained module that integrates the floor, wall, ceiling, and utilities, as illustrated in Figure 6-1. This cube-shape design has six sides that can be connected to each other (Salvador, et al., 2002). **The units can be made uniquely in form by arranging, coupling, and stacking the modules differently**. In the factory, self-contained modules are manufactured by installing floor, wall, ceiling, and functional utilities such as kitchen and bathroom. Such roof and façade building systems are produced as separate modules to be installed later when the self-contained modules have been assembled into the whole building at the construction site.

Such roof and façade building systems, that are constructed as separate modules, are referred as swapping modularity (Salvador, et al., 2002). **The detachment of façade building system makes it possible to apply different kind of façade that serves as the visual variance of the complete building without extra work adjusting the other component and modules**. With this arrangement, IC firms maintain their ability to offer variations in their products while their module is standardized as illustrated in Figure 6-2. This standardization also means that the number of components and complexity level are lower, hence increasing the operational performance. While the common way in modular housing is to imply the main module as a sectional module and façades as the component swapping, it is possible to be creatively implemented in different ways.

This also implies that a broader ability to have changes in the design of modular construction is only likely to be implemented on the component swapping modules, including the change in material selection. Bio-based material, if not considered in the initial design, was hardly adopted in the main module component once the production had been started.

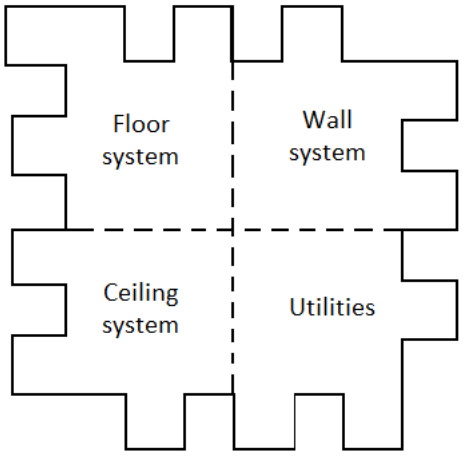


Figure 6-1. Construction of self-contained module

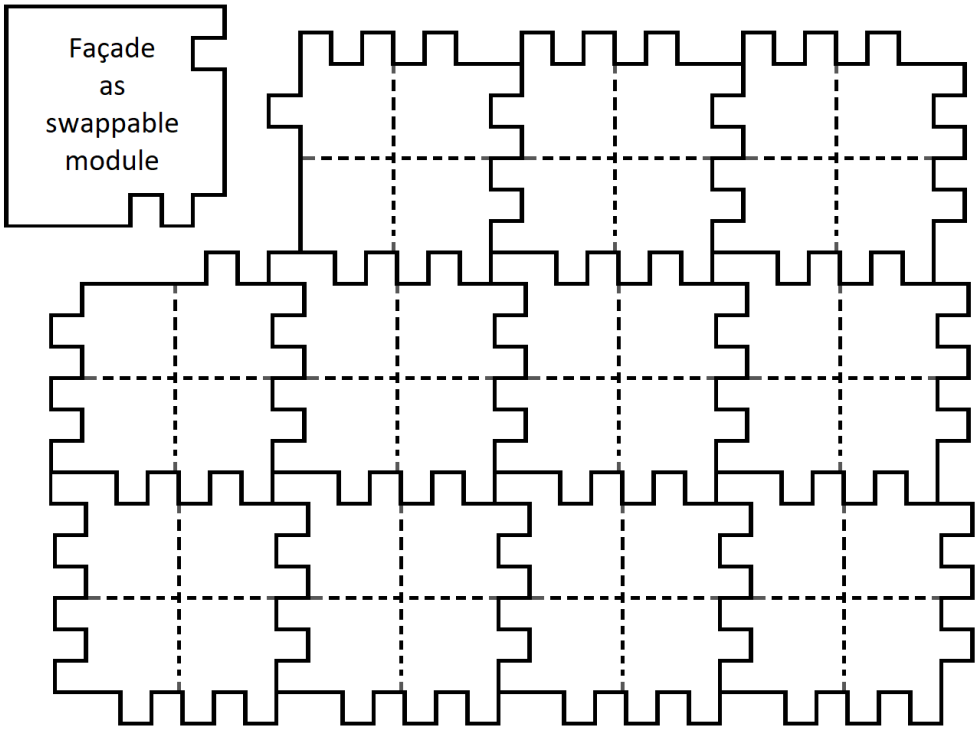


Figure 6-2. Façade as swappable module in the building construction illustration based on Salvador et al. (2002)

6.3. Inclusion of bio-based material in modular construction planning

In a manufacturing setting, it's vital to have control over the resources as continues and stable production is a priority. The planning and control over production capacity hold two important aspects (Bertrand & Muntslag, 1993). Technical capacity that looks over production machinery and labor resources. The other one is planning and control over the materials. In choosing the material, production capacity is subjected to the availability of material. The choice of material can be firstly determined based on either or both of them depending on the priority (Bertrand & Muntslag, 1993). When prioritizing the production capacity, selected material must have an adequate supply that meets production capacity and vice versa. This decision will serve as the basis for determining production capacity, as recorded in the bill of materials. Additionally, the production process will receive input from the client, where a predetermined variation is provided for the client to choose from.

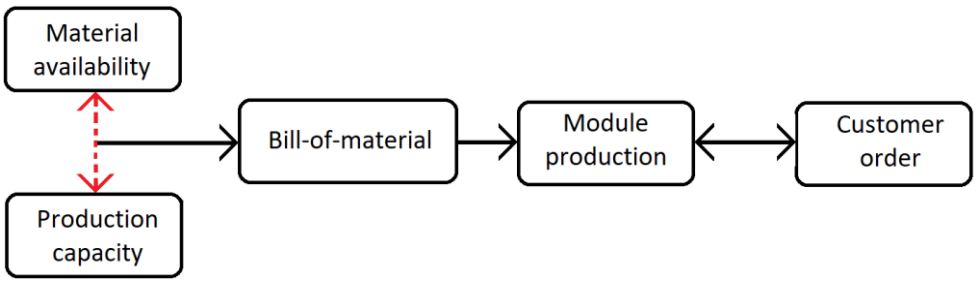


Figure 6-3. Material resource planning illustration based on Bertrand & Munslag (1993)

Bio-based materials as alternative construction materials are, therefore, still in question in terms of the volume and price to be used on a manufacturing scale. The case studies show that Company B and Company C emphasize their material selection on their production capacity. With the assumption that the specification and volume of available bio-based material have not been able to substitute the conventional material, the adoption is far from optimized. On the other side, Company A chooses its

material the other way around. By perceiving sufficient bio-based material supply chains, Company A based its production capacity on material availability. This way, Company A is able to majorly use bio-based materials in their production. Figure 6-3 illustrates material resource planning where the connection of material availability and production capacity interplay in the material selection.

The applicability of Manufacturing Resource Planning II (MRP II), therefore, can be revisited with the standardization in the modular construction industry. Standardization reduces the variability and custom requirements traditionally seen in Engineering-to-Order (ETO), highlighting the evolving nature of production planning and control in the construction industry. Hence, **more manufacturing principles shall be put into account as IC moves the industry's towards standardization**.

6.4. Bio-based material sourcing in modular construction

In the context of supply chain management within the construction industry, two predominant forms of supplier arrangements exist in the case studies. Transactional-based and partnership-based relationships. Transactional-based is the relationship between seller and buyer without any attachment and commitment for transactions (University of Minnesota Libraries, 2015). This model offers the company flexibility and enables it to seek the most economical options in the market. However, it also necessitates a larger budget allocation for continual supplier identification and negotiation for each separate transaction. Over time, a preferred supplier may emerge from frequent transactions, though without binding agreements. This arrangement reduces the cost of finding new suppliers for every transaction, drawing on the familiarity and trust built from previous interactions. To integrate bio-based materials into this system, specialized bio-based suppliers are necessary. These suppliers must demonstrate reliability and cost-effectiveness before being shortlisted as preferred suppliers, thus ensuring more secure planning and demand fulfillment.

On the other hand, partnership-based supplier arrangements foster a deeper, more collaborative relationship, encompassing elements such as continual feedback loops and, in some instances, shared decision-making. Such partnerships are particularly advantageous for securing material supplies and the advancement of product development, as suppliers can be better involved and integrate constructive feedback into their products (University of Minnesota Libraries, 2015). Resources-sharing between partners is also common, presenting mutual benefits, yet, this approach exponentially amplifies coordination complexities. In a partnership-based model, each partner not only communicates with the central coordinator but also coordinates with each other, thereby amplifying the complexity and layers of supervision. Furthermore, decision-making becomes increasingly challenging as consensus must be reached among all partners. This intricate interconnectivity makes implementing changes a complex task as seen in Figure 6-4. Because the partnership model involves shared resources, parties could invest in R&D initiatives to explore optimal improvement. Such a collaborative approach would allow for a smoother transition, backed by collective expertise and investment. The adoption of bio-based material in this scheme can only be realized when the partnership has one or more partners that possess expertise in bio-based materials. However, if this expertise is lacking, bio-based material integration becomes unlikely and it is essential to bring on board a new partner with the necessary knowledge to incorporate bio-based materials into the system.

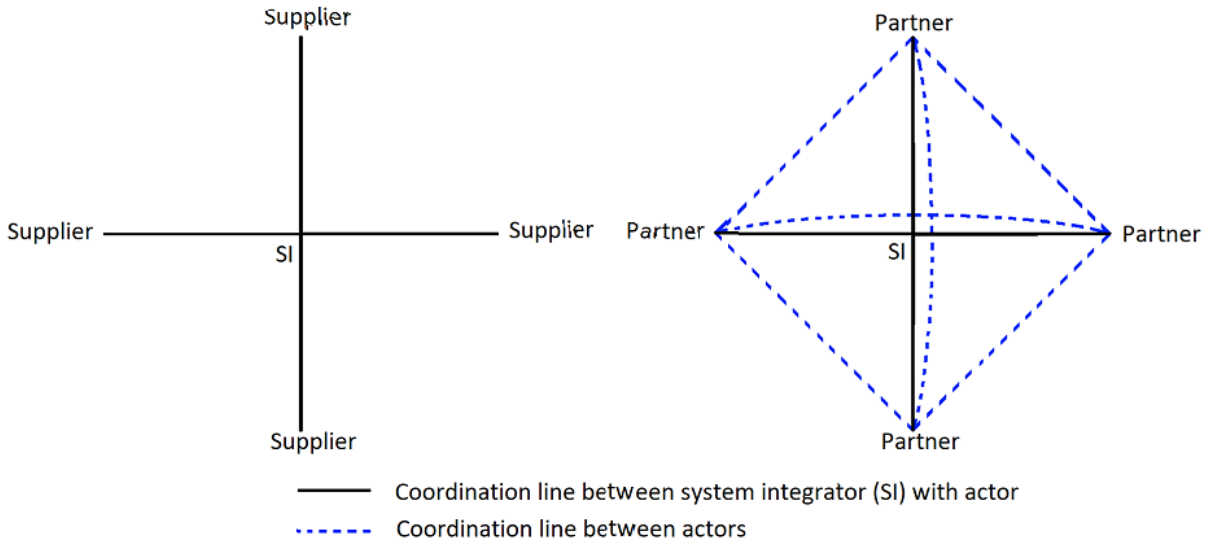


Figure 6-4. Number of coordination illustration adopted from Hobday (2000)

The preference for transactional relationships in the modular construction sector is often driven by the desire to maintain flexibility in the operations. This approach primarily revolves around selecting widely available materials in the market, thereby ensuring handiness and convenience of the resources. **Only in cases where materials are seen to be scarce, forming long-term relationships with suppliers becomes a sensible approach**. This can be refer to not only the material supplies, but also the resources and services provided by the suppliers. This situation presents a challenge for emerging materials that are trying to enter the market. The standardization norms among modular builders vary a lot, leaning more towards a closed product design where material suppliers are required to tailor their offerings based on specific requirements. This customization is contrary to the principles of an open product architecture that promotes standardized components, which could potentially benefit both material suppliers and modular builders. Transitioning from a closed to an open product architecture could empower material suppliers to develop more standardized components, aligning with the general needs of modular builders while maintaining modular builders' flexibility in selecting suppliers (Mikkola & Skjøtt-Larsen, 2004). This shift, however, brings forth a critical contemplation regarding the IC principles that advocate for long-term relationships with stakeholders (Lessing, 2006). It beckons an inquiry into whether there will be less product development in modular construction companies with the adoption of an open product architecture.

6.5. Future strategies to nurture bio-based industrialized construction ecosystem

For successful adoption of bio-based materials in the IC system, SWOT analysis is performed as a foundational tool for identifying both the advantages and challenges inherent in bio-based material adoption, establishing a basis for strategy formulation. Key strategies are proposed to leverage the strengths and opportunities, mitigate the threats, and address the weaknesses (Weihrich, 1982). This structured approach ensures that the strategies developed are well-aligned with the current and potential future scenarios, making the SWOT analysis a critical step in strategizing for the successful integration of bio-based materials in the IC system.

Strengths

The coupling of bio-based materials with modular construction systems is a powerful; combination that holds promises for transforming the future of sustainable construction. The economies of scale benefit of IC methods enables cost reduction while mass producing. This is useful and even essential for sustainable builders to compensate for the higher price of bio-based material to maintain a

competitive price of the product. As a result, bio-based construction material can be produced and implemented on a larger scale and the **future-proof housing solution becomes affordable**.

Weaknesses

Nonetheless, the adoption of bio-based material is not without its weaknesses. IC system requires comprehensive planning in the design phase. Once these systems are established, accommodating new elements or implementing changes becomes inconceivable undertakings. This rigidity in adapting to novel components extends to the adoption of bio-based materials. Currently, bio-based materials emerge as alternatives to unsustainable conventional construction materials, but not as direct substitutes that have similar properties to the existing material in the system. This leads to **difficulties in adopting 'unique' bio-based alternatives in the existing modular construction system** as many of the bio-based are not yet ready for industrial production scale.

Opportunities

With the urgency of both the housing crisis and carbon emissions reduction, sustainable housing construction is being explored. Both the policymakers and the housing association are actively evaluating and exploring the practical possibility of bio-based applications as construction materials. To successfully enter the market, a high level of both adoption of bio-based material and production capacity must be ensured. This means it is an **open window for not only bio-based housing builders but all the involved parties in the supply chain**. By actively involved and participating in the community, the companies in the case studies secured their projects. There is no restriction for the technical requirement, the government is seeking innovation in this urgently needed transition. With the manufacturing nature, farmers, material producers, component manufacturers, and system integrators must be working side by side to develop a rigid supply chain. Since it is more difficult to redesign the existing production, the opportunities are suitable for motivated new entrants or the ambitious existing bio-based modular housing supply chain.

Threats

In addition to the urgency that had been mentioned in the opportunities, it is important to keep the balance between quality and quantity. Quality is associated with the production capacity of modular construction while quantity on the sustainability part. When **putting more focus on quantity**, bio-based material improvement can hardly compete in tenders. To nurture bio-based modular construction, a balance requirement must be set to keep the both benefit of economies of scale from IC and future-proof alternatives from bio-based material. This had been experienced by the companies who failed to get the tenders due to the lower production capacity in comparison with the conventional modular builders.

The SWOT matrix further summarized and organized the key findings to determine necessary actions to be addressed to relevant parties as seen in Table 6-1. In the rapidly evolving landscape of sustainable construction, modular builders as the innovators in the construction industry, have developed design and engineering processes with digital technology and automation (Lessing, 2006). However, their roles in improving supply chain performance and restructuring contractual frameworks, as also said by Lessing (2006), require a collective effort, extending beyond the capabilities of modular builders alone. Modular construction companies, therefore, find themselves at a significant crossroads, presenting a viable and innovative solution to longstanding housing and environmental issues. Governments, housing associations, and established construction firms are all currently in a state of flux, eagerly seeking the most effective and sustainable methods to address these challenges.

For housing associations, the incorporation of bio-based materials is substantial to offer sustainable, durable, and cost-effective housing solutions. The application of bio-based materials is applicable to

both owner-occupied and rental-based housing markets. In owner-occupied housing, the selection of bio-based materials is crucial to ensure sustainability over the long term, given the mandate for new constructions in the Netherlands to be nearly carbon neutral (Rijkswaterstaat, 2021). These materials contribute to reducing the environmental impact, improving energy efficiency, aligning with homeowners' sustainable investment aspirations, and potentially augmenting property value. On the other hand, for rental or temporary housing, bio-based materials play a vital role in sustainable building. With the nature of bio-based material that can be reused, recycled, and composed at the end of the lifecycle. Therefore, contributing to a circular economy and reducing waste in the housing sector. The collaboration between housing associations, bio-based modular companies, and other stakeholders can foster a more integrated approach towards sustainable housing and contribute to the broader goals of environmental sustainability and housing affordability.

To foster innovation, governmental agencies have already taken proactive measures to establish networks and incubators aimed at nurturing new ideas and technologies (De Circulaire Bouweconomie, 2018). This has created an incredibly conducive and welcoming ecosystem for nascent industries like bio-based modular construction to flourish. Company A, a pioneer in this space, reports heightened interest from authorities and potential clients who are keen to explore the revolutionary possibilities that this form of construction offers. This enthusiasm is further evidenced by the high level of competition in housing innovation challenges, in which both Company A and B participated shortly after their inception. Remarkably, Company A managed to clinch a victory in one such challenge just six months post-establishment, despite lacking a factory to actualize the idea it had presented. This period is the time when no major player in the market and no standard had been implemented, hence being the **early adopter** gives the opportunity to influence the market as it matures.

Contrary, in a climate where the urgency of the housing crisis often overshadows the need for sustainable construction methods, emerging companies specializing in bio-based modular housing face destructive challenges. These companies, testified by Company A, often find it difficult to compete in tenders that prioritize the sheer volume of housing production over sustainability credentials. Established firms, like Company C, with matured supply chains focused on conventional materials, typically have the upper hand in such scenarios. For example, a tender that Company A failed to secure, was subsequently won by Company C. As a result, it becomes imperative for emerging bio-based modular builders to scale up their production capabilities. This involves not just focusing on individual company achievements but also on **strengthening their supply chains**, as the industry is increasingly leaning towards manufacturing efficiencies over one-off project successes. This has a good chance of happening, especially when there is low awareness about the advantages of using bio-based materials. The acceptance rate further depends upon both consumer and regulator knowledge (Jones & Brischke, 2017). While consumer knowledge is highly influenced by how modular builders communicate their environmental impact, material performance, and product specification to their potential customers, regulator knowledge is impactful to life-cycle assessment and tender form that influences the financial and procedural aspects of adopting bio-based materials.

There exists a tension between economic feasibility and the imperative for sustainability. While modular construction systems are often geared towards economical materials, the emergent spotlight on sustainability opens a window of opportunity for integrating bio-based materials. One key issue is that there are few bio-based materials currently available that are suitable for easy substitution in existing systems. However, this landscape is evolving, with emerging bio-based material producers actively in the development phase. In this context, **collaborative research and development** between modular construction companies and these emerging producers could offer mutual benefits. For modular builders, such a partnership would facilitate better familiarity with the new materials,

enabling them to steer product development in directions that align with their building systems. Emerging material developers also stand to benefit, as collaborating with modular builders would allow them to test their products while sharing the associated costs, which could be crucial for small businesses operating with limited capital. After all, regardless of the practical constraints, bio-based materials hold a significant environmental advantage. The commitment to supporting sustainable construction doesn't necessarily require companies to completely overhaul their systems. Instead, it can be manifested when companies begin to diversify their systems to incorporate more sustainable practices.

Table 6-1. SWOT matrix

	Opportunity Open window for bio-based housing supply chain	**Threat** Focus only on quantity (production capacity)
Strength Affordable future-proof housing	Get early adopters advantage in bio-based modular construction sector	Supply chain integration to strengthen the production
Weakness Difficulties in implementing bio-based material in existing modular building systems	Joint research and development with emerging bio-based material supplier	Authority intervention to prevent the exploitation of IC applications that escalate the use of carbon-intensive material

Furthermore, a much more concerning situation where neither the demand side nor modular construction companies seem strongly motivated to prioritize sustainable alternatives. This is exacerbated by the limited availability of bio-based materials on the market, pushing the prospect of environmentally sustainable construction even further away. Under these circumstances, it becomes critical for **authorities to intervene**, offering clear directives that heighten awareness of the

environmental crisis among both suppliers and consumers. In the absence of such obligation, the transition to sustainable materials is likely to remain slow, as parties on both sides of the market may not feel compelled to act with the urgency that the situation warrants.

6.6. Research limitations

This research encounters several limitations that need to be taken into account. Firstly, investigations into the supply chain could not be conducted as the suppliers of wood as the primary biobased material are located outside of the country. Consequently, no interviews were conducted with the material suppliers. Secondly, Company B with a different business model is primarily engaged in project management and coordination activities of the partners, thereby limiting insights into the technical aspects. Furthermore, due to the separate locations of Company B's office and the assembly hall, a site visit was conducted only to the office where most of Company B's activities take place. There was no visit to the assembly hall, thus no observation of the actual assembly process of the modules. However, a model house is present at the office for demonstration purposes. Thirdly, the interview and available documents were limited within each case. Even though multiple participants were interviewed for each case, the role of the participants was the same and not much documentation exists that relates to the research. The analysis could be deeper if more interviews and more documentation were available. Fourthly, while there are more modular builders available in the Netherlands, due to time constraints, only three companies were selected for the case studies. The three different cases show very distinct approaches, indicating a potential variety in the broader industry landscape. Studying a broader range of cases would have been valuable to the research, as it could have provided a more diversified understanding of modular construction systems in practice.

Interviews were also conducted with external parties to gain a more holistic understanding of the bio-based materials construction ecosystem. While these interviews are not directly reflected in the report, they enriched the contextual understanding of the research. Representatives from governmental bodies and consultancy firms were also interviewed to gather diverse perspectives and insights. However, interviews with housing associations, which represent the client side, were not conducted as this research is primarily focused on the supply side of the market. The absence of the client-side perspective could be viewed as a limitation, as understanding the client's perspective could have added a valuable dimension to the research. More explorative interviews can also enhance the quality and result of research due to the novelty of the research in the field relating to bio-based material and modular construction.

7. Conclusions and recommendations

The conclusion of the exploratory research is presented in this chapter. The answer to the previously defined research question is discussed along with future recommendations.

7.1 Conclusions

The exploratory research started with the aim of understanding the relationship between bio-based materials and industrialized construction by conducting the analysis on literature studies and three case studies. To conclude the research, each sub-research question will be answered as follows.

1. **What are the applications of bio-based materials and industrialized construction in the building industry domain that has been identified in academic literature?**

Bio-based material for building construction

Many academic researchers have studied the applications of bio-based materials in the building construction. In the context of wall applications, the use of straw-based walls has demonstrated comparable performances to conventional brick walls. Environmental, economic, and social advantages were observed when substituting conventional material with bio-based material. In terms of building insulation, bio-based materials exhibit immense potential as sustainable heat sources for natural gas-free housing solutions. Straw-based insulation materials have shown potential energy savings and cost-effectiveness over time, especially in colder climate regions. Meanwhile, in façade applications, bio-based materials such as wood and biocomposite provide natural-looking building exteriors, while enhancing durability through moisture management properties that are good for preventing decay and mold growth. These are the examples that can be extended to other bio-based materials.

Furthermore, the most highlighted features of bio-based construction materials are their low-energy production process and carbon capture capabilities. Besides being environmentally beneficial with high recyclability and biodegradability, bio-based materials are possible to reduce construction costs and yield operational savings. The benefit can be broadens when better and healthier living condition for the inhabitant is taken into account and sustainable sourcing where raw material can be planted annually and taken as a secondary product from other industry.

Industrialized building construction

Industrialized construction is an approach to enhance the productivity and effectiveness of the construction sector. It is done by adopting manufacturing nature to building constructions, enabling economies of scale through mass production. Eight principles can be taken in transforming traditional construction practices to IC by continuous improvement of prefabrication, technical system solutions, planning and control process, integrated logistics, long-term relationships, use of ICT tool, measurement and re-use of experiences, and customer and market focus principles.

2. **How do Dutch industrialized construction companies incorporate bio-based materials in their systems?**

Motivation to adopt bio-based material for industrialized construction companies

The Dutch industrialized construction companies incorporate bio-based materials within the system as a commitment to fulfil their social and environmental responsibilities. However, using bio-based material is only one of the ways to perform sustainable and circular practices. The selection of

sustainable and circular strategies often hinges on the perceived viability for their specific operational contexts.

Decision to adopt bio-based material in industrialized construction system

Incorporating bio-based materials into modular systems is more likely to occur when considered during the planning phase. Once the production process commences, substituting existing materials with bio-based alternatives may not often be the most cost-effective choice. Notably, the transition to bio-based materials is presumed to be relatively easier in panelized construction due to its segregated elements. In fact, a higher adoption of bio-based materials is observed within panelized construction systems.

Bio-based material selection

Industrialized construction systems tend to favor well-performing materials with a proven track record of performance in the construction industry. This preference is to ensure the quality of the final product and to guarantee a stable supply chain that is requisite for large-scale production. Consequently, the adoption of bio-based materials within modular construction remains notably limited, because most of the bio-based materials are currently at their development phase. Thus lacking the assurance required for industrial scale manufacturing, with the exception of wood.

Contribution to bio-based material development

While the emerging bio-based material is still on the development phase. IC companies can integrate these materials into the systems on a trial basis. This way, companies can customize the material better for their systems, while also facilitating material suppliers in refining and maturing their products.

3. What are the enablers and barriers to adopt bio-based materials in the Dutch industrialized construction systems?

Enablers

The specific market segment of sustainable housing encompasses a strong commitment to contribute in achieving sustainable and circular goals in the building sector. Government support plays a pivotal role in fostering growth that incentivize the adoption of bio-based material and construction practices. Sustainable goals also encourage developers to demand higher energy efficiency standards and the use of healthier in the buildings.

The emerging bio-based material for building applications is currently under development. This offers a promising opportunity to enhance the integration of bio-based materials within IC systems by the collaboration between IC firms and material suppliers. IC firms, with their knowledge and experience, can tailor the materials to better suit their specific construction systems. While, bio-based material suppliers can benefit from co-developing their products, reducing significant testing-related costs. The collaboration will also accelerate the material's market entrance and increase the chance of longer-term partnership.

IC aims to increase the productivity and effectiveness of the construction process, strategically improving production scalability. This approach offers notable advantages in terms of cost reduction, which can be essential to accommodate the integration of bio-based materials that are often more expensive. IC not only improves production efficiency but also provides a strategic pathway to incorporate bio-based materials, promoting sustainable practices while maintaining a competitive market position.

Barriers

A significant portion of bio-based materials is still in the developmental stage, leading to limited availability in the market. This scarcity often drives up the price, making these materials less appealing substitutes for conventional construction materials.

Industrialized construction systems fundamentally operate on the principles of standardization to reap the benefits of economies of scale. However, standardization creates a certain level of resistance to change within these systems. The systems also require consistency in materials to maintain their production control and efficiency. In addition, bio-based materials often possess unique characteristics and properties that might not be compatible with existing systems. Therefore, careful consideration is required to integrate bio-based materials without compromising the inherent benefits of industrialized construction.

Market awareness for bio-based building materials remains low due to limited understanding within the market. The market is comfortable and familiar with conventional building materials, hence do not feel the necessity for improvement.

4. **How can industrialized construction companies enhance the performance of their supply chains?**

Overall, a holistic approach that encompasses technology adoption, process optimization, collaboration, and strategic investments is crucial in supply chain performance. Strategically organizing the supply planning and orders can strengthen the competitive position for sustainable and long-term success as follows:

- Build a track record to demonstrate reliability and trustworthiness. Having good control over the product quality and process flow that integrates feedback from the clients.
- Optimized scheduling and resource allocation are necessary to enhance responsiveness. Identifying bottlenecks in the supply chain and focusing on countermeasures that can significantly improve lead times and overall production throughput.
- Choose the most cost-efficient sourcing that can effectively augment the agility of material resources and labor. If capital is limited, Outsourcing through these partnerships can not only accelerate product development but also distribute risks, costs, and expertise while sharing resources for mutual benefit.
- Localizing the supply chain can reduce overall transportation costs and improve the integration of logistics processes while reducing uncertainty in the material supplies.
- Opting for strategic investments that accelerate the production cycle. Whether on machinery, working spaces, or other resources that can reduce dependency and vulnerability to the supply chain.

5. **What are strategies to adopt local bio-based materials in the Dutch industrialized construction systems?**

Based on the research, strategic actions can be taken to increase the adoption of bio-based material in IC systems. The following are the recommended strategies subject to collaboration between industrialized building companies and authorities:

- Increase engagement in the bio-based construction sectors to gain attract more players.

- Firm regulation to prevent misuse of IC application.

The recommendations below require collaboration between industrialized construction companies and other stakeholders in the supply chains:

- Supply chain integration to scale up the production capacity and performance.
- Joint research and development to speed product development.

7.1. Recommendations

To finally answer the research question “How to integrate more bio-based materials in industrialized construction systems?” the following are the recommendations made for industrialized construction companies and regulatory bodies.

As the research is taken from modular construction company perspectives, more elaboration has been explained in the report. Companies can take a hybrid approach to sourcing the material that uses both transactional and partnership. While maintaining transactional-based relations to source readily accessible material, a collaboration to develop specific components can be done. The collaboration is intended to foster prospective materials that are under development. By involving these diverse stakeholders, the modular construction industry can adopt a holistic and collaborative approach to its challenges, thereby expediting the adoption of sustainable practices and enhancing performance metrics.

Comprehensive regulations that include minimum adoption of sustainable practices shall be implemented. Public procurement policies should be aligned with these objectives by prioritizing sustainable construction. This would not only set a standard for the industry but also create a consistent demand that encourages companies to adhere to sustainable practices in addition to green financing. To facilitate a comprehensive focus on sustainable and modular construction, a multi-stakeholder approach such as affordable sustainability certifications encourages widespread adoption of eco-friendly practices. Academia and involvement to refine methodologies and technologies. Impartial case studies to evaluate the practical benefits and challenges of modular construction, publishing these findings for the broader industry.

7.2. Future research

After conducting the empirical study, several areas were found intriguing for future exploration. Since the investigation into the emerging bio-based material producers has not been covered properly with only two encounters with material suppliers, an in-depth study concentrating on these actors could reveal critical insights into the challenges of bio-based material development. Additionally, conducting a single-case study dedicated to exploring an entire supply chain would offer comprehensive perspectives, particularly given the manufacturing-intensive nature of modular construction.

Beyond the realm of bio-based materials, further research could also focus on modular construction companies that operate under a partnership model, like Company B, to examine the intricacies of coordination and technical implications in such settings. Finally, while the current study is largely supply-centric, an examination of the demand side could project another side of the market, determining further the adoption and implementation of bio-based materials and modular construction.

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Appendix

Appendix A: Interview protocol

Interview Protocol

General intro (3 mins)

- Explain the research objective and the goal of the interview.
  - The research purpose is to identify the opportunity to promote and expand the adoption of local biobased material resources in the industrialized construction sector.
- Explain the interview protocol (structure and duration).
  - The interview consists of open-ended questions in a semi-structured interview.
  - It will take approximately 30-45 minutes.
  - There are no right and wrong as well as minimum and maximum responses.
  - You are free to give any answers as desired.
- Inform consent and permission to record and generate a transcription of the interview.
- Assure the participant's anonymity, and data access will only be available for research staff, and planning deletion of recordings.

General information

1. Name :
2. Company :

For IC companies (A)

3. Can you tell me about/describe your product to me?
   a. What activities does your company do to deliver your product or service?
4. Who are your clients and partners?
5. Does your product contain bio-based materials?
   a. What material do you use?
   b. What is the proportion of bio-based material in your product?
6. How did you start to integrate bio-based materials?
   a. How do you choose your material?
   b. How do you manage your supplies?
7. In your opinion, what are the benefits of using bio-based material?
   a. What are the future opportunities?
8. What motivates the company to use bio-based material?
9. What are the challenges to use bio-based material?
   a. How do you manage to overcome the challenges?
10. Do you project any risks by using bio-based material?
    a. What improvement do we need to make a more conducive ecosystem for bio-based material adoption?
11. (if no local materials) Would you consider using local material resources? Why or why not?
12. (if yes local materials) What are the challenges specific to the use of local materials, compared to non-local bio-based materials.
    Do you have any recommendations of whom I should speak to?

Appendix B: Research ethics

Information Sheet and Consent Form

You are invited to participate in a study of "Expediting the Adoption of Local Bio-based Material Resources for Industrialized Building Construction in The Netherlands". This study is for a master thesis by Arika Dhia Suryana from Faculty of Civil Engineering and Geosciences, TU Delft. Please read below information carefully and let us know if you need further information.

Primary investigator : Arika Dhia Suryana;

Supervisor : Dr. Daniel M. Hall;

Data Steward : Lora Armstrong

Purpose:

The research purpose is to identify the opportunity to promote and expand the adoption of local bio-based material resources in the industrialized construction sector. The participants are the stakeholders that are likely to be in the supply chain and willing to share their practical experience and visionary views towards the topic.

Participation:

The interview will consist of open-ended questions in a semi-structured interview that will take approximately 40-60 minutes. There are no right and wrong as well as minimum and maximum responses, the participants are free to give any answers as desired. The participation will be based on a voluntary basis and you may withdraw at any time.

Confidentiality:

The interview will be video/audio recorded with participant's consent. We acknowledge the risk of a breach in keeping digital information, therefore to mitigate the risk the data will be kept in strict confidentiality in a password-protected database. Access to the data will be limited only to the primary investigator and research supervisor only. The recording will be automatically transcribed and analyzed for content using pseudonymisation keys before being discarded. The participants have the right to review the transcription and request to exclude part of the interview and any personal data prior to the irrevocable anonymization of the collected data without giving any reasons. Original files will be permanently deleted after the conclusion of the study and no identifiable information will be shared.

Participants can address their concerns to the contacts provided. Below you can find the informed consent form for this research. Please tick the appropriate boxes to indicate your consent; alternatively, we can record your answers during the interview.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • Recording of the interview. • A semi-structured interview with open-ended questions related to practical experience and visionary views related to the research topic. • The recording will be automatically transcribed and manually edited to correct the autogenerated transcription mistakes. • The recording will be stored in a password-protected and limited-access database. It will be destroyed after the conclusion of the research.	☐	☐
4. I understand that I will not be financially compensated for my participation.	☐	☐
5. I understand that the study will end by September 2023.		
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks. • The risk of leaked personal information. • The risk of leaked business/organization strategies. • The risk of reputation damage from leaked information. I understand these will be mitigated by publishing only aggregated data (code book and combination of analysis of all the interviews). The transcripts of the interviews will not be made public and will only be available to primary investigator and research supervisor. Personal information will not be published or made available to anyone not involved in the research. The personal data will be stored in a password-protected database and deleted once the research is completed September 2023). The interview will be filled with open-ended questions. Participant can choose how to respond to each question that may be detrimental to you/your organization. You may choose not to respond to any of them, and you have the option to end the interview at any time.	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII) [name, contact information, company name] and associated personally identifiable research data (PIRD) with the potential risk of my identity being revealed the risk of re-identification and the subsequent risk of affecting my public or professional reputation.	☐	☐
8. I understand that some of this PIRD is considered as sensitive data within GDPR legislation, specifically business operational and organizational views.	☐	☐
9. I understand that the steps outlined below will be taken to reduce the risk of a data breach and protect my identity in the event. The interview will be conducted in complete anonymity. Personal information will not be published or made available to anyone who is not involved in the research. After the research is completed, the personal data will be deleted.	☐	☐
10. I understand that personal information collected about me that can identify me, such as my name and contact details, will not be shared beyond the study team.	☐	☐

11. I understand that the (identifiable) personal data I provide will be destroyed after the research has ended. This will be conducted after the research conclusion, which is anticipated to be around September 2023.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that the de-identified information I provide will be used for the following purposes after the research study. The master thesis and the interview results will be made public on the TU Delft Repository (https://repository.tudelft.nl/). The anonymized coded of the interviews will be included in the appendix to the master thesis.	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐
D: (LONG-TERM) DATA STORAGE, ACCESS, AND REUSE		
14. I give permission for the de-identified data and the results of the interviews, such as the combination of encoded answers from all respondents to be included in the research which will be archived in the TU Delft repository (https://repository.tudelft.nl/). The transcribed interviews will not be made available to the public or stored on the TU Delft repository.	☐	☐
15. I understand that access to the repository and where the master thesis is stored and other forms of publication are openly available on the internet.	☐	☐

Signatures

_____	_____	_____
Name of participant	Signature	Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_____	_____	_____
Researcher name	Signature	Date