Ensuring adaptability in modular construction

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Abstract

Sustainable development is growing, transforming and adapting according to the social, economic and environmental demands in different fields. More specifically, in the building sector, due to the increased environmental pressure covering different stages of building's lifespan from the production phase to the management of building waste (COM 2014,p2), an interest regarding the issue of adaptability in buildings is repeating over the years as it involves actors from several disciplines including planners, architects and engineers. This thesis explores how production technology/ practices in prefabricated modular construction can influence the process of building adaptation to future social alterations.

With a broader standpoint narrative, and using the theoretical base from previous studies regarding adaptability and disassembly in buildings, together with my own field study in production facilities and interviews with the experts, this research study explores the current construction sector.

Through case analyses focusing on the construction systems and applied strategies for flexibility/adaptability, within construction, I expose the limitations of the current industrialized system to deliver solutions that embrace the sustainable transition in the construction sector.

The approach of the problem builts on two perspectives. The first is related with the adaptability strategies as introduced by Schmidt III et al. (2012), and examines the compatibility of the systems in adopting those strategies. The second perspective sees through the glasses of the economic sociology of how the construction industry has developed and how, after has fallen to path-dependencies, is now locked-in.

After observations and the (application) of the evaluation tool that corresponds to the industrial phases of construction, I propose solutions that will have returns in the short and long term for the industry. Finally, a plan to overcome industrial lock-in is presented.

1. INTRODUCTION

1.1 Background

It is a fact of the days we live in, that consumption of material resources and CO_2 emissions increase respectively to the population increment and income. More specifically, only during the last century the world population has risen more than four times to 7,6 billion and global economic output (global GDP) more than 20 times (Krausmann et al. 2009; UN 2017). Furthermore, regarding material consumption, its percentage has grown eight times, which means that people use the equal of 1.7 Earths in order to provide resources for use as well as absorb our waste (GFN n.d.). Nevertheless, in 2001, 100 million tonnes of carbon were the outcome of CO_2 emissions increment an annual rate of 3.5% (Sherbinin et al. 2007).

The numbers of construction and demolition waste in Europe are alarming since, according to the numbers of Eurostat in 2017, the amount of construction and demolition waste in 2014 was 868 Mt, equivalent to one-third of total waste produced across EU member states (Repolho, 2017).This amount includes the waste produced during the construction, total or partial demolition operations and refurbishment processes. However, the average percentage of recycling and material recovery of activities related to buildings is only 55% varying widely from country to country (COM, 2016).

Considering the EU goal for 2020, about the reduction of construction and demolition waste in 70% (Official Journal of the European Communities, 2006), motives regarding the design of adaptable buildings emerge. Lifetime extension contributes to the reduction of their environmental impact, embodied energy and waste production (Gosling et al, 2008). In 2011 the European Commission (EC) (2011) released the "Roadmap to a Resource Efficient Europe", which is a description of the challenges the world is facing, along with the strategy to convert those challenges into opportunities. It describes the transition in energy, industry, agriculture, fisheries, transport systems, producer and consumer behavior. Particularly in the construction sector the main objective of the or" conducted by the European Commission (EC) (2014), is to reduce the buildings' environmental drawbacks by becoming resource-efficient and as a consequence, improve the competitiveness of the construction businesses.

Over the next 40 years, we will need globally to enlarge the urban space more than has been built up in the past four millennia (Biello, 2012).Therefore, the building sector offers ground for opportunities to reach local and global environmental goals, such as the UN Sustainable Development Goals (United Nations, 2015).

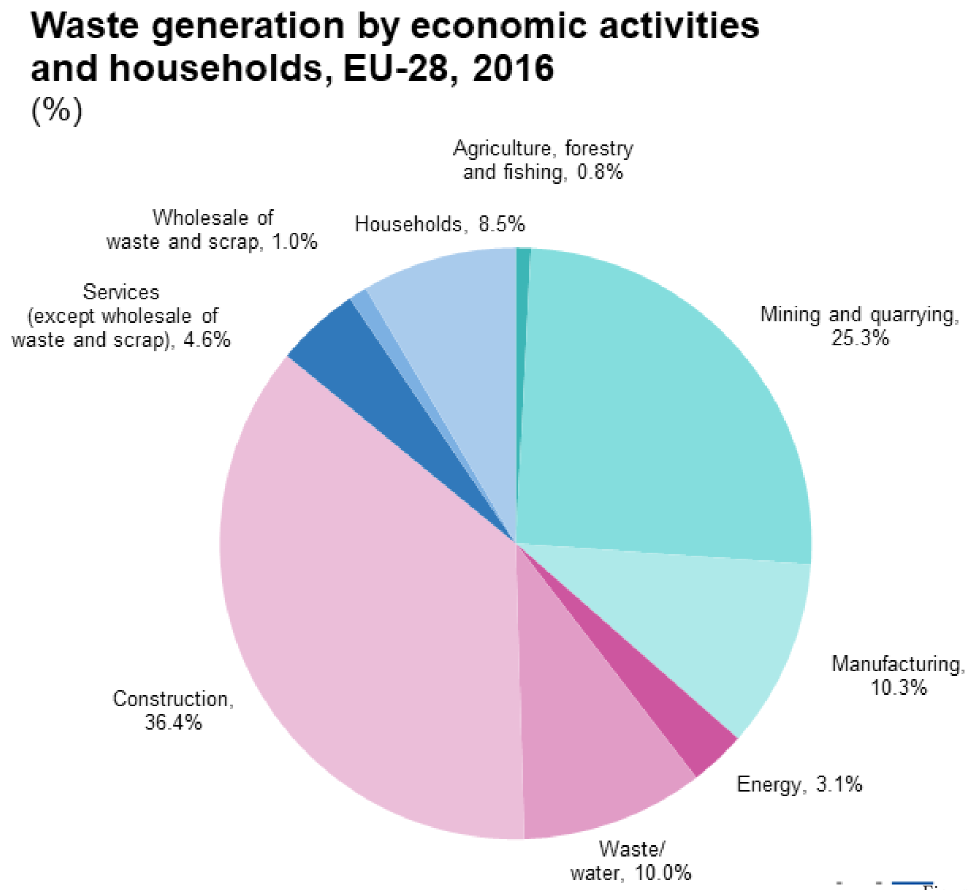


Figure 1.1

Political and industrial sectors on the other hand, have nowadays increased their involvement to change from linear (take, make, use and dispose) to circular (reduce, reuse and recycle) business models (Charlotte et al, 2019). That revision of the business models will help to minimize environmental impact as well as secure future needs and at the same time utilizes the most of the material value and establish the desired economic growth (Advisory Board for Cirkulær Økonomi, 2017; Ellen MacArthur Foundation, 2015b; European Commission, 2016, 2017a; United Nations, 2015). According to recent studies, the construction industry represents an environmental impact of 20-35% (European Commission, 2006), scoring a similar impact as categories like global warming and smog formation. In addition, the building industry represents an increment of 40% of the global production and consumption of materials (Becqué et al., 2016).

There is a number of studies dedicated to studying the environmental impacts of buildings and suggesting opportunities on how to decrease those impacts. Chau et al. (2015) present three types of life cycle studies, the Life Cycle Assessment, the Life Cycle Energy Assessment and the Life Cycle Carbon Emissions Assessment. They explain that all those three subdivisions provide the tools for evaluation and comparison of the environmental impacts of buildings, however, some limitations of them reveal their weak nature as decision-making support tools.

One could say that material sustainability refers to the ability to use only renewable natural resources not faster than they can be renewed. Designers and engineers could get closer to this ideal by applying Design for Adaptability and Deconstruction methods in the early design phases of a project since reclaimed and recycled materials are considered to be alternatives for renewable resources (Kestner et al., 2010). A frequent application of early demolition is due to the reason that buildings are designed to be static rather than to be readjustableing (Durmisevic, 2006). For building and construction projects, the application of adaptability means that it will be still promoting usability and longer life-spans because it is allows changes overduring the time, at a lower cost (Moffatt & Russell 2001; CE Guide n.d).

Circle House demonstrates a paradigm of circular construction. It is located in Lisbjerg, and it consists of 60 new dwellings by 2020. The uniqueness of this project is that 90% of its components can be separated and reused without downcycling while its price remains in the borders of social housing (https://www.lejerbo.dk/om-lejerbo/byggeri/circle-house). The design followed the principle of Design for Disassembly and it is a load bearing construction (Repolho, 2017). The key element of Circle House is that in its interior the assembly is visible and electrical cables and installations are placed in panels in the staircase. Therefore, it is easy to repair, maintain and disassemble the house. Moreover, according to the Product-Life Extension principles of design , the components that have longer life-span should compose the internal layers of the shell and vice versa (Repolho, 2017).

With the Design for Disassembly it is possible to increase the end of life of a product as the materials and components of can be deconstructed and reused in other settings. That can also give the flexibility to products to be repaired or upgraded and hence prologue its life. Moreover, due to the easy separation of the components, it enables the product to be recycled even with the reuse of the whole components.

Not only the occupants and users of the buildings concerned about the potential obsolescence of their homes but also owners of large corporations and government agencies are involved in this matter too (Slaughter and Slaughter, 2010). That is because facilities with short lifespan are cost and resource ineffective, since not only the time of which the building could return the costs of the initial investment is limited, but also because of the increment of demolition and waste disposal, that also affect the return on the initial investment (Slaughter and Slaughter, 2010).

Benefits of adaptive design in buildings include durability, due to easier repair and maintenance, reduction of replacement / upgrading costs, and the introduction of more cost-effective subsequent modifications to the building through the application of standard connections (Kestner et al., 2010) . All those advantages could be applied in projects that are produced based on mass customization in the construction industry. Social housing is a form of affordable housing that follows industrialized production. More specifically, the definition of affordable housing was created and refers to housing that their price should not constitute more than 30% of the median household's income (UNHabitat, 2016). It is hard to conceptualize and measure affordability as complicated as defining the aspects of housing affordability itself (Gabriel et al 2005).

In the Danish context, the group that affordable housing refers to is public sector workers and middle class families with children (Bech-Danielsen, 2011). Copenhagens' housing market differs considerably from the rest of Denmark. In Copenhagen 18% of the housing stock are owner- occupied, private rental is 19%, private cooperative housing (private co-ops, in Danish "andelsboliger") represents 33 % and social housing 20 % (kk.dk/boligbarometer 2014).

The way that low costs are sustained is due to the prefab production of housing modules. There are different design concepts where different social housing associations have ordered a number of housing units within the same design, all of them having the same producer of modules. The structural system of the social houses, that is based on prefabrication during the last ten years is the volumetric wooden modules with a load-bearing partition wall system. That means that each order comes in large volumes of 100-500 units which leads again to lower production prices (Ole and Gro, 2016).

However, the world we live in, constantly changes from social, economic and environmental aspects, architecture and building development are affected by those changes. The usual actions taken to respond to change, in the building sector, is demolishing and reconstruction even if those practices are highly not sustainable since there is a huge amount of waste in resources. One of the strategies for achieving sustainable architecture, an alternative to demolition, is prolonging buildings' life by making it adaptable to respond in future changes. A number of factors has to be taken into account when designing for adaptable buildings, but most important, from a technical point of view, the building has to allow for partial or complete disassembly of its elements and their components. With a purpose to ensure building adaptation to future user needs, Brand (1994) examines the application of design for disassembly in relation with the theory of building layers in order to enable flexibility of building parts. Adaptable buildings seem to be the solution in accomodate change and in that way extend the lifespan of the building, satisfy the purpose and needs and that has economical as well as ecological benefits (Kronenburg, 2007).

1.2 Problem formulation

The objective of this research is to examine the optimization of material resources in the construction sector by ensuring the longevity of building components. The approach in that problem is reflected in the two sub-questions emerging that are inherently connected to long-term sustainability.

What are the barriers in the current production technology, of prefab modular construction, which affect the response of the structures in demands of later adaptation?

How to promote sustainable transition in the building sector through the sociotechnical complex?

This thesis draws on analysis of the Danish construction industry, and it is based on qualitative studies on the production industries of prefabricated volumetric modules and on their work for circular construction. In addressing the research questions, the current thesis evolves through linking topics that together illustrate the sector of industrialized construction.

• It describes the development of the construction industry over the last 60 years, in order to understand what are the effects of the developments in the techno-institutional complex related to the construction industry.

• Through desk research, the advantages of Design for Adaptability as well as the requirements to facilitate disassembly, in order to ensure later building adaptation, are listed.

• Field research was carried out during this thesis concerning on how modular construction takes place and what is the production technology used.It took place in two facilities of production of prefabricated houses where the manufacturing process was observed and also the effects of the current methods at the end of the product's' lifetime. Design for adaptability requires a partial or complete disassembly of the house components, which implies reverse thinking of production and assembly.Therefore, focus of the visits was to examine if the current practices used in the production and off-site assembly phase, respond to the requirements of disassembly to assure adaptability of the structures.

• Lastly, the implications of the current production technology are discussed in relation to the adaptability and social alterations that potentially could occur on social housing.

1.3 Structure of the report

The report is structured as follows: The second chapter provides a brief description of the theoretical framework this project is based on, and discusses the methodological been approach used for the collection of data. Moving on, the third chapter illustrates the historical evolution of the Danish construction sector and analyses from a theoretical perspective the origin of the system's' stability.

Following in the fourth chapter, I examine the state of the art in regards to the building adaptability. I do that first through the definition of concepts and terms from the literature, second through the two past prize winning projects that Vandkunsten was part of, the Tinggåarden case which is about a historical paradigm and Lisberg Bakke case, the current one. These two cases are great examples of innovating social housing as they have been selected as winning competition projects and inspiring ideas of adaptable strategies. I use them in my research to examine the possibilities of their structures in response to potential cases of adaptation, in the third part of my analysis, in comparison with the structure of the prefab volumetric modules.

The next chapter aims to illustrate the full picture of the case companies as well as the current practices they use and in its sub-chapters, I present the analysis of this study. The structure of the analysis is divided into three stages. The manufacture stage, the assembly stage, and the 'unit'- adaptation stage. First, at the manufacture stage, I take a closer look into the materials and the process of production of the parts of the modules, later, at the assembly stage, I describe the practice of assembly of the building elements, the relations, and interconnections of the building layers to understand how the DfD can be applied. In the last stage, the adaptability stage, I draw the response of the current system to different scenarios of adaptability at the end of life in the current housing concept.

Chapter six is the discussion in which I give my proposals according to the results of my analysis as well as the reflections to the process of the project as well as proposals for further research. Lastly, chapter seven is the conclusion of the project in which the research question is answered.

2. RESEARCH DESIGN

In this chapter, I expand on the background theory of the project as well as on my approach in addressing the research question. I build on the theory of systems and related to the systems of production in the construction industry. Moreover, I describe the methodology I followed for the collection of data and the translation of them to valuable results.

2.1 Theory

The background theory of this study is based on the socio-economic understanding of how the construction industry has been developed. Several researchers have addressed the theory of lock-in. organizational and institutional research fields, they refer to it as the technological evolution and innovation in economics, aiming to draw the picture of different kinds of lock-in across the economic, institutional and organizational spectrum (Klitkou et al. 2015).

The meaning of the lock-in expresses the tendency of the systems to maintain specific technologies due to their positive feedback (increasing returns) of adoption (Arthur, 1994b; Unruh, 2000, 2002) despite the existence of new alternatives (Doganova and Karnøe, 2012). It has been broadly applied to describe the tendency in the use of fossil fuel-based technologies, regardless of their environmental impacts. In the current research, it is used as a fundamental description of the reasons, from technological, political and institutional perspectives, that keep the construction industry locked in unsustainable practices.The technological systems that fall in continuity, a path-dependence process, get fixed through transformations across technological infrastructures, organizations, society and governing institutions establishing what is called techno-institutional complex (TIC) (Unruh, 2002). A technological system is defined as a network that includes interconnected components with physical, social and informational elements (Foxton, 2002).

Adopting the work of Gottlieb and Frederiksen, (2019), firstly, I unfold the historical development of the construction industry in Denmark in order to map the influence on the industry, that comes with the techno institutional alterations. The main issue regarding the rational clarification of the construction sector was to overcome the traditional constructing practices, involving technologies, methods, regulations, so to meet the housing storage.The way to overcome the housing storage was through the repetition of the rationalization of the manufacturing industries. However, the production practices of the time were following a series of irrational collection of building material such as bricks, which were preserved according to traditional crafts. Such a system could never support social housing storage (Jensen et al, 2011).

Followed by the description of the current sector as it is, I target the causes that lead to the stability of the system and I explain in further detail the ingredients of the lock-in in the spectrum of the existing technological process of prefabricated modular production.

2.2 Methods

In the current chapter I discuss the method used in order to approach my research questions. To get a feel for the field, I contacted the architecture firm Vandkunsten, known for its work on social housing, implying circular economy etc. They provided me space to work on, time and contacts of the relevant actors to interview for my research, which brought me the opportunity to discuss in-depth different parameters of the project. The cooperation between me and the company was built upon the exploration of the research question with reference to the projects of Almenbolig+, Vandkunsten is part of, and also enriched my perception towards the adaptability concept, by analyzing the qualities of two exemplars projects introduced by the company.

Planning for longevity the prefabricated modules is a way of building in order to fulfill future social demands. Design for adaptability requires partial or complete disassembly of the house components, which implies reverse thinking of production and assembly. Therefore, part of this thesis focuses on two facilities of production of prefabricated houses in order to understand their manufacturing process as well as the impact of the different production and assembly methods, those factories use, at the end life of the product. Focus of the visits was if the current practices, used in the production and off-site assembly phase, respond to the requirements of disassembly to assure adaptability of the structures. .

After my observations in the field visits, I created an evaluation tool and used it as a method for analysing the response of the current production system in regards to the requirements for adaptability. In order to ensure the validity of the chosen approach method, relevant actors from the industry accessed the grading of the system as well as myself according to my observations on the field visits. In the last stage of my research, I conceptualize the problem of the industrial lock-in in the building sector and its implication on sustainable solutions.

2.2.1 Vandkunsten and social housing

As part of this project, I am collaborating with the architecture firm Vandkunsten, which are pioneers in social housing in Denmark. Vandkunsten is engaged with the circularity of building components and materials through research and practice. The cooperation between me and the company was built upon the exploration of the research question with reference to the projects of Almenbolig+, Vandkunsten is part of, and also enriched my perception towards the adaptability concept, by analyzing the qualities of two exemplars projects introduced by the company. In this section I am giving a brief description of Vandkunsten as an organisation.

Starting from the winning competition of Tinggården, Vandkunsten has a long story in the concept of social housing. The firm was founded in 1969 by a group of five architects preparing for the Competition Project 35 for low-rise, high-density, residential architecture. Their approach was involving the residents to the decision making processes such as programming, planning, daily operations, and renovations. Project 35 won the competition for architecture by conceptualizing a new housing form coupling building apartments and detached homes. After that success, the firm won all the housing competitions held in 1971-1978.

Moving further, another project the EcoHouse 99 won the competition for sustainably non-profit housing. The key of success of this project was the energy efficiency achieved and the well-regulated indoor climate using the existing technology of the time. Furthermore, the firm provoked the quality of adaptive reuse of buildings with the conversion of the Danish Navy concrete structure into a residential complex. With the project Læsø the firm won the competition to build a modern version of the traditional houses of the area. Combining innovating materials, the seaweed for insulation and cladding together with prefab wooden modules they demonstrate alternative methods with a capacity for industrialization.

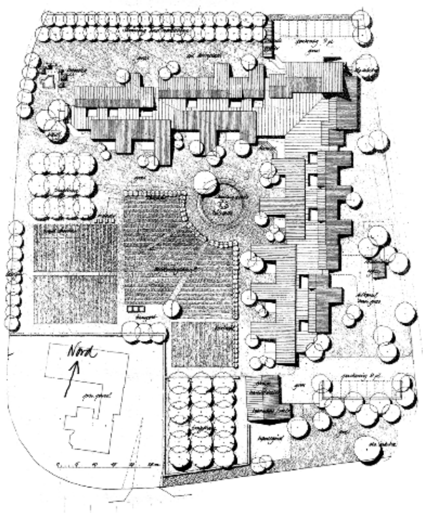


Figure 2.1: Tinggarden plan

With the social housing concept Almenbolig+3, Vandkunsten contributed in the social, economic and environmental sustainability of the concept and by being the winner of the competition of Almen+ generation 5 in 2016 is Vandkunsten and pushed the concept even further. In 2015, the architecture firm won Nykredit's Sustainability Award due to their work approach since for more than 40 years they manifest environmental awareness combined with high artistic architecture quality. Lastly, in 2018, the firm designed a wooden-based building concept, Lisbjerg Bakke, which allows flexibility in the design of the facade and freedom to adjust the plan of the layout according to the needs of the occupants.

Given my interest in improving the production of social housing by making the housing units adaptable and flexible, so as to extend building's' lifetime, I started with desk research and followed by field studies.

2.2.2 Case study of 2 companies

To get an understanding of the production processes, I visited and conducted interviews with managers in two danish companies of production of volumetric housing modules. There are two reasons for choosing those two companies. First, they are the only ones in producing buildings in 3D boxes which is the system used in the social housing project I research on. Second, they differ in practice since the one is a fully automated in production while the other relies more on experienced craftsmanship.

Vandkunsten collaborates with both and therefore, they provided me with contact persons who would let me interview them and also give me a tour of the facilities to gather material for my observations.

2.2.3 Desk research

To begin with, I read academic articles, reports, and books on the strategies of prolonging the lifetime of buildings as well as the principles and applications of flexibility and adaptation in the built environment.

This research was carried out to gasp the work previously done by Vandkunsten on social housing. As a result of the desk research I chose to narrow my focus on the type of prefabricated volumetric construction which is the same building method used for the construction of social housing projects Vandkunsten was part of.

2.2.4 Field study

In order to gather direct information about a project, I reached out to many actors related to prefabricated construction. During my stay in the architecture firm Vandkunsten, I gained knowledge regarding the field of study through semi-structured interviews with the architects and engineers of the projects related to my study, or non-structured as the openness in the conversations seemed necessary. The purpose of the questions addressed to the architecture firm intended to capture the idea, dilemmas, and requirements of the designs under research as well as to unfold the standpoint of the professionals regarding the construction system under this study. More specifically, I carried out multiple semi-structured interviews and informal conversations regarding the technical specifications of the prefabricated volumetric modules with the architect Kristian Martinsen and the architect and partner of the firm Soren Nielsen. Furthermore, I conducted two structured interviews with the architects Anne-Mette Manelius Gresien and Kim Dalgaard for Tinggården and Lisbjerg Bakke cases respectively. Those interviews supported the third part of my analysis regarding the identification of the possibilities of the exemplars' structural systems in response to potential cases of adaptation in comparison with the structure of the prefab volumetric modules.

On the other hand, the interviews with actors from the production facilities target the holistic representation of the practices and the sources of lock-in within the current industry. Those interviews included one sales-manager, Mogens Madsen, one project-manager, Dan Faber Madsen, and one HSE (health, safet, environmental) manager Joan Thiesen. The goal in these sessions was for me to gain a concrete understanding of the production process and the practices used as well as the flexibility, the structural system provides.

In general, the majority of the interviews took place during a tour on site were semi-structured interviews or informal conversations. A semi-structured interview allows for an open, uncontrolled dialogue with actors, allowing for it to elaborate in the path that sets the interviewee's answer. However, there is still a structure to navigate the dialogue into its purpose if and when needed. These were usually simple notes/questions inspiring from the literature and prepared previous to the meeting with the two authors. Many semi-structured interviews and related conversations took part in the office of Vandkunsten, since it was the place I was hosted in for my research, with professional architects and engineers.

2.2.4.1 Evaluation tool

One of the most vital things I had to do in order to understand the technicalities and challenges of the process of adaptation was to visit the two factories of modular construction. In that way, I would be able to experience the manufacturing and assembling of the modules while keeping notes for later questions as well as for my evaluation of the system regarding disassembly and further adaptation.

To follow up my conversations/visits to the companies, I created a table to evaluate the current system. The purpose of this evaluation tool was to display an overview of the strengths and weaknesses of the current production system of prefabricated modular houses in relation with the longevity of its products. The structure of the table was inspired by the book of Schmidt III et al. (2012), and 'grades' the extent to which the current industrial system can adapt to different types of social and physical change as well as the requirements for disassembly of the modules. The current industrial system is divided into four phases that are related to the topic of my research. The social and physical changes are related to the building layers. Schmidt III et al.'s table, (2012), shows how different causes and effects can influence the building layers s, (Brand, 1995).

The dimensions of the table listed vertically correspond to different phases in the production process. The elements of those phases were gathered from my observations and interviews with relevant people in the two factories. The dimensions, listed horizontally, are the ones which affect building adaptability.

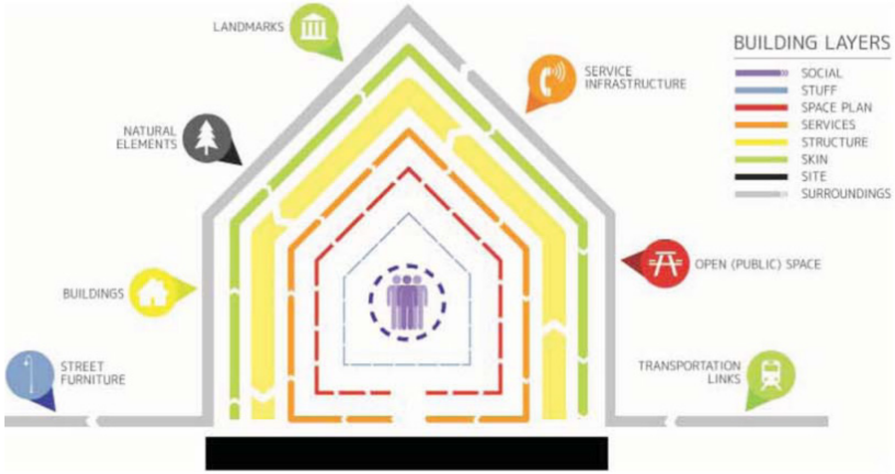


Figure 2.2: Building layers (Schmidt III et al.,2012)

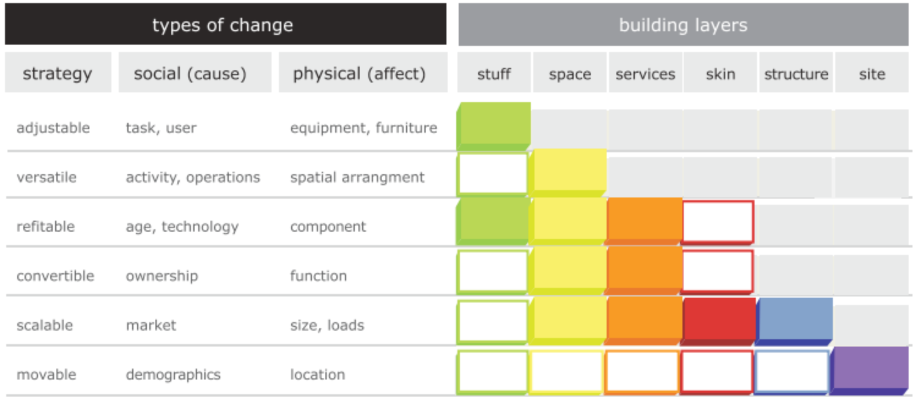


Figure 2.3: Relation between building layers and types of change(Schmidt III et al.,2012)

The cells of the table that are not directly associated with the question are left blank.

In order to succeed in the overall evaluation of the table, I had to ask from the specialists to fill it and also I filled it by myself according to my understanding from my observations and interviews. For the facilitation of the assessment of the table, I created a file with the description and instructions about how to assist the table and I sent it via email to the relevant people.

3. CHARACTERIZING THE CONSTRUCTION INDUSTRY

When a construction project uses a high degree of industrialisation and prefabrication it usually demands specificity (Beim et al., 2010). The use of new information technology brings the concept of mass customisation,industrially produced 'unique' or individually customised solutions, in which huge amounts of customised data can now be handled in a standardised way(Beim et al., 2010, p.29). However, the difference in architecture and construction systems, in contrast with other production industries (clothes, cars), is that their products (buildings) have to be designed to respond in a great number of different purposes and users throughout their long lifespan (Beim et al., 2010,p.30). Due to the challenges, in terms of money, time and complexity, of applying alterations in the building's structure, preplanning for complete or partial disassembly of its elements is required to enable a feasible solution that meets the changing social demands. Therefore, my approach to the research question calls for investigation in the production facilities of modular construction. The goal of the research is to understand if the requirements for adaptation, in terms of disassembly aspects, are fulfilled by the industrial developers, who produce dwellings for social housing.

Looking closer at the construction industry practices, the strategies that apply prefabrication can be divided in three categories:
A) Traditional product delivery:
supply of the materials and components on-site with craft-founded interfaces
B) Integrated product delivery in which the house is organised and developed in a complex of sub-assemblies with clear interfaces.
C) Turnkey delivery in which manufacturers have the authority of the entire supply chain, process and value chain through the creation of "all-inclusive" building systems.
This research project focus
es on the 'turnkey delivery' construction strategy. In that case,concepts are created with different brand name of the production company itself(Beim et al., 2010). In that way the social housing concepts Almenbolig+ use the product of the factory but named according to the client, the social housing company, and not from the producer.
The structural systems involved are volumetric systems/modules which have gained ground in the market in their light version (made of wood). Volumetric systems provide a huge reduction of the amount of interfaces connected on site as well as allow the use of pre-fitted equipment in the buildings and therefore maximizing prefabrication (Beim et al., 2010). The structural subsystem of the volumetric modules in this study is the load-bearing partition wall system and the description of it is presented more detailed in the chapter 5.

3.1 The birth of the sector

The following section gives a brief description of the historical development of the Danish construction industry from 1940s-now as it is presented in the article of Gottlieb and Frederiksen, 2019, page 7-15

"*Developments in the Danish construction industry are marked by two political milestones that occurred in the1940 and 1990 respectively. The first milestone is associated with the establishment of the Ministry of Internal Affairs' Construction Committee. This Committee, established by the government, to deal with the influences on the growth of the sector due to labor and housing shortage in the 1940ies. The next milestone came in 1990 with a document that revealed resource consumption and distribution in the construction sector. This expression sparked in a debate and actions within the construction sector with regard to improve productivity and efficiency. An example is the market ideal of the post-1990s which encompassed competing for discourses regarding economic development and social unrest provoked by the increased mobility of labor and capital (Gottlieb and Frederiksen, 2019).*

During the 1940s-1960s, the industrialization of the Danish society took place: .along with the need to ensure the quality of the working environment in the sector, arises the 'working class'. These were important matters of concern of a social-capitalist social order. The construction was also framed as a tool for societal modernization. The post-war efforts took place in the broader political and general economic sphere. The economic crisis of the post-war era and the lack of efficiency in production constituted the two major problems that 'Denmark for the Future' (a Social Democratic post-war program) emphasized. The lack of efficiency was the result not only of particular economic conditions during the war but also of a lack of planning and cooperation across business and industry. The construction industry was regulated and supported by research conducted by the national building research institute in 1947.

Following the changes in the field, the new practice arose in construction. The existing system was based on traditional construction activities, associations and tacit knowledge which were not harmonized across the sector. The practice of construction also changed and developed into separate functions that filter the temporal, spatial and managerial building properties, supported by technical, organizational and regulatory documents of that period. New building techniques and materials were introduced with timber and bricks being replaced by pre-manufactured reinforced concrete elements to facilitate the organization of construction site into more ordered factory-like settings. The national building institute provided instructions regarding the optimization of solutions and methods, as well as measurement tools to alleviate problems created by the use of new materials. Moreover, planning and calculation procedures became extremely important and as a result, a phase-model for coordinating legal relations to establish coherence between strategy and operation (Gottlieb and Jensen, 2012)

New regulatory regime ensures new operating methods and norms. This regime chided the law no.117 of April 26th, 1947 on prefab housing offering financial support to this specific construction method. That was the beginning of the establishment of principles for a national system of organization, logistics, and legislation in buildings and building elements. In 1958 the Danish Standard on 'Modular Agreement for the Building Industry' was released. Following in 1961 the first national building code was released which ensured that buildings were compatible with a series of norms, standards, industry codes and guidelines which all of them promote the political will to modernize the Danish society.

Other major changes included major organizational changes such as reconfigurations of roles and responsibilities of different actors and the introduction of new contracting forms. The new professions arose in the construction industry: such as the planning engineer. This way due to the increased complexity of the building process and affected the relationship between other actors such as clients and consultants. In 1968, engineers and architects' association was provoked to develop a set of general for consulting services. In this way, consultants for the client a legitimate party.

Other professions were also reshaped by the new form of the construction sector. The law of 1947, regarding prefabricated housing offered financial treatment to buildings erected with this specific building method, and the note in 1953, known as the 'mason-circular' on 'non-traditional building', created a sharp distinction between skilled and unskilled labor by requiring that 15% of the skilled labor could be used in non-traditional projects. This was followed by another department note in 1960 changing the money for subsidies non-traditional buildings, resulting in the replacement of the traditional skilled craftsman, knowledge artisans with an assemblage worker disciplines which did not leave space for the craftsmen to rely on their practical experience. Regulatory measures presented them from their traditional legitimate role.

3.2 1990-Present

The approval of the Maastrich Treaty (Gottlieb and Frederiksen, 2019) in combination with the opening of Eastern European markets in the early 1990s required adjustments within because of a strong discourse on market efficiency and values. Regulations were adjusted into an attempt to 1) improve the productivity of the sector and 2) to reorient and increase international competitiveness.
This discourse was shaped by the extensive discussion between the government and businesses regarding the lock-in situation of the construction sector. actors within construction could not address on their own. The policy was, therefore, based on the idea of promoting a new market scheme in which companies were equipped with the required competencies to compete on the open market and create new modes of collaboration.

In the early 1990s, industrial economics and productivity analyses were introduced as tools for producing knowledge on construction and to integrate the sector into the market, by considering it to be a 'resource area'. The 'resource area' notion was introduced by the Ministry of Business Affairs as the way to frame the industrial sector with the aim of creating a more efficient enterprise policy. In addition to this, another tool was introduced by this 'liberal solution', in the form of a shared development program, that would set priorities regarding innovation, capacity building and competences. The two most important actions of this development program were the 'Project Productivity' and the 'Project New Forms of Collaboration' which set the ground for the evolution of relational contracting in Denmark, through partnering and various types of partnerships.

Despite heavy public investments during the 1990s' in the construction industry, a new report in 2000 revealed a lack of development, prompting a debate for the re-orientation of the political efforts. That re-orientation came a year after with the change in the political scene which led to the annulment of the Ministry of Housing. Several councils, funds and support schemes regarding the construction and housing sector were repealed over the following years.

The task force report of the construction industry led to a much stronger emphasis on low voluntary exchanges between producers would be enough for ensuring development, i.e liberalization, and increased market-orientation.In a European context, the national standards were replaced by international ones. With Denmark's verification of the Maastricht Treaty came the ambition of being able to export in the internal market of the European Union. However, by 2000, it was impossible to integrate into the European market since Danish standards were putting limits on the use of the products in other countries. Therefore, the Danish government committed in the development of Europian standards for construction products which with the aim of increasing international competitions reducing costs and promoting innovation in the Danish industry

Parallel with these developments, regulation "changed from substantive or material regulation towards reflexive regulation" (Gottlieb and Frederiksen, 2019). Reflexive regulation is when the law instead of being an instrument that modifies patterns and behavioral structures, is performed as a system of coordination of action of semi-autonomous social subsystems. This legal transition to international standards established the legislative and regulatory complex of the construction industry.

With the rise of new contact forms such as partnerships, guidelines, and standards could not perform in the same way as in traditional institutionalized contact forms. Accordingly, adjustments and exemptions in the traditional system arose, in order to create space for innovation and value creation for the client and society (Gottlieb and Haugbølle, 2013). These new contact forms could not be applied in construction products because the building code was a barrier to the spread of new products and functions.

The political alterations in 1990s emphasizing nominal law industry prac-

tice. The performance-based regulatory regime called for accountability, i.e responsible companies that could be held accountable for their actions (Bertelli, 2006). Emphasis was given to monitoring that companies live up to performance goals.

In spite of these socio-technical changes, The Danish construction sector continues to be characterized by slow productivity growth than other dominant countries e.g. Belgium and Austria and by lack of unity (Ellen MacArthur Foundation, 2013). For that reason the Danish Productivity Commission underlined the need for improving productivity, mostly in the construction sector, so to establish the system competitiveness (Danish Productivity Commission, 2014). More specifically, the sector consists of many small and medium-sized firms employing craftsmen, contractors, consultants, architects, and engineers. These are material producers who are in charge of delivering the materials and components and lastly all the actors involved with the operational management and maintenance of the building (Smith Innovation 2016). According to Fernie et al. (2006), the aforementioned practitioners of the sector have launched a number of initiatives to address the fragmented client and contractor bodies. As a suggestion to this issue, the writers conclude that the further consolidation of the various bodies could provide high-level representation agencies. One of the trials to achieve unity in the sector is the CIB (International Council for Research and Innovation in Building and Construction) initiative 'Revaluing Construction' (Barrett and Lee, 2005). The purpose of this attempt is to construct a shared vision within the sector, that combines and coordinates the different notions between actors in order to establish a useful coherent development (Ang, 2004).

The environmental problem arises, due to multiple actors' varied motivations without common operational best practices having as result big amounts of material waste and minimum reuse of building components and materials (Josephson and Saukkoriip, 2007). Buildings are built to be static products with a long lifespan, more than 50 years usually; a fact that increases the complexity of the scenarios for the end-of-life of the product. Moreover, the purpose of a building can change during its lifetime changes in human needs with regard to humans' function and form. Therefore, there is a need for a performance-based regulatory to set the goals of the building's' purpose as well as a plan for its usable components at the end of life of its utility.

3.3 A Sector as it is

3.3.1 Sources of lock-in

As noted by (Gottlieb and Frederiksen, 2019) the construction industry has been characterized as "locked-in" into particular production patterns. However, on what follows, I expand on the notion of lock-in to further characterize the construction industry as locked-in to production patterns that are not favorable for Design for Disassembly.

The first source of technological lock-in is associated with the path-dependent nature and direction of technological progress. Researchers have used different terms to refer to those frames either as technological regimes by Nelson & Winter (1982) or as technological paradigms from Dosi (1982). Both terms describe the existence of specific ways of working within each technological community (engineers, firms, technology institutes, etc.) and therefore, specific engineering ideas and a set of possible alternatives are addressed to a technological problem. The second source of lock-in is related to the idea of increasing returns to adoption. According to David (1985) and Arthur (1989), in the case where there are multiple technologies competing for market share, the one with the increasing returns is more likely to be the adopted technology and dominate the market. Once a technology arrives in adoption, it has benefits in comparison with the rest of the options since it is inspiring for further acceptance, improvement and lastly leadership. The rest of the technologies which were not chosen for early adoption usually end up locked out of the market without the power to challenge the improved technology (Perkins, 2003).

Arthur (1994) identified four major categories of increasing returns: scale economies, learning effects, adaptive expectations, and network economies. First, scale-economies refer to the fact when technology has a large investment, production costs decrease asare they are spread over the increasing production volume. Therefore, it is very unlikely that a company will invest in a more sustainable technology after the high cost of the previous investment. Learning effects have to do with the improvements in practice over time, as a specific technology is used and its ‘qualities’ stabilized. The idea of ‘learning by doing’ was first introduced by Arrow, (1962), and accordingly technologies follow learning curves which show a unit costs decline with cumulative production (IEA, 2000). Adaptive expectations arise when both producers and users are satisfied with the quality, performance, and longevity of the chosen technology which leads to the lack of interest of the market to push for an alternative and more sustainable technology (Foxon, 2002). Lastly, network economies arise when actors adopt a specific technology in order to be compatible with other actors with the same technology (Foxon, 2002).

All the aforementioned categories of increasing returns for technologies are also relevant for the institutions (North, 1990). He argues, “the interdependent web of an institutional matrix produces massive increasing returns.” Special interest present political institutions are they are devoted to increasing returns for four reasons: the central role of collective action, the big quantity of institutions, the options for using political forces to complement asymmetries of power, and the complexity and opacity of politics (Pierson, 2000). In politics, the actions of an individual or of a community and the results of them are interconnected with the actions of others. That leads to high start-up costs and adaptive expectations. Moreover, since institutions model behavioral and legal rules, by including learning, coordination, and expectation effects once they are established, it is difficult to change (Foxon, 2002). Asymmetries of power arise when actors who have the authority to apply rules to others, they make use of that authority to eventually empower their own position (Foxon, 2002). Finally, the complexity and opacity of the actions of politics and the results of those actions, place politics in a questionable position and establishes it vulnerable to mistakes (Foxon, 2002).

Taken together, these developments lead to path dependency on technological change. Throughout history, events played a role in technological evolution because they open space for some technologies to evolve (Arthur, 1989) and then once technology starts evolving, it goes further due to the laws of increasing returns. That leads the industry to lock on a principle set up which gets the control of the marketplace (Utterback 1994: 24). Nevertheless, path dependence can also be created by negative external situations such as budget constraints, spatial constraints, or a time constraint (Page, 2006). Applications of constraints can be seen in competing technologies, legal doctrines and city locations (Page, 2006). Every time that there is a limitation of other alternatives path dependence has been created (Page, 2006).

3.3.2 What is a lock-in and why it is relevant

The industry of study in this project is the prefabricated construction industry which evolves manufacture, assembly off-site and in-site and transportation. Manufacturing and assembly off-site can be either following manual processes or automatized processes. Either of those processes of production does not address in their products to be part of the circular economy. The current technological process of producing volumetric modules goes through the following steps:

1) Concept – the purpose of the volumetric modules needs to be defined in relation to a particular market demand such as the market of social housing.

2) Design – the volumetric modules need to be engineered and detailed – this information is typically captured in engineering and architectural drawings.

3)Planning and control – the process of manufacture needs to be planned and then controlled against the plan. Planning differs slightly if the factory uses automation or craftsmanship.

4) Manufacture – the discrete components and sub-assemblies of the final vol-

umetric modules must be transformed from raw materials into their final form.

5) Assembly – the discrete components must be assembled to create the finished volumetric module.

6) On-site assembly – lifting, placing and connecting of the volumetric modules on-site.

The notion of lock-in refers to the tendency of the markets to not systematically switch to new solutions (Doganova and Karnøe, 2012). The sources of lock-in can be a collection of factors such as standardization, or management which are in favor of established actors and of social institutions related to a specific economic domain of activity (Doganova and Karnøe, 2012). Those factors are formed from heterogeneous elements. The following table from Unruh represents the different sources of lock-in. Examples from the case of the construction industry of prefab houses are visible in all the categories of sources.

Types of lock-in	
Lock-in type	*Examples*
Technological	*Load-bearing partition wall system, lifting equipment*
Organizational	*Craftsman work, automatization*
Industrial	*Height floor standards, interconnection of building layers, airtightness*
Societal	*Social housing companies, cheaper to build new than adapt the old*
Institutional	*Government policy goals and planning, legal frameworks*

Table 3.1.Types of lockin

Technological refers to dominant designs which in the case of prefab volumetric modules that can be found in the structural used system (load-bearing partition wall system) as well as to the lifting equipment connected to the inside of the structural system. Organizational refers to the routines of work and management that can be found in the craftsmanship and automatization used in the production facilities. Industrial involves industry standards, technological inter-relatedness and co-specialized assets such as height floor standards, type of joints connections or standards regarding airtightness. The type of societal lock-in is related to social norms, practices and future expectations. Prefabricated housing is being used broadly in social housing constructions due to the time and the low construction cost. The social housing companies, as well as the manufacturer, do not have a scenario for the end of life of the structure against obsolescence. Finally, regarding the institutional lock-in, Foxon, 2002, refers to institutions as 'any kind of form of constraint that human beings devise to shape human interaction'. These forms could be from legislation to informal constraints such as codes of behavior.

3.3.3 A sector that it is locked-in

These steps of production are subject to different forms of lock-in. With the chosen theoretical background it is possible to describe the industrialized construction system as well as to understand the dependencies of technologies and systems which, not only are very costly to change but also change does not necessarily promise economic profit for the companies. Moreover, following the learning effects of the established technologies, the manufacturers evolve their practices in order to minimize the time of production and which influences the organizational lock-in. There is no interest to shift the process of production to e.g to design for long life the 3D house modules, as such shifting would require reverse thinking of production and assembly, processes that are part of the industrial lock-in. One way to change the industrial type of lock-in would be the enforcement of regulations including the compatibility of building elements and components in order to make them useful after the end of life of the buildings. If this type of regulation were introduced in the Danish construction sector could become more competitive as a "first mover" in the global market industry since environmental problems are likely to continue to be a global concern.

From the side of the client, the main interest is the relationship between quality, cost and time for every project, elements that have satisfactory delivery in the current system and drive to the societal lock-in. Consequently, both producers and clients have fallen into adaptive expectations, another factor of increasing returns. The institutional lock-in of the industry much depends on political institutions. Those institutions affect the practices and requirements applied to the prefabricated construction as they decide for the building regulations, which are the boundaries that shape the concept of the projects. Regarding the creation of regulations for the circularity of the products, including buildings, political/governmental institutions would force the producers to makeshift to their practices even though those shifts call for high investments.

The approach towards adaptability has changed over the years, in the past, there was more the conception of functional aspects of buildings in contrast with the present where adaptability has been approached more as systems integration problem and architectural tectonics (Heidrich et al. 2017). Budget, time and regulatory constraints eliminate the building requirements while the increment of systems complexity and capability is another constraint that blocks structures from being adaptable (Heidrich et al. 2017). Therefore, it is challenging to alter buildings' spaces/functions if it is not planned, or systems due to the difficulty and expense of relevant adjustments.

One other challenge in the construction industry is the lack of financial incentives to use recovery materials as well as measurement tools to ensure that the reclaiming materials are appropriate in terms of quantity and quality for reuse. Client awareness and the issue of cohesion between the actors during the building's lifetime is another challenge that has been analyzed from Häkkinen and Belloni,(2011), in the sustainable buildings' framework. According to the survey of Adams et. al, 2017, not all the supply chains share the same benefits of adopting a circular economy model construction. Even if there has been a lot of exploration regarding resource efficiency of construction products and their life chain, still there is a lack of accuracy of the procedures that need to be undertaken from each discipline of the construction sector to enable their practices more circular (Adams et al.,2017). Some other limitations in the construction industry that are related to deconstruction practice are the amount of extra time required, the cost implications for deconstruction, the lack of building standards for reclaimed and recycled materials, and lastly the lack of designs that enable deconstruction (Kibert, 2000a).

4. CONSTRUCTING ADAPTABLE BUILDINGS

The challenging spaces within the building sector are listed in the paper of Manewa, 2016, and presented as "environment considerations", "innovations in technology", "planning and policy issues", "social requirements", "political forces" and "economic considerations". For buildings to meet the macro-level changes they have often to alter their 'function' the purpose they are made for, the 'capacity' to respond in the population they hold and the 'flow', the performance to internal and external forces (Slaughter, 2000). Buildings that fail to meet the changing needs of society become obsolete and thus require demolition. That is one of the critical concerns within the existing building stock as demolition is not recommended as an option for sustainable construction while the existing building stock constitutes important physical, economic, social and cultural capital to any nation (Kohler and Hassler, 2002).

In a sustainable built environment, adaptable buildings are broadly known as a basic ingredient that can provide tailored responses that are flexible according to stakeholder needs (Kendall and Ando, 2005). Social housing in Denmark is provided and managed by social housing companies. Therefore, those companies are the clients of the building industry and the created stock building belongs to them. The benefits of producing and owning a stock that can be easily adjusted to meet new market needs are seen in both the economic and environmental spectrum.

In this chapter, I explore the overall context of the study by introducing the type of construction under research and the notions of design strategies directly related to my research question. Furthermore, I present two exemplars of social housing cases that constitute my inspiration material due to their approach to adaptability and I conclude with the analysis of them after interviews with professional architects from Vandkunsten. Lastly, I present the adaptability strategies, as introduced by Neufville, (2009), that I based on for the creation of the evaluation tool. This literature perspective serves fundamental background knowledge of the field that I approach within this research.

4.1 Modular construction and advantages

There are many definitions of prefabricated construction. Gibb (1999), refers to prefabrication as off-site fabrication and includes the process of design, manufacture of units or modules, transport, and installation on-site. The construction method using prefabricated components can be seen in three types. First, is the semi-prefabricated construction where a part of the building has been built in situ, and complementary components are factory-built or modules. The second is the case of comprehensive prefabrication, where all parts of the building are prefabricated in the factory and assembled on-site. The last case of prefabrication is when the whole building is produced in the factory as one module and called volumetric modular building (Tam et al., 2007).

The main application of modular construction in the past was in portable or temporary buildings; however, today's' prefabricated construction technology using volumetric units can now be used in a wide range of building types such as schools, offices, hospitals, supermarkets and high-rise residential buildings (Lawson).

There are some key definitions regarding off-site construction that describe the components of prefabrication presented by Buildoffsite (Gibb and Pendlebury, 2006b), which are related to this study and are the following:

"• Modular construction—Three- dimensional or volumetric units that are generally fitted out in a factory and are delivered to the site as the main structural elements of the building.
• Planar construction—Two- dimensional panels, used mainly for walls, that can be prefinished with their insulation and boarding attached before delivery to the site.
• Hybrid construction—Mixed-use of linear elements, panels, and modules to create a mixed- construction system.
• Cladding panels—Prefabricated façade elements that are attached to the building to form the completed building envelope.
• Pods—Nonstructural modular units, such as toilets and bathrooms, that are supported directly on the floors of the building."

The approach of modular design is described by Gosling et al, 2016 in three parts. First, as a grid layout with repeatable spaces, second, thinking of buildings as systems rather than an assembly of parts and third, underlines the importance of repetition, standardization and interfaces to simplify buildings construction (Gosling et al., 2016)

There are several advantages of the application of modular construction presented by Lawrson as following:

1)Shorter duration of construction, resulting in shorter site management costs as well as early return on the investment.

2) Higher quality of modules due to the factory- based construction process and pre delivery checks.

3) Economy correlated with production. Larger projects or in repeated projects using the same modular specification.

4) Excellent insulation from acoustic and thermal perspective because of the double-skin nature of the construction, which means that each module is effectively isolated from its neighbours.

5) Reduced design cost to the client

6) Use of lightweight, less material and less waste produced in comparison with the on-site construction as well as providing greater opportunities for recycling in factory production.

7) Reduced requirement for on- site labour which leads to safer construction in terms of the factory and site activities

8) Less noise pollution to the neighbourhood during construction

9) Ability to disassemble the building and reuse the modules elsewhere.

Moreover, according to the environmental evaluation by the European Program Eurohouse (Long,1999), modular construction has some positive impacts on sustainability. Those are the following:

"- from 30 to 60% in the reduction of times on site through a more efficient coordination of the different construction packages;

- the reduction of 50% of water quantity in comparison to a traditional construction;

- 50 reduction% of the quantity of material utilized and produced by excavations;

- wider use of recycled materials (like timber, steel, aluminum, etc.);

- up to 80% in the reduction of waste materials during on site works;

- up to 60% in the reduction of CO_2 emissions and of annual energy consumes during building life cycle;

- possible reutilization and reuse of prefabricated elements."

Full modular systems are widely used for those buildings that their units' layout has been characterized by repetition such as multistorey apartments, student dorms, hotels, hospitals, and prisons or security buildings while in houses, office buildings or sports buildings are not that popular(table 1,3, Lawrson).

4.2 Design for Disassembly and Deconstruction

The goal of Design for disassembly approach is to facilitate the process and procedure of deconstruction through planning and design (Ellen MacArthur Foundation, 2013). The DfD process is essential to maintain raw materials (Webster, 2007). Deconstruction, on the other hand, is referred to as the process where during the demolition of a building, the demolished materials are kept for future purposes (Ellen MacArthur Foundation, 2013).

According to the study of Nelson in 2004, during the 30 years period between 2000 and 2030, it is estimated that 27% of today's' building stock in the US will be replaced and also that the rise of new buildings until the year 2030 will be more than 50% of the existing buildings since 2000. There are two options here. Either all that mass building replacement and construction can be a huge waste of resources for the generation after 2030, or Dfd building methods and strategies can be integrated in order not only to increase building life through repair and renovation but also to design buildings that compose the building stock for future building materials. The concept of Design for Disassembly (DfD) in the built environment scopes to the closing of material loops, which is one of the most demanding goals for sustainable buildings (Kibert, 2013). Further researchers have elaborate the concept of DfD such as Durmisevic (2006) who produced a tool based on the disassembly potential of a building in order to estimate it's transformable space and Davico (2013) who introduced an approach for the evaluation of the project's' capacity to be flexible and adaptable. Furthermore, the DfD approach emerges a new concept for buildings' material and components to be reused in future concepts, a thing that would be beneficial from an economical and environmental perspective for the stakeholders of the building industry.

The economic benefits include expect of the potential savings in resources, the creation of a new market for the reclaimed materials and also of a service for the ease of DfD, deconstruction, reuse and recycling of building elements (Chini, 2005; Kibert and Chini, 2000). According to Webster's argument (2007), building with DfD features will have potential greater economical value.

Regarding the environmental benefits of DfD and deconstruction is the notion of closing material loops. In relation to the cradle to cradle model, closed-loop, is the case of 'waste' turns into 'feed', a metaphor to the biological metabolism presented in Nature (McDonough and Braungart, 2002). The advantages of closing a loop include 1) prolonging the life of raw materials, 2) decrease of the cost of materials and lastly reduction of the embodied energy and C02 emissions of the building sector (U.S. Environmental Protection Agency (EPA), 2008; Chong and Hermreck, 2009) .

One of the challenges for the reuse of building materials and elements is the damage of materials in-site during the deconstruction process that makes the components lose their value (Nakajima and Russel, 2014). This is caused by false building methods or because of the way that structural elements are used, without considering the potential deconstruction process. It is very crucial for DfD the joining methods of the structural elements to be in such a way that facilitates the process of demolition (Webster and Costello, 2005). Another factor that affects the ease of the process of deconstruction is the quantity and the size of building materials as well as the joining methods that are not easy to disassemble (Srour et al, 2010). Moreover, EPA (2008) find that construction materials and their joints between the components have become extremely complex having as result to weaken the recyclability and reusability of reclaimed materials. DfD involves standardization of size of components, mechanical joint methods instead of chemical products and materials that are simply composed in order to simplify the recycling and reuse processes.

The time of deconstruction is also a constraint for DfD. In general, the time required for disassembly is from three to eight times more than the time for demolishing (Rios et al, 2015). That means that since time is a critical factor, demolition practices will be preferred rather than deconstruction. However, with DfD techniques we can reduce the time of deconstruction. According to Rios et al., 2015, those techniques include first to settle a pre-planning phase before the beginning of construction, second to create documentation in order to facilitate the deconstruction and the materials recovery processes, third to provide training in human resources and last to label all the construction materials while at the same time avoid materials that could be hazardous and require even more time in the deconstruction process than the rest.

4.3 Adaptability/ Flexibility

The potential obsolescence of the building is a matter of concern from building owners and government building owners to house owners. That obsolescence is the result of the building's inability to adapt to the future needs over time. At the same time, it is not economically as well as resource beneficial to create structures with a short life span due to the costs of demolition and waste disposal that do not return to the investment.

Flexible designs have a variety of forms that produce several types of responses according to different needs. In the building sector, the most common appliances of flexible design are in regards to the use of underused space, expansion capacity, demountable partitions, and mobile or modular furnishings (Bischof and Blessing, 2008). According to Edwards, 2005, and Shuchi et al. 2012, flexibility is the ability to welcome change without affecting the environment.

According to Schmidt III et al.,2010, adaptability is the capacity of a building to transform either its functions, occupants or systems without impact on the environment. In other words, it is the ability of a building to evolve through its life span according to the changing needs (Schmidt et al, 2010). The purpose of adaptable design, AD, is to expand the utility of the product in changing circumstances. AD is superior to the design with reusable or recyclable components since it does not require a new production process but reuses the same product in its present state by expanding some of its functions for new operational modes (Gu et al., 2004).

At this point, it would be meaningful to differentiate the terms, flexibility and adaptability, as their definition is varied according to the researchers' discipline every time is being used. Flexibility is about the multifunctional use of the building design, while adaptability defines the way that flexible use can be technologically implemented (Gijsbers & Lichtenberg, 2012). A flexible building has been designed in order to provide easy rearrangement of its internal equipment in order to complete specific needs at a specific time (Addis & Schouten, 2004). On the other hand, an adaptable house has a structure that is able to change or extend in order to fit in the changing requirements of the occupants. The purpose of the design of the adaptable building is to prolong its life by accommodating new uses or patterns of use (Addis & Schouten, 2004). It refers to the design of a structure which empowers future additions and functions inside and around the house. Moreover, it is very important to note that adaptable design housing etiquette demands simple and cost-effective adjustments to be implemented when they are planned into the fundamental design of the house (Gu et al., 2004).

Schmidt III and Austin, (2016), identified six adaptability types related to the type of change. Those types are depending on the building layer which technical and social changes will affect. The strategies referring to spatial change such as versatile and convertible seem to be more frequent than the physical changes. Moreover, it appears that spatial types of change influence all over the building layers while physical types are applied in one or two building layers (Schmidt III and Austin, 2016). The main goal for identifying the types is in order to translate the needs of change to practical appliances on the building layers. Providing to the stakeholders a common framework facilitates to clarify their goals during the design process (Schmidt III and Austin, 2016).

The six types of adaptability can be spread along a spatial–physical spectrum that corresponds with the 3Rs of sustainability.

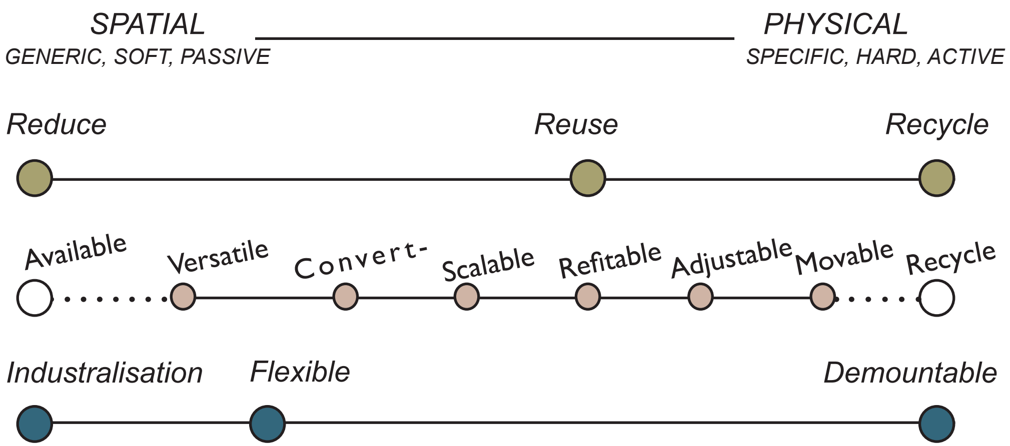


Figure 4.1 (Schmidt III et al.,2012)

Versatile

Versatility is the competence of the building to change the spatial layout of the rooms. The versatile strategy enables the easy and cheap modification of space to address different user activities, new work patterns or the numeric capacity of the occupants. This strategy influences the the 'stuff ', 'space plan' and 'service' layers of the building as it alters its physical parameters such as the number and location of columns, the plan shape and depth, the overall area, the location of services and lighting, and the portability of walls, furniture, and fixtures.

Convertible

Convertible strategies involve changing the function of the building due to social conversions regarding the market, social demands, ownership or occupancy for instance. Convertible design is easier applied in akin structural typologies otherwise, it demands proper planning. Strategies to access the convertibility revolve around the capacity and location of various physical elements such as services, circulation, floor loadings, and fire design. One of the common tactics to allow fluctuations of the load is the increased over-floor capacity from the first place. Storey height, structural grid, plan depth and total usable area are some of the other criteria related to that type of change.

Scalable

Scalable buildings are the ones that can alter their size either vertically or horizontally. Depending on whether vertical or horizontal additions, different building parts are addressed, for instance, the additional load capacity for the slabs and foundation or the type of roof structure for vertical alterations. Building's' scalability can emerge through transitions in the market and demographic conditions.

Refitable

Refitable buildings convert their performance by transforming their space, skin or services. Often social demands occur in this type of change. Those include modifications in the law, regulations, environmental conditions, technologies or materials. The response of the building in these social demands requires accessibility in the above-mentioned layers with the service system layer being the most challenging layer when is associated with other layers.

Adjustable

The design of an adjustable building ensures that the 'stuff' inside the buildings' space, such as furniture, can be rearranged easily according to the changing needs of eighter occupants, environment or technology. Adjustable designs increase the indoor environment and users' comfort and control within it as well as reducing necessities for new equipment and furniture.

Movable

This strategy is the least to occur compared with all the other types, however, it is quite essential under specific conditions for specific building structural typologies. The climate conditions and the movement of population

4.4 Exemplars

In this section I am doing an analysis of the state of the art in adaptable social housing based on two success stories Vandkunsten was part of. The criteria for choosing the specific projects were based on the adaptability strategies applied which differ in concept due to the changing social demands, technological development, and environmental pressure. By analyzing the responses of the different construction systems that have been applied, their advantages and drawbacks, I can have a complete evaluation of the construction system related to the research question. In order to do so, I use those exemplars in the third stage of my analysis, the adaptation stage, where three scenarios of building transformation are presented.

The information gathered for the analysis of the two exemplars comes from websites, interviews with professional staff in Vandkunsten as well as drawings offered by them.

4.4.1Tinggården

History

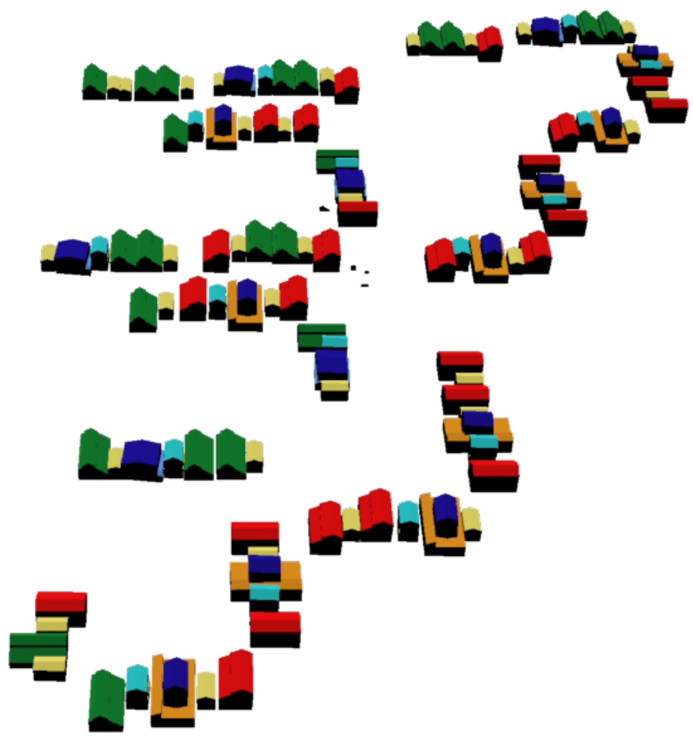
Tinggården is a non-profit housing company and was built in two stages first in 1978 and the second part in 1983. Tinggårdens' world reputation is due to its position as a paradigm in the country's' building sector. It is established as one of the first world's first low-rise buildings and nowadays among other things it hosts thousands of visitors related to the industry.

Typology

The houses of Tinggården were built with the traditional building method, cast and concrete with wood and brick facades (Manelius Greisen, interview). The housing complex is about 200 units divided into 12 family groups. Each of those groups consists of 12 to 18 family apartments sharing a communal house, with a kitchen and living room, and some common areas. The size of the apartments ranges from one-bedroom apartment to 6-room apartment while in the first stage of Tinggården there was the possibility of choosing the size of the apartment by new arrangements in agreement with the neighbor and the housing company. The rearrangements of the interior on an ongoing basis are the product of the simple housing type in combination with the flexible walls.
The design seeks to combine and form individually critically design parts, residence units, and elevation elements. Considering the tense economy the chosen construction strategy proposes the use of simple materials, the least possible residential spaces, the coupling of compact spaces with continuous heating and lightly constructed bedroom levels (Schäfer,1979). As we can see there are 5 different basic housing types and on the top of it, multiple combinations of housing forms due to the freedom of arrangement of the s room and the t1,t2 rooms, the light bedroom levels. That means that space is divided according to the needs of changing families during the time. Regarding the energy crisis, the energy equipment was designed with the idea to implement central heating plants under inclined ceilings, which can integrate solar collectors (Schäfer,1979). Moreover, Tinggården has its own heating plant which enables it self supplying with heating (Manelius Greisen, interview).

Strategy for adaptability

The reason for referring toTinggåarden as a case study of this project is because of the spatial flexibility that is applied in this case. The adjustment of



4.2 Tinggardern 3D Typology

space in size by the middle light bedroom is a smart strategy that provides flexibility with the minimum technical requirements. Since the extra room exists between two dwellings by the default construction, the only extra intervention will be the door opening which has already been pre designed on both sides of the room to be applicable in both the attached dwellings (Manelius Greisen, interview). That means that construction costs for adaptation as well as environmental costs are staying at the minimum. Facade renovation is an easy task since it is made of wood and every now and then it is painted since the community is very efficient in the maintenance of the facility (Manelius Greisen, interview). Therefore, the building's lifespan corresponds to the functionality of the building (Manelius Greisen, interview). As it provides spatial variations, strong and empowered community the only reason for demolition in a few decades could be if it was too expensive to update the essential building parts such as thermal installations (Manelius Greisen, interview).

4.4.2 Lisbjerg Bakke

History

Lisberg Bakke is a newly built public housing with an experimental way of thinking (Dalgaard,interview), which means that the building system is very new without the existence of a corresponding building construction industry (Dalgaard,interview). The multi-story residential building is consisting by 3-4 floors and is located in the hills 10km from Aarhus. The first families moved into Easter 2018. The homes are DGNB certified and in 2014, the building was named the Sustainable Public Housing of the Future by the Ministry of City, Housing and Rural Affairs (https://www.al2bolig.dk/selskaber/al2bolig/afdelinger/128-lisbjerg-bakke/). The construction was awarded for the innovative facades of the apartments that have been made by wood and also for the good of daylight that the large windows provide.

Typology

The complex consists of 40 dwellings of 50-115 m2 and a common room. The houses are organized in two large groups of three building typologies and are sorted around small squares along a continuous city street. The project is using hybrid building technology and in combination with its pillar beam system, it provides great flexibility as well as promotes actions of future recycling of the materials. For instance, the facade provides full freedom of the replacement of the facade cassettes and the making of window holes as it is consisting of a non-loading-bearing system. Facades and windows are prepared for balcony installation. Moreover, the interior layout, it provides spatial flexibility and it is possible for the residents to apply the changes by themselves (Dalgaard,interview). Since the whole structure is connected with mechanical joints it facilitates the renovation of the house, but without applying changes in the structure of it (Dalgaard,interview).

Materials

All the components used are standardized with additional information for the roof installation since it is important to set up the roof first on the structure before the facade in order for the second to be protected from the humidity of the weather (Dalgaard,interview). The main structure is connected with steel assembly units (steel brackets)(Dalgaard,interview). The result of the smart use of the materials is a strong combination that establishes the hybrid structure. For example, the exterior of the dwellings is made of untreated unprofiled red spruce, that is preferred to being replaced regularly rather than being painted. On the other hand, windows are made of untreated aluminum from outside and of lacquered wood from inside while the staircase is made by untreated concrete interior. Floors and staircases are made of concrete while the interior layout uses gypsum walls.

The foundation of the structure uses the traditional danish system, concrete with posts connected to the inside envelope of the building (Dalgaard,interview). It is easy to disassemble the wooden parts, but the concrete parts are difficult since they are cast on site. However, the next series of the building might use prefab concrete elements which could facilitate the deconstruction of those parts.

https://www.licitationen.dk/article/view/586708/toptjekkede_traehuse_pa_

Even if the wood as a material has good thermal characteristics, however, its use should not be considered sustainable unless there is replanting the forest. Nevertheless, one strong advantage of wood in comparison with the concrete is that wood can be easily assembled and disassembled with mechanical joints. That makes it reusable and recyclable.

Figure 4.3 Lisbjerg Bakke: The wooden houses at Lisbjerg Bakke north of Aarhus are mainly built of wood. The building was named "Construction of the Year 2018"

Lastly, wood is considered to be a repository of CO2 as long as it is not burnt or composed and it is not so disturbing for the environment as the concrete production (Dalgaard,interview).

Strategy for adaptability

The case of Lisberg Bakke housing complex is worth mentioning because of the flexibility of its structure and because of the use of environmentally friendly materials. The non-load-bearing system opens the opportunity for easy renovation and reuse of its components again and again. The capability of the building to have easy dismantling of its elements is a matter not only of prolonging its life, through the renovation of its materials, but also of easily recycling each of its components or downcycle them.

The following Table 4.1 summarises information from my interviews with the professionals in Vandkunsten.

	Tinggarden	Lisberg Bakke
Year	First in 1978 and the second part in 1983.	2018
Building structure	Load-bearing walls	Non-loading bearing structure. post and beam. Infill system. Complete separation from the structure and the skin.
Building method	On-site, Cast and concrete, with brick walls, traditional structure	Concrete cast on-site with prefab wooden facades
Adaptation strategy	Versatile	Versatile, refitable, scalable (horizontal)
Process of spatial adaptation	It has been designed to measure the rent and you pay by modules and also negotiation between the neighbors. The technical aspect is easy because even if it is concrete the doors opening are planned. Nothing is changing with the installations by taking the room. The housing organization is the complicated part because their system is not ready for that flexibility.	Flexibility of layout because you can adapt the interior to different circumstances in the lifetime. Services are not changeable the system allows to put services where to facilitate flexibility. "Installations are fixed in the plan because it is very difficult to relocate them as it has an effect at all the building. Where to place the installations is a critical thing. You could expand the structure in technical terms." (Dalgaard,interview)

Table 4.1. Summary table

	Tinggarden	Lisberg Bakke
Year	First in 1978 and the second part in 1983.	2018
Process of renovation	The building parts are not designed for renovation. The concrete is not exposed, the roofs and they have new windows which are extra elements. The first generation has a better roof than the second. It's very traditional everything you install. Walls are load-bearing	Only the things from inside can be changed from the occupants. The rest need experts. Everything is connected with screws. The non-load bearing Big flexibility if you want to renovate the house but the main structure is difficult. The exterior is very easy to change, the interior requires more work due to the finishes.
Maintenance+repair costs	The concrete is part of the load-bearing structure and is not exposed. They can renovate the extra elements such as roof and windows. The first version of Tinggarden has a better roof. The roof is on timber construction. Easy renovation the wood facades get painted, they are very good at the maintenance of the facility. The walls are load-bearing the decks we don't know	
Building Life-span	The lifespan is regarding the functional part. It has nothing to do with the life span, but is a political matter. The reason for demolition could be in a few decades if it was too expensive to update anything. Since the project is so iconic maybe in some years it may be listed. Maybe there will come some regulations about demolishing. Robust system and easy to renovate.	A lot for the wooden ones due to the fact that they are not that static as the concrete ones. Inside wood is protected with fire gypsum plates. The only threat for the wooden buildings is the fire. Wood lasts long because of the flexibility that provides robustness.

	Tinggarden	Lisberg Bakke
Year	First in 1978 and the second part in 1983.	2018
Foundation	Traditional foundation	The basic structure is not movable. All the wooden parts can be deconstructed but the concrete is difficult. The next series of the building may have prefab concrete but this is cast on site. On top of the inside walls, there is insulation,gypsum boards which is hard to deconstruct. Is easier to deconstruction partially that the whole.

Table 4.1

In sum, Tinggarden is an example of a traditional concrete structure cast-on site with brick walls and wooden facades. The adaptation strategy used is versatility, in which interior spaces have been designed in order to ensure easy rearrangement. Concrete structures are very stable, however, Tingareden is characterized as a high density-low rise project and won a competition for its design by empowering the community. From a technical point of view, the process of adaptation is easily facilitated due to the diversity of the dwellings and the pre-designed plan for it. Regarding maintenance, renovation and repair costs, the system appears to be durable since the concrete is protected by the wooden facade which is easily maintained (e.g painted) by those responsible for the building maintenance.

Due to the flexibility of the complex and the strong community that has been created, the building is considered to have a long life span since it is possible to re-purpose the buildings according to the different families' needs. The reason for demolition would be in a few decades when it becomes too expensive to update all the installations. Also, potential new regulations about building demolishing will make it expensive.

The project of Lisbjerg Bakke constitutes an experiment of hybrid structure with prefabricated wooden elements. The non-load bearing structural system facilitates the change of space, performance, and size along the horizontal direction. The prefabricated wooden elements can be disassembled and reused. The structure is, however, is not movable due to the number of adaptable strategies it offers, Lisbjerg Bakke has the potential to accommodate changing needs. Moreover, the next version of it will include prefabricated concrete elements and that will ensure full flexibility and reuse of its elements.

Lisberg bakke also offers the possibility of partial disassembly which helps the longevity of the structure since the components can be upgraded and never end up obsolete. Moreover, the mechanical joints and screwed connections prevent the materials from hazards so to promote them for reuse and not down-cycling. Lastly documentation for how to assemble the building is provided to the contacts and also instructions for how to cover the building site during the wet periods due to the high risk of some building elements.

5. MODULAR CONSTRUCTION IN DENMARK

Description

The object of this study is the off-site construction type using prefabricated volumetric modular construction with wooden based modules. A volumetric system consists of three-dimensional modules of enclosed space are combined and connected on-site to create one single building. Each volume has its own structural sub-system, which in the case of this study it is a load-bearing partition walls system. It is about intersecting stabilized longitudinal walls that constitute the structure of the dwelling. The interior walls are non-load-bearing and it can come up to 4 stories.

Due to logistics, the boxes present some limitations to their size. The maximum width of 4,6 meters and length 14 meters, but most commonly used is 12 meters. The height is a maximum of 4,6 meters. The dimensions can vary from project to project and the combination of the boxes gives a bigger floor plan. The cabin of the bathroom is a separate concrete module, and all the technical equipment is installed on the floors while the roof is placed on-site. Also, the facade is put on site with hooks.

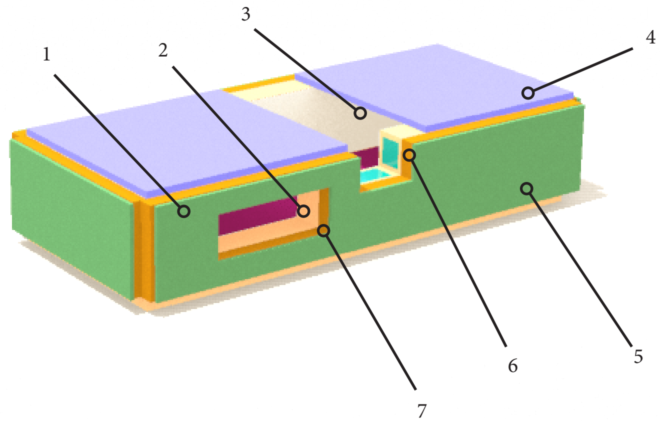
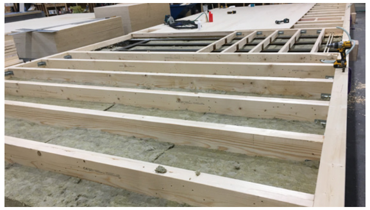


Figure 5.1

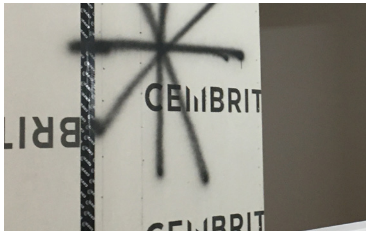
1 Figure 5.2:



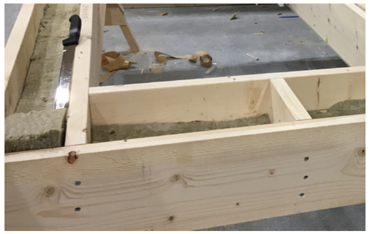
2 Figure 5.3:

3 Figure 5.4: Interior gypsum plates and paint

4 Figure 5.5: First layer of roof



5 Figure 5.6: Windbreakers



6 Figure 5.7: Insulation on the wall

7 Figure 5.8: Second layer of exterior wall

5.1 The case companies

There are two companies in Denmark producing volumetric housing modules. These companies are BM Byggeindustri A / S and Scandiby, both of which will be briefly described in the following.

BM Byggeindustri A / S

The first visited facility is the production line of BM Byggeindustri A / S located in Hobro. BM Byggeindustri A / S was among the first construction companies to work with modular volumetric construction and carpentry (https://bmbyggeindustri.dk/). Over the years the company has grown in a medium-sized company and after the development of core competencies the BM Tagkassetter ApS was founded in 1987 (https://bmbyggeindustri.dk/). The two parts BM Byggeindustri A / S and BM Tagkassetter ApS merged in October 2011, and continued operating under the umbrella of Byggeindustri A / S.

The factory is divided in different facilities each of them addresses a different stage of the manufacturing of the modules. There is one which is the storage of the materials along with the production of floors and walls, one other for the production of bathrooms as a separate module, and one for the assembly of the building parts into one volumetric module. From the production of building parts until the off-site assembly and placement of the volumetric modules, experienced staff undertakes manual processes. In general, hand tools are used as opposed to robotics and automated machinery. BM Byggeindustri A / S is the main construction partner of Vandkunsten for the projects of social housing KAB.

The staff team of the company consists of production managers, engineering managers, project managers, sellers as well as experienced craftsmen who construct the building parts and assembly them off-site.

Scandibyg

The company Scandibyg is considered to be a pioneer within the Danish market for industrialized construction, with specialization in the development, production and construction of modular prefabrication. Scandibyg produces space-sized building modules containing turnkey living rooms, rooms, kitchen and bathroom. The building modules can be used for housing construction, offices, institutions and research/ health facilities either for private or public clients. The production area is 18,000 m2 and it is all under roof in dry heated walls in order to avoid moisture in the structure of the modules. Their production is highly automated and it is organized in four production lines to assure flexibility. The production capacity is 100,000 m2 annually.

The staff consists of building designers, engineers, production managers, sellers, tender calculators as well as plumbing and electrical installers. At the construction sites they work with their own construction management and assembly teams.

5.2 Analysis of the production processes

This chapter provides a detailed description of the construction processes taking place in each stage of the modular construction. According to the talks with employees in the prefab construction industry, the current technical limitations of adaptability (and therefore, the limited chances to prolong buildings' lifespan), could potentially be overcome, depending on the requirements /concept that the clients set. However, this thesis argues that all these stakeholders need to find a way to cooperate in order to effectively deliver adaptable buildings. Since the construction of adaptable buildings expected to increase the construction costs, the only way to promote that strategy of construction will be by altering the perception of stakeholders (Pinder et al., 2013).

The focus point of my analysis is what it takes to disassemble the structure and the implications this can have for later adaption. The production process is divided into two stages: manufacturing and assembly, assembly and adaption. More specifically, the analysis in the manufacturing stage refers to the process of creation of the elements like walls and floors. Understanding the structure and creation of the building elements is significant for the later disassembly of them in order to better be able to use the materials with the minimum or no hazards. The second stage is the assembly of the building elements. During this stage, emphasis is given to the assembly tools being used in the connections of the building layers as well as in the interconnection between them. Moreover, I look at the on-site process of assembly, how the volumetric modules are connected with each other as well as how they are connected with the foundation.

The two facilities I visited differ in many ways, i.e in terms of construction practices and technologies since one of the companies is using automatization and keeps all the construction departments, from the storage to the assembly, under the same roof while the other is 'ess automated nad is based on more conventional production processes. Some of the advantages of automatization are related to the time savings, the high-quality achieved and the better working environment for the staff. Moreover, a fully automated production line is more likely to create products that can be easily disassembled with the same machinery that used to assemble them e.g. the use of screws instead of nails for the connection of the elements.

5.2.1 Manufacture stage

Both companies use the same structural system consisting of a wooden load-bearing partition wall system. In general, this type of structure consists of many discrete floor elements (unit diaphragms) (Ramaji and Memari, 2013). These elements are filled later with components such as wooden panels, e.g. OSB panels or mfd panels, but they are also fitted with insulation and gypsum or plaster walls. The elements of the volumetric modules are floors, walls, roofs and bathroom cabin. The process of constructing them in the two manufacturing companies differs significantly.

In BM Byggeindustri A / S the walls and floor parts lay around in the department of production while the staff work on them manually. The floors of the modules consist of a structural system, made of wooden elements, except the spot of the floor of the bathroom cabin that is supported with metal brackets, that are screwed and bolted into place vertically in wooden timbers (Figure 5.9). This structural system is used for the distribution of lateral story loads to lateral load-bearing elements of the volumetric structure (Ramaji and Memari, 2013). However, many other components of the wall and floor elements are connected with the use of fasteners and therefore nails can be found in different places on the material. An example of this practice is the placement of windbreakers in parts of the wall which are usually nailed in place (Figure 5.10). Therefore, the disassembly of the components from the building elements has unpredictable results in terms of time and quality of materials after separation.

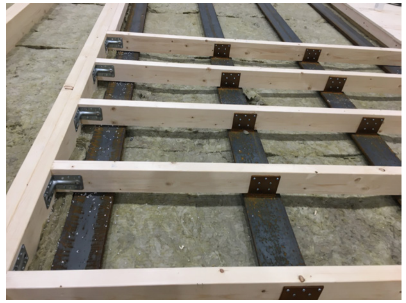


Figure 5.9

Scandibyg, on the other hand, uses robotics for the creation of walls and floors, which means that machinery has taken place the handwork. Automatisation is commonly recognized as being more cost-effective than craftspersons (Neelamkavil, 2009).Some of the advantages of the automated process, which eventually eliminate the overall costs, is the improvement of cost efficiency, increment of the buildings' life cycle value and facilitation of the interoperability among the lifecycle systems of the project (Neelamkavil, 2009). In that sense, more efficient joint tools could be used such as the 'screwnail' developed by Seliger et al., where nail edges ensure the tool on the rotation of the component while the screw is compelled into the material in order to secure lateral direction (opposite direction for the separation of the tool from the material). That type of connection is strong enough to transfer the required forces and torques for disassembly (Neelamkavil, 2009).However, in the current production, screws, fasteners and glue are used in a number of places in the components (Figure 5.11) while nails and glue are used in the corners of connection of the building elements (Thiesen, interview). When it comes to the assembly stage of the building elements, nails are used the use of nails in the corners of connection of the building elements since that practice requires less time and effort from the staff and does not demand planning for holes or mechanical joints.

Both manufacturers install the plumbing system, needed for the services (e.g. heating), and the piping system, needed for the distribution of substances other than water, on the floors and only some wiring passes through the exterior walls. The attachment of those pipes in the floor modules makes use of bolts and screws.

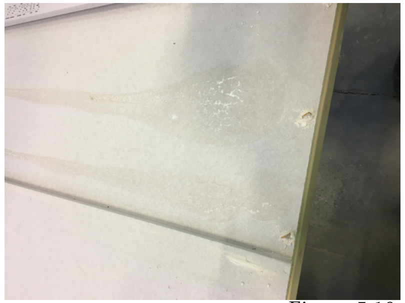


Figure 5.10

Figure 5.11

Figure 5.12

The lifting equipment (Figure 5.12) is also put into the elements at this stage of the modules' production. In BM Byggeindustri A / S they put fixtures on the lifting wires which are passing from the bottom of the module and end up to the side of the outside wall. Once they put the modules on-site they take off the wires, in order to use them in the next one. As a consequence, the fixtures of the lifting equipment even if they are staying on the house, get lost due to their location (placed inside the walls) which does not facilitate the ease reuse of them. Scandibyg, on the other hand, uses different lifting equipment/system. Through the lower part of the box, they pass a wire from one side to the other on which has been installed a piece of lifting equipment. In this case as well, when the boxes are put on-site the lifting equipment is detached to be used in the next building project. Since some of the fixtures of the lifting equipment remain inside of the structure of the volumetric module, the procedure of its removal from the site is not efficiently facilitated. Therefore, the volumes are not designed for further relocation, an effect that established the building as mostly permanent in its position.

5.2.2 Assembly stage

5.2.2.1 off-site

The sequence of assembly in both production facilities pursue the following steps: starting with the creation of building elements (walls, floors, wc cabin, technical equipment, roof), continuing with putting together all those elements and the first layer of the roof, and in the final stage of the off-site process, the staff puts windows, doors and paint the volumetric modules. The second layer of the roof is put on-site. Both companies pinch together floor modules and exterior wall modules mainly with nails and a chemical product such as glue. The inside non-load bearing walls, since they are not that heavy, they are attached with the use of glue, as well as the roof, which is glued on the walls. The separate module of the bathroom is the first element to be placed on the floor. The predisposition of pipes and installations on floors makes it difficult to disassemble the bathrooms from the rest of the building since such an action would require to disassemble first the roof and the walls so to enable the access for the disassembly of the floor.

5.2.2.2 on-site

Regarding the on-site process of assembly, things begin with the foundation (Figure 5.13). The foundation consists of concrete slabs, insulation, heating pipes, and a radon membrane, to which the volumetric modules are later attached to make sure that radon does not evaporate into the building. The foundation is made of concrete, and glue is only used at that level, the 0, to attach the boxes to the foundation. Tape is used around the volumetric modules to make the seal airtight. Regarding the placement of the volumetric modules on site, first, screws are anchored firmly to the ground and with the use of a chemical product the volumetric module is anchored to the screws.

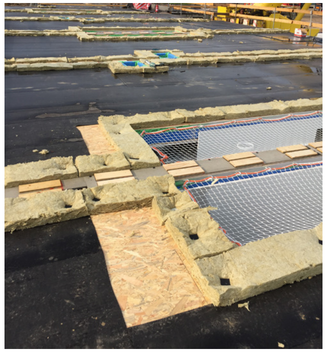


Figure 5.13: Foundation

Figure 5.14: Vertical connection

Figure 5.15: Placing on site

Continuing with the assembly on-site it is important to note that the volumetric modules are not fixed together with any mechanical joint either for the horizontal connection (when needed to create one big space) or for the vertical connection (in multistorey buildings). In the case of horizontal connection for the creation of one single dwelling, modules are produced with one side open which has been reinforced (Figure 5.16). After their location on-site with their open sides facing each other, gypsum plates are put from the interior side to cover the small gap between the two volumes. The last step is to seal them from outside.

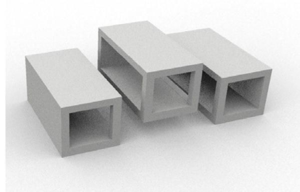


Figure 5.16: Vertical connection/ conceptual

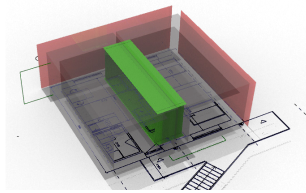


Figure 5.17: Veritcal connection with gypsum plates/conceptual

In the case of vertical connection, boxes are installed one up to the other with the help of some wooden blocks to ensure the anchor position. If it is about the creation of one single-family apartment, the volumetric module is equipped with stairs from the production stage and only the last two steps of the stairs are put on site together with gypsum plates so to connect the boxes from the interior side. Finally, there are some connections in the corners because of the wind. The horizontal and vertical joints in the facade for the wind and driving rain sealants are closed as quickly as possible when the volumetric modules are mounted on -site (Figure 5.19).

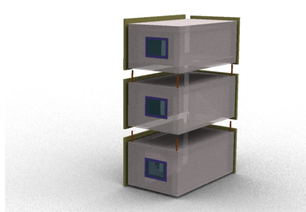


Figure 5.18: Horizontal connection/ conceptual

According to ScandiByg (Thiesen,interview), it is usually easier to separate the whole module from the site in order to refurbish or reuse it than it is to separate the elements (walls, floors etc) of each module (Thiesen,interview). The only obstacle in doing so is the current lifting practice, which does not facilitate the removal of the modules after being placed on-site. As mentioned previously, once the modules are stacked to the desired position, the lifting mechanism detaches from the lifting equipment, which is included in the volumetric module, and therefore it is very challenging for the lifting mechanism to find the lifting point again. However, this practice could change if a new system of lifting equipment were to be implemented. This is something that could be done (Thiesen,interview).

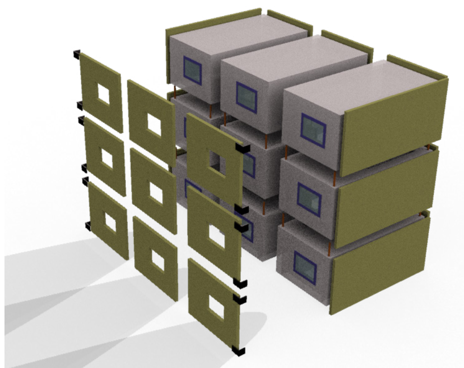


Figure 5.19: Vertical connection with facade/ conceptual

Conclusion regarding the production processes

From the conversations with the experts, I gained a solid understanding of their system's production approach. According to (Madsen, interview) the current modules are not designed for future disassembly/deconstruction and, as a consequence, the production system is not designed to ease future changes, resulting in limitations of the building lifespan. The modular construction system of volumetric wooden modules could, however, become more competitive if it is designed to be responsive to different societal needs. Nevertheless, the manufacturers' current priority is to create a robust construction with respect to the physical aspects of the structure, and to make the structure compatible with future user/owner's demands in order to avoid building obsolescence, which is the main reason for demolition.

The following table (Table 5.1) summarizes material from the interviews taken during my visit to the facilities.

	Scandibyg	BM Byg
Building structure	Load bearing partition wall system. The main building structure is wood and on top of that they have some wooden boards, like osb plates or mfd boards, and together with that, they have insulation and gypsum or plaster walls.	Volumetric system with a load-bearing partition wall system. It can be up to 4 stories. The inside walls are not bearing.
Connections	Screws are used for some connections and in the corners a chemical product (glue) is used.	The connections are made with screws.
Foundation	The foundation is concrete the radon membrane is added to make sure that the substance does not evaporate through. They put tape around to make the connection airtight. Blocks, insulation in foundation, heating pipes, they put the boxes on the top of the radon membrane They use a chemical product to anchor the box by putting a screw. Those screws need to be anchored firmly to the ground.	
Dimensions	Maximum width 4,6 meters and length 14 meters but mot common 12 meters. The height is max 4,6. Dimensions can vary from project to project.	Height can be about 4 meters and width is a maximum of 5 meters.
How easy to disassemble	Floors and walls are pitched together with nails. It is not easy but it can be done. The whole element is easier to separate than a plate. You have to take the roof out first. Bathrooms are not movable.	"It is not planned for the modules to be disassembled. You can dismount all. You can have a concept to be reusable and movable but it should be planned from the beginning because you have to find another way to put them together. "

Table 5.1. Sumary table

	Scandibyg	BM Byg
How easy to separate the elements	The inside walls are not heavy and they are attached to the floor by glue and the roof is attached to them by glue. However, it is preferred the use of mechanical connections in the building elements, instead of the chemical ones, in order to render them reusable (Addis & Schouten, 2004). The outside are more difficult. 1rst make sure about electrical wiring (depending on the plugs) . “If you remove the entire wall you need calculation to take it out. Maybe a part can be taken out. You don’t remove the entire wall, you just cut the wall. If you want to take it all out then you could make it in three parts and take one out. it ‘s easier to make adaptation when the houses are spread in the space instead of having long raws of houses.”	“If you want to take out a part of the outside wall you have to plan it from the beginning so to reinforce something on the top and bottom. It can be done but it’s more work and if you want to do it for the owner you have to plan them to be non-bearing.”
Airtightness	The airtightness is checked on the construction site by blowing some air. Typical failures of the airtightness: If things are not sealed up correctly. Or the assembly.	They control it from the beginning. In general, they take the 1rst module of a line and they test it for the whole line. They check them one by one when they have a series.

	Scandibyg	BM Byg
Process of adapt. (spatial)	There is no connection between the modules. They have some air in between, and they will be connected from inside the walls and floors and sealed outside. “First, you have to take part of the facade which it’s not a big deal and then put the box next to the other, then the gypsum plates in between them. Outside you put windbreak plates and sealed them with tape to be airtight. After you put the facade plates. The facade plates are sitting on hooks. They are put manually on the hooks. The new bricks will be shown. “	If you want to take out a part of the outside wall you have to plan it from the beginning, so to reinforce something on the top and bottom. Like make a timber frame. It can be done but it’s more work and if you want to do it for the owner you have to plan them to be non-bearing. In principle, if you take something out you have to replace it with something else.”
Lifting equipment	There is a wire in the down part of the box passing from one side to the other and has some connecting lifting equipment. They don’t leave the equipment in the box. They remove it to put it in another box . There is little space down from the boxes so to put something underneath to take it.	“But you cannot lift them easy from each other again because they take off the wires. They have to lift them in a specific way because of it the weight of the module. Those wires are connected to the bottom and then they take out the wires to use them to the next one. The connections are staying in the house but it is not easy to find them again. When you want to make a house movable you have to think about the lifting equipment in the beginning so as to not get lost. “

	Scandibyg	BM Byg
Access for deconstruction	They don't have cases yet when the people are taking down the building. Partial decosntruction:First, you have to take part of the facade which it's not a big deal and then put the box next to the other, then the gypsum plates in between them. Outside you put windbreak plates and sealed them with tape to be airtight. After you put the facade plates. The facade plates are sitting on hooks. They put manually on the hooks. The new bricks will be shown.	The assembly is not visible. If you were doing on-site the building it would be visible.
How they handle the waste from deconstruction	They refurbish by taking back the modules. But they did not disassemlby the roof they just got inside the boxes and took everything apart except the walls. They didn't change the location of the bathroom just change the toilets.	

In sum, the ways in which the modules are assembled has implications for how feasible it is to disassembly and re-arrange the modules. According to Scandibyg, everything it is possible if it is planned for.

5.3 Analysis of adaptability

In order to access adaptability in more detail, I created a matrix that staff of the two case companies were asked to assess how well the current industrial system of prefabricated houses responds in physical and social demands as well as demands of disassembly requirements. With the evaluation tool, I could visualize the weaknesses of the production system as well as what kind of improvement would have the most impact on the total design of prefabricated modules. The left vertical column of the table introduces the four phases of the industrial system. Each element of that column represents the specifications of each phase of the system. Moving on the x-axis, it is divided in three dimensions. The first dimension is related to the social changes that might occur during the lifetime of a building. The other two dimensions refer to the physical changes and disassembly requirements so to consolidate the building adaptable. The conceptualization of the tool was a result of my observations and interviews from the facility in combination with literature by Schmidt III et al. (2016) and Brand (1995). The elements of disassembly requirements are also taken by the literature related to Design for Disassembly.

5.3.1 Evaluation tool analysis

During the research period of this project, I gained a solid understanding of the prefabricated construction process and how the building's systems can be designed and produced to correspond in future social needs. According to Adams et al. (2016), the discipline of Sustainably Design in order to adopt more systemic approaches has as starting point social issues along to technological interventions. With that in mind, the evaluation tool, I created, intended to map the impact of production practices to the building layers and the disassembly demands in order to ensure future adaptability relating to potential alterations in the society. My first goal was to get the opinion of the experts regarding the capabilities of the industrial system by requesting them to fill out the evaluation tool. However, it turned out that this was not an easy process since the tool was long and required too much time from the actors to complete it. Moreover, the instructions of assessing it was conceptually loaded, revealing the gap between our disciplines. The result was the very limited feedback on the matrix from the stakeholders of the two factory staff. Since these results were not sufficient for my analysis, I modified the tool by limiting its size /scope by excluding the social parameters, as it turned out it was a matter of disorientation, and I made a second attempt to collect the feedback I needed.

In order to detect which of the assembly processes were problematic, I developed a color-coding scheme as shown in Table 5.2 and I translated the evaluation tool in 'sources of dilemmas' due to the qualitative nature of those defects. To do so, I structured the outcomes of the evaluation tool in a colored variation and then I identified the degree that the existing practices affect the building layers and respond to disassembly requirements.

	Use of nails	Use of glue	Use of screws	Component accessibility	Functional separation	Interrelation of elements	Production of basic modules
Space							
Services							
Skin							
Structure							
Site							
Time required to dismantle the elements							
Information provided							

Table 5.2

- Full compatible
- Good compatible
- Minimum acceptable compatible
- Poor compatible

As can be seen from the figure 5.2, for each layer of the building there are problematic processes with regard to disassembling the building.he low scoring in 'Component accessibility' and 'interrelation of elements' indicates a limitation of the system in applying changes to specific layers without affecting other layers. First,since the system is assembled off-site, the connections of the components and elements are hidden inside the structure causing difficulties in the later disassembly. Secondly, elements such as exterior walls and floors are pinched together since they constitute the structure of the volumetric module, hindering the latter separation of them. 'Functional separation' is also scored with acceptable compatibility in those layers which means that their functions are interdependent and therefore, changes applied to one layer, have an effect on the function of another. For instance, it is preferred the bathroom cabins of each apartment in a multistorey building to be placed in the same place on each floor since they are the only heavy concrete modules of the wooden structure (Madsen, interview). Therefore, under specific social circumstances, that require the modification of the layout of the box, such as market changes, the layer of space is not fully compatible with the relocation of the bathroom cabin (on the services layer) since , services,skin and structure are interconnected. Moreover, disassembly requirements such as 'time required to dismantle the elements', 'separation of components' and 'separation of elements' scored acceptable compatibility in relation to the criterion of ' Functional Separation' and ' Component accessibility'. That result suggests that there is no plan for the process of partial disassembly of the volumetric modules. As a consequence, the industrialized construction system is not easily adaptable to long term changes that alterations in the market, ownership or demographics could prompt. Another disassembly requirement that had the lowest score in the evaluation was 'information required for dismantling the elements' which means that either the information of assembly for disassembly being provided is inefficient or information is not provided at all.

Furthermore, BM Byg Industry does not produce 'basic volumetric modules' that can be used as extra additions in case of renovation or adaptation of existing buildings. However, some basic components of floors and walls or bathroom cabins are produced either for sale to third parties or for the needs of several projects. The absence of multiple lifting strategies is considered in the scoring as 'acceptable compatible' with the requirements of disassembly. The result is based on the extended need in time and human effort as the current system does not facilitate the relocation and easy disassembly of the building elements or even of the whole volume. Also, the operation of relocation of the volumetric modules of a multistorey building from the site is constrained from the unique option provided as a lifting strategy. When the 'boxes' are mounted on-site there is not enough space between the floor of the top one and the roof of the one underneath to fit the lifting mechanism and extract the lifting equipment. Since the lifting equipment is attached to the modules from the production stage of the building elements, that implies a predetermined lifting strategy of them. Moreover, another criterion with low scoring accessed in all the building layers are the foundations' capacity to carry greater load which plays an important role in the scalability of the building, in case of vertical addition (Schmidt III and Austin, 2016).

Regarding the practice of assembly, the joining tools used to connect the building elements and their components affect their disassembly, since it is possible to cause implications in their later separation and also to be hazardous for the material of them. The use of nails in the skin and structure layers seems to be ambiguous regarding the time and effort for the disassembly of components and elements. However, in the layers of space and services, the 'use of nails' scored full compatibility. That proves a routine that nails are rarely used in those layers as other joining methods are preferred, such as the use of glue or the use of screws. That can be confirmed from the interview with Thiesen from Scandibyg stating "The inside walls are not heavy and they are attached to the floor by glue and the roof is attached to them by glue". The use of glue was evaluated as 'good' concerning the facilitation of later disassembly of components and elements in the layers of services and space. However, it requires the same amount of time for the separation of elements as a nailed connection. The use of screws on the other hand, requires less time to dismantle the elements, as it was evaluated on the matrix, than the aforementioned types of connections. Using screws can, however, present challenges when it comes to the separation of structural parts or parts of the skin. That might be due to the not extensive use of them as it requires more time and human effort to drill the surfaces and screw on them, in comparison with the use of a fastener such as nails. The use of screws and chemicals (such as glue) in the foundation appears to have no influence in the later detachment of the structure from it.

Conclusion of the evaluation tool results

In conclusion, the feedback from the actors of the industrial sector reveals some limitations of the system regarding the time and effort needed to disassemble the building components and their elements. The current production system has limited compatibility with regard to disassembly of the structure, leading to complications in future scenarios of adaptation of the structure.

The reasons that justify the aforementioned statement are mainly the inefficiency of the system to meet the disassembly requirements. First, the load-bearing wall structural system of the volumetric modules does not present flexibility as it is closely interconnected with the rest of the layers, except from the site, and that implies difficulties concerning the partial disassembly of the boxes. Secondly, the analysis highlights the extended time and effort needed to disassemble the building elements and their components a fact that does not favor future adjustments. Lastly, the lack of instructions for building's' disassembly clearly does not facilitate such a process.

5.4 Comparing the adaptability of the current system with the exemplars

This section focuses on how the industrialized construction processes presented in this study respond in three scenarios of adaptation (scalable, and movable and refitable) presented by Schmidt III et al., (2012), in comparison with the exemplars, Tinggaarden and Lisbjerg Bakke. The use of those scenarios reveals the limitations of the different concepts' to respond to potential social demands.

Space expansion

Buildings' space enlargement can be demanded when there are changes in ownership (e.g. from social housing company to student apartments), market needs (e.g. from houses to offices) as well as for demographic reasons (e.g. changes in the number of inhabitants). This is my attempt to make a clearer distinction between what is possible with the production system of this study and the structural systems of Tinggarden and Lisbjerg Bakke.

Space expansion in 'boxes' implies partial disassembly of the exterior wall, structural element of the building, and the facade. This is feasible since the layer of the skin is separated from the layer of the structure, and also it is mounted on-site. As mentioned above the volumetric module system structure is based on a load-bearing partition wall system, and therefore, the removal of one of the exterior walls requires first, reinforcement of the specific side of the volume. Hence, from the production phase the exterior walls that have space for expansion should be pre reinforced maybe in three parts so to allow flexibility in the size of the wall opening.

In contrast, the structures of the two exemplars allow for structural expansion, albeit in different ways due to their different structures. In Tingaarden designers had foreseen the need for this kind of alteration, and tackled them by placing the extra room in strategic spots within the buildings' layout. For instance, pre-designed door openings simplified the spatial transitions. The hybrid structure of Lisbjerg Bakke, on the other hand, is expandable as it uses a non load-bearing structural system that completely separates the building structure from the skin and also allows for the re-use of detachable components, since they are screwed to the building skeleton. Moreover, it provides a very flexible interior layout since the family homes can change size by the rearrangement of the non-load bearing partition walls. The hybrid system offers full flexibility of space plan since there is no floor span limit unlike with the volumetric modular system which has clear restrictions regarding the three dimensions.

Relocation of services and installations

The social pressures that could be the reason for this demand could be related to the building's age and need of renovation, shifts in ownership or adjustments of the building's size according to the new market demands. From the conversation with the experts, this is one of the hardest adjustments to make. It is, therefore, preferred to locate the services' installations in the floors rather than in the walls. Indeed, both companies of modular construction I researched, are installing most of the services in the floors in order to allow for the inside non-load bearing walls to be relocatable.

However, to increase adaptability in the future, stakeholders should consider how to relocate services in the space plan of the building in order to enable it to expand or modify the interior.

Changing buildings' services and installations is also a challenging form of adaptation for the two exemplars to respond to. The structural systems of the case studies do not facilitate relocation as it is post and beam cast on site. From the interviews with the architects in Vandkunsten it was made clear that installations for the services are the ones who fix the floor plan because it is very difficult to relocate them as it has an effect on the entire building (interview with Kim). "Finding strategic locations for the installations is the challenge for the architects" (interview with Kim)

Removing a whole building to a new site

Building relocation is a very challenging adaptation strategy as it requires the entire structure to be movable. This could, perhaps, be relevant when demographic changes create the demand. The structural system of the volumetric boxes is suitable for moving, since by regulation, boxes are built to be very airtight. Moreover, the whole structure could be detached from the foundation as it is placed on the radon membrane and taped together.

However, the different lifting types of equipment both companies use do not facilitate later lifting, because the lifting fixtures get lost inside the building's structure once they have been detached from the lifting mechanism. This obstacle could potentially be removed by applying different technology (Thiesen, interview) but according to the manufacturers, since there is no demand from the clients for that kind of system, there is no need to change the system (Madsen, interview).

Comparing the current structural system with the ones of the two exemplars, it is clear that the current one has more possibilities to respond to this kind of adaptation. Tingaarden has been built on-site with the traditional building method, which renders the structure static. The post and beam structure of Lisbjerg Bakke is, one the other hand, not movable. However, the option this post and beam structure provides is the disassembly of all the wooden parts such as walls, which can be reused, but not the concrete parts such as floors and staircases, which are connected with the foundation. However, still, the inside walls are equipped with insulation and gypsum boards which also makes it difficult to disassemble (Dalgaard,interview).

5.4.1 Conclusion of third part

Although the production companies of prefabrication claim flexibility of the modules, due to the fact that users can decide the position of the interior walls, this is limited considering what have been achieved in the structures Tinggarden and Lisberjg Bakke. The design of Tinggarden allows for spatial enlargement of a dwelling after negotiation with the neighbors. The hybrid system of Lisberg Bakke, on the other hand, allows for complete reconfiguration of the spatial plan without limitations on the size of the floor plan. All the three structural systems under this study provide some limitations, however, the combination of them can give some advantages in the design of adaptable structures. The question is what it takes, from the production process perspective of the boxes, to achieve compatibility with the combination of the structural systems of the exemplars.

The concept of future social housing can be updated by drawing inspiration from the Tinggarden project's' value of the preplanned flexible floor span, which led to the project's success, and eventually to offer an opportunity for families to grow, develop neighbors' negotiation and create communities (Figure 5.20). That could be done by the combination of the hybrid structural system of Lisberg Bakke, as the structural system of the extension, which offers easy rearrangement of the interior layout, with the system of prefab volumetric modules equipped with the needed services and installations so to achieve full flexibility of the extension's' layout. Moreover, the settlement of the installations and services on the boxes creates a holistic movable structural system as the structural system of Lisberg Bakke alone does not facilitate the relocation of those elements. From the production phase of the modules, it would required reinforcement of the exterior walls, together with the plan for the later disas-

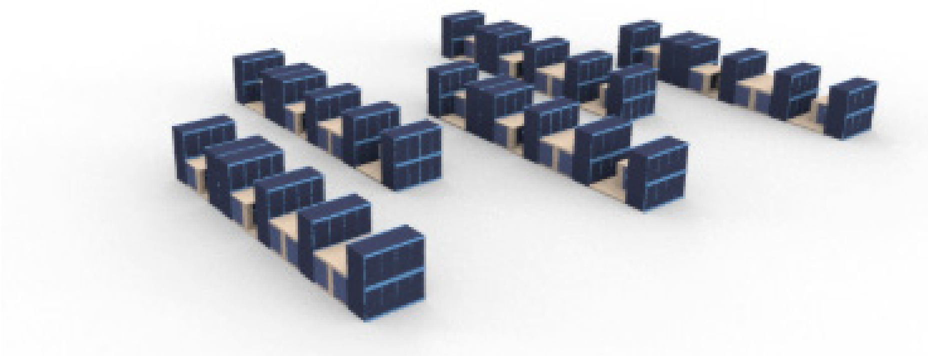


Figure 5.20: Concept volumetric modules together with hybrid stucture

sembly of them, as well as preparation for the later integration of mechanical joints in their exterior corners.

However, the practical development of this structural typology presents restrictions regarding the construction work taking place on-site. Firstly,due to the fact that the adaptation process will occur some decades after the first occupation, it is impossible to use the building method on-site with a crane as it is used in the prefabricated construction. Moreover, even if pillars and beams were pre-installed, due to weather conditions hazards would be created in those elements while the pre-installed foundation in the empty space between the modules would not provide any benefits.

6. DISCUSSION

The first part of this chapter examines solutions from the literature that respond to the deficiencies of the production system under this study, regarding the freedom of alterations the existing processes provide. Those solutions according to the time that will have returns, in comparison with the size of investment for the developers, are distributed in short term and long term solutions. In the second part, the strategy for escaping the lock-in of the construction sector is discussed. The proposal for the transition of the building sector into a more sustainable one requires mobilization in all types of involved actors and stakeholders. The last part of the discussion explains the procedure of this research, the reasons for the steps not taken as well as proposal of further investigation after overcoming the barriers I met.

6.1 Proposals

Framed structure

The first proposal entails altering the structure of the volumetric modules. The feedback of the stakeholders on the evaluation tool exposed limitations that occurred in the structure of the volumetric modules. More specifically, the load-bearing wall system presents a functional delimitation as it is hard to remove the outside wall, since it is a structural element, and this blocks the future expansion of the structure of the volumetric module. One solution could be designing the modules by a combination of the load-bearing wall system and a framed wooden structure to reinforce the sides that allow space for expansion. Even though this strategy constitutes a low rise in the cost of manufacture, it will provide spatial freedom to the structure and thus, returns certain benefits regarding future use and ease of the process of adaptation (Figure 6.1). Moreover, it implies a short term solution as it is easily applicable from the production perspective and if contractors adopt it now they will increase the value of their products and also make them more suitable for any kind of reuse with no further changes.

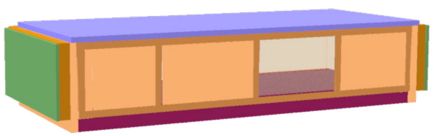


Figure 6.1: Proposal with timber frame

Wireless sensors and control systems (Guy and Ciarimboli, n.d)

'Functional separation' is another criterion that has also scored as 'acceptable compatible' within all the building layers, except the site. Since some of the building elements involve installations of systems for the services and wiring, this complicates the relations of different uses and also the potential for partial disassembly. In order to optimize the volumetric modules so as to be easily disassembled, one of the goals is to eliminate the wiring for HVAC systems and control systems as much as possible. One way of reducing the wiring in buildings is to use sensors and transmitters, which do not have wiring. This allows for the systems' components to be replaced and relocated without any further influence on the rest of the building systems. Some of the advantages of those systems are the reduction of complexity of service systems, the reduction of hazards to the components from the attachment systems and the faster disassembly process (Guy and Ciarimboli, n.d). Lastly, wireless systems can store the building's information regarding its components by reading radio frequency identification (RFID) tags and other sensors (Guy, and Ciarimboli, n.d). Those systems are considered to be a high investment in production, however, the benefits of it will show returns in the long term since it is likely to increase their capabilities to respond to future policy demands.

Connections

BM byg does not provide 'information for the disassembly of the elements'. Documentation of assembly procedures, component interfaces are as well as provision of visual material, e.g pictures, to indicate the installations' location inside the structure are strategies that should be considered from the manufacturers. Moreover, given the 'component accessibility' and the 'use of nails' as material for connection, the process of disassembly is rated as 'acceptable'. Creating less and larger building elements such as walls, floors in order to minimize the number of connections is not always enough to ensure the flexibility needed for reuse or recycling. Such a process requires accessible connections and clear instructions to be efficient. Moreover, the use of nails and chemical products in the structure and skin layers does not ease the disassembly of their elements and the later reuse of them. Clips, angles and plates, bolts, double-headed nails, are means to make the wood members easier to disassemble (Guy and Ciarimboli, n.di). This solution can be adopted in short term from the production industry while the benefits of its adoption will ease the process of disassembly of building elements and components for future adaptation and reuse.

Lifting equipment

Neither the Lisbjerg Bakke project, nor the volumetrice modules, both structures that include off-site construction, do not enable the movability of the whole structure. Indeed, there are housing companies in Denmark, such as CPHVillage that want to invest in a number of modules that in a span of 10 years, they will relocate them. Another reason for the relocation of a structure could be for the need of disassembly of it back in the factory's' facility in order to extract its components for reuse. The hybrid structure of Lisbjerg Bakke allows for full disassembly of the components except for the concrete parts that have been cast on-site, and therefore, one could say that still is possible the detachment of the whole in pieces. The relocation of the volumetric modules, On the other hand, it becomes challenging in the case of multistorey buildings. Such a process requires modifications in the manufacturing stage where parts of the lifting equipment are placed inside the floor or wall elements of the box. That position does not facilitate the access of the crane of the lifting mechanism since it is hidden from the boxes on the side or under. To simplify the process and therefore create the value of such an action, since it is less frequent but can be very demanding, calculations, different methods, and different lifting mechanisms will be needed. The easiest way would be to place the connections of lifting equipment for the lifting mechanism on the top part of the volumetric modules. Since the modules are very airtight such an action is feasible. All those applications call for the system's' reconfiguration and a monetary investment which does not offer tangible advantages for the contractor in the short term. However, future policies and changes in market needs could eventually force the developers to technologically to improve the strategy of the relocation of their products and thus, anticipation for that kind of alteration will make them more competitive in the industrial sector.

6.2 Strategy to escape the lock-in in construction industry

One of the main factors that prevents the development of adaptability in buildings is the cost due to the belief that adaptability results in higher construction costs (Pinder et al, 2013). For instance, according to Norwegian Building Institute study, solutions such as higher floor-to-ceiling heights, system walls and soundproof suspended ceilings, lead to the increment of the initial construction costs in office buildings (Arge and Landstad, 2002). However, according to Slaughter (2001), from a sample of 48 buildings in the US, the design strategies of adaptability resulted only in a 1% increase in initial construction costs in comparison with less adaptable strategies. Therefore, it seems that costs of increased adaptability are not yet conclusive. Moreover, conflicting interests of stakeholders can be seen as another obstacle to constructing adaptable buildings. For instance, stakeholders with a long-term interest in buildings, such as owners, institutional investors, and developers, investing in adaptable solutions will provide them future returns since it will minimize the rates of depreciation (Pinder et al., 2013). On the contrary, the developers that construct buildings for sale are likely to have doubtful benefits of such a strategy since it is not predestined which actor will launch the future action of adaptation and, therefore, benefit from the initial investment (Pinder et al., 2013). Furthermore, the property estimation plays an important role in the market, however, its valuation can be an obstacle in the innovation of property markets (Pinder et al., 2013). Indeed, without the proof that a design strategy has added value to the building in the past, valuers will not estimate any further value to those characteristics in the present. This fact can create a loop where developers do not include those characteristics in design, since valuers do not estimate the value those characteristics offer, and valuers have ignorance of the characteristics that add value since developers will not include them in their designs.

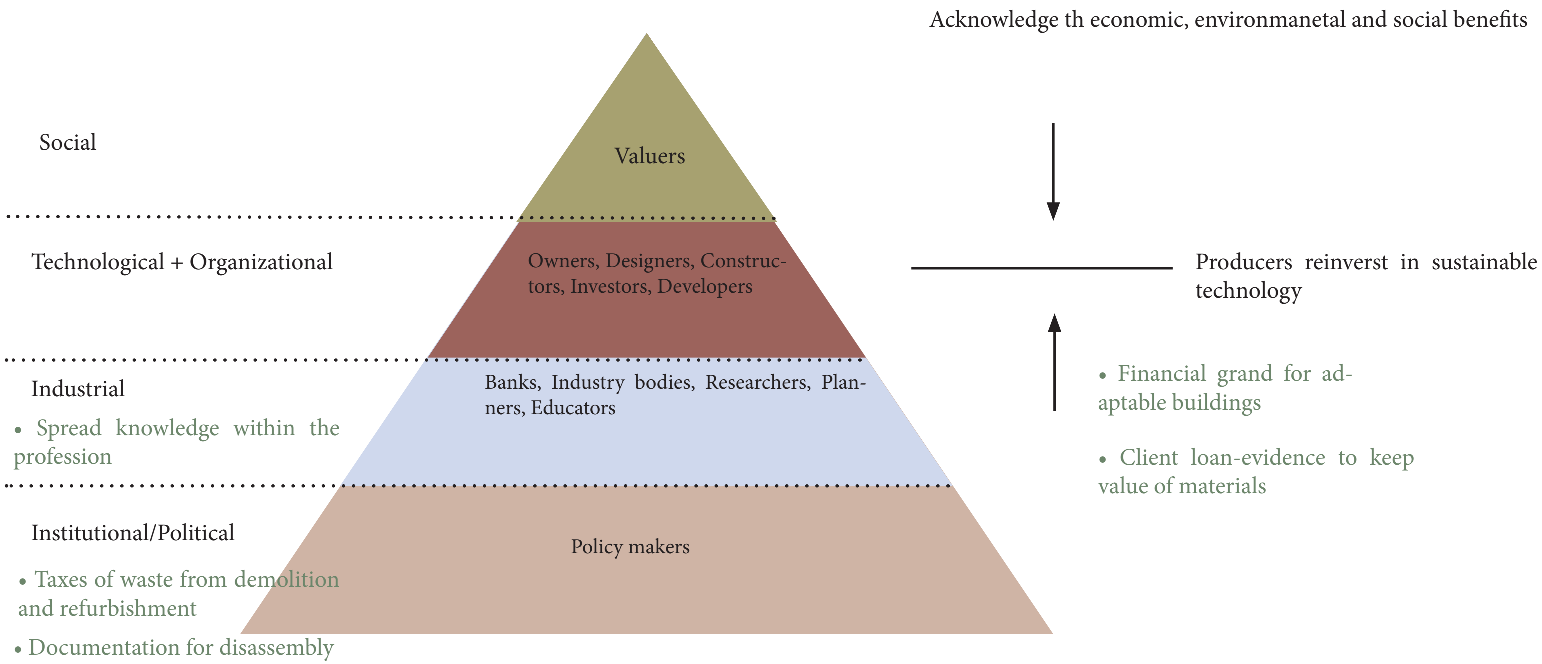


Figure 6.2

To escape lock-in, a collective action from various stakeholders is required (Figure 6.2). Since monetary investments aim in the reduction of production costs and in the improvement of the existing products, this limits the development of new solutions by re-investment in dominant design competencies. Those investments provide usually permanent solutions, which mostly are specialized, durable and non-tradable assets (Ghemawat, 1991). Cutting these investments requires first to address the institutional lock-in, which has the biggest influence on the other sectors. In the case of sustainable prefab production, political forces, such as policy makers, by raising the taxes of waste from building demolition and refurbishment create a greater interest amongst producers since they will have a responsibility of particular building elements and components (Guggemos and Horvath, 2003). That will have an impact on the scale economies since companies will have to re-invest to a more sustainable technology for their products in order to avoid taxes coming from their future products, and not in the technology of improving the existing one. Policy makers, therefore, should evaluate whether the manufacturers are going to follow the policy action or block it instead(Unruh, 2002). Moreover, governments can directly provide support for R&D with funding or can also promote the industry R&D (Seto et al.,2016).

Moving on the industrial lock-in, goals should be set for researchers and industry stakeholders to rate the adaptability potential as an ingredient to address the 'green' building certification schemes such as BREEAM and LEED (Pinder et al., 2013), which now gives 1 point credit for Design for Flexibility and only applied for healthcare buildings. DGNB on the other hand, includes the criterion

of Flexibility and Adaptability (ECO2.1). However, information for disassembly of building elements is not included in the documentation needed (ECO2.1 REF). For instance, SBI, the Danish Building Research Institute, could set design criteria regarding the potential of building's' adaptation to include in the Ecolabelling Denmark in order to ensure that new constructions, especially regarding the social housing sector, are taking those criteria into account. Furthermore, even though cost estimation of planning for adaptable structures is uncertain, the fact that is perceived by many more expensive serves as one of the economic barriers. A proposal to overcome these barriers could be addressed by banks through the provision of a financial grant with favorable interest rates for adaptable buildings even if those are less risky investments (Pinder et al., 2013). That type of grants could act as a matter of influence for network economies because industry bodies will tend to become more compatible and coordinated with each other to achieve financial help. Continuing further with the actors related to the construction industry, the educational system and researchers could limit the learning effects of a dominant technology by spreading innovative knowledge within the profession and by substantiating the benefits of sustainable technology.
All the aforementioned will have an impact on the adaptive expectations of the valuers who will recognize the economic, social and environmental benefits of opening the space for adaptable buildings. Moreover, as Seto et al. (2016) state, competitive economic markets benefit several types of innovation and disruption, and that introduces a transition in the marketplace. One of these markets could be promoted banks by the provision of a favorable client loan under the evidence that the building has been built according to methods that keep the component/material value high. By altering the client's' and users' expectations, a push will force the technological actors to design and build according to the criteria for disassembly and design for adaptability. As follows, actors from the technological and organizational complex will be driven to change their practices in more sustainable ones. More specifically, designers and constructors will produce adaptable structures by fulfilling disassembly aspects in order to meet the expectations of clients and society for the reuse of products or components. Investors, on the other hand, will acknowledge the big returns and the higher-value growth potential of such design through the political pressure and development of niches. Eventually, that will draw a positive effect on the developers (eg Scandibyg) who aim for higher prices of sales and to prevent obsolescence of their products. (Pinder et al., 2013). Therefore, the aforementioned long term solutions for the optimization of their products regarding disassembly, if they adopted now from the industrial facilities, they will have big returns for the developers.

6.3 Reflexions

The aforementioned proposals regarding the improvements in modular construction are the product of the analysis of my empirical data. That analysis is, however, subject to some limitations which are presented in the following text. The empirical material was based on the two production facilities of volumetric modules in Denmark that the architecture firm Vandkunsten cooperates with. This means that the industrial system I describe is limited and I cannot speak for the norms of the whole industrial system of volumetric timber modules. The existence of companies within the sector that use more sufficient practices regarding the disassembly requirements needs further investigation. A wider view on the sum of prefab housing production facilities would presumably also have had an influence on the short and long term proposals for the system. Moreover, topics for further research regarding the combination of structural systems and their advantages from both economical and environmental aspects, such as reduction of resources through reuse, is also needed.

Another factor that proved troublesome is the variety of stakeholders I came in contact with during my research. My initial idea was to approach the occupants living in buildings composed my modular construction, to gain experience of people's' spacial needs and how these might change over time, potentially affecting the need for adaptation. To do so, I created a file with a brief description of my interest and I delivered it in the post-boxes of residents of those structures. However, I failed to establish contacts with them, in order to understand social needs, and hence I researched through the literature to find the potential cases of adaptation. Furthermore, another stakeholder that I did not include in the research and further analysis is the Danish social housing companies. Having the chance to discuss with actors from AKB and KAB would have enriched my knowledge about the needs of the housing concepts they produce as well their financial interests in respect with the lifespan of those structures. A scenario that requires further study would be the investment in concepts which invest in a number of volumetric modules that will need to be relocated in a specific timeframe. Currently, that kind of concept arises with the housing company for students, CPH Village, showing the first interests.

Lastly, the gained knowledge came from the unique visit I had on those facilities, as they are placed in the center and north of Jutland. The construction phases of both factories' projects were in the production stage of the modules and therefore, my observations are limited in the off-site construction. That defined the descriptions regarding the on-site assembly since they were based completely on the statements of the interviewees. Moreover, the evaluation tool proved to be a weak boundary object between the researcher and the actors from the industry since due to the difficulties that arose for the last in assessing it. That result reveals the gap between the various disciplines of the building sector. The possibility of a workshop for the facilitation of the tool and exchange of knowledge through our disciplines would have ensured further data validation.

7. CONCLUSION

The objective of this thesis was to investigate the strategies to prolong buildings' structures and their components' lifetime in order to enable material waste reduction. Based on this objective, this study sets two questions. The first is regarding the limitations of the current production in prefab modular construction, which affect the response of the structures to demands of later adaptation. The second is related to the transition of the building sector to a more sustainable one through reconfigurations in the sociotechnical complex.

The division of my analysis in three parts provided the following sub-conclusions regarding the effect of the current industrial practices in each production stage and how those affect future decision making. The first part confirmed the initial assumption about the product disassembly impairment given the current practices on the studied industries. The most important finding of this part was the limitations in the current lifting strategies regarding the relocation of the whole volumetric module after assembled with the others on-site, creating a multistorey building.

In the second part, the assessment of the experts' evaluation tool in terms of the product structure and human effort, which keeps the system inflexible. Such reasons involve the hazardous assembly practices for the material, causing reduction of the component value due to the lack of provision of information for dismantling the building elements for the facilitation further actions of adaptation, along with the difficult access to building components and the weak separation of building's' functions. Gosling et al., 2016 suggest the conceptualization of buildings as systems in terms of functionality, not as an assembly of parts, a fact that comes in contrast with the previously described characteristics. However, the structural system of the volumetric modules is the result of the exterior walls subassemblies providing only a single function, that is linked with all the rest of the building parts, the load-bearing support. Moreover, Rios et al, 2015 underlined the importance to reduce the time of deconstruction in order to be preferred instead of demolition, and therefore, documentation for dismantling the building is needed. The last part of my analysis looks at future adaptation scenarios in order to target the constraints of different construction systems in the assurance of compatibility with possible adaptations. Those constraints involve implications of the current production of the modules such as the weak strategy of lifting mechanism that does not ensure movability, the load-bearing structure of the modules which restricts its spatial possibilities as well as the inflexibility for the services' layer.

The second question aims towards reconfiguration of the industrial system concerning the construction industry. In this study, the answer to this question is firstly based on an evolutionary approach of the Danish building sector that has drawn the tendency of transitions, over time, to follow co-evolutionary processes that are restricted by path-dependencies. More specifically, from the post second world war period, major solutions came from the institutional regime to overcome managerial problems, such as the lack of productivity and planning, with regulation and support from the national building institute (Gottlieb and Frederiksen, 2019). Those changes gave the opportunity to the industrial sector to evolve in new construction practices, such as the use of prefabricated concrete. Again to stabilize and promote those practices, institutions established evaluation tools to overcome implications created by the materials. The rationalized building system and industrialization developed in the modern period were enabled due to the practices created during the previous developments. Heavy public investments in the 90's and political alterations, (Gottlieb and Frederiksen, 2019), guide the industry to scale economies, learning effects adaptive expectations, and network economies, all four categories of increasing returns of adoption.

Social housing constitutes an important form of the Danish housing market and hence, designing for optimization of the building resources requires adjustments in the industrial system, through the promotion of disassembly and adaptability in the building's planning phase. However, those adjustments often lead to the increment of production prices, an undesirable consequence in the market of that model of accommodation. Moreover, the analysis showed the lack of developers' interest to alter their practices and the system's design in order to enable future adaptability of their structures if it is not a requirement set by the client. That lack of interest is due to the aforementioned increasing returns of adoption of the industrialized system.

The sector calls for reorientation from the political, institutional, industrial-technological and social spectrum. Therefore, considering the systemic transition of the building sector, I built my approach to the theory of techno-institutional lock-in which blocks the construction industry and industrialization in a path-dependency that is hard to escape. I used the theory to explain how to break the increasing returns of adoption both in the technological and institutional spheres. Starting the transition from the institutional complex, I indicated the power of policymakers to influence the industrial regime through regulations for documentation and the taxes for building waste. After that first step, a collective action within the industrial sector is suggested where banks offer financial interest to the clients in return documentation that ensures the longevity of the structure along with the researchers and innovators to bring knowledge and alternative strategies within the profession. Through these alterations in market mechanisms, it is feasible to increase the interest of the adoption of new solutions in production and assembly practices on companies as the ones explored under this study. Implementation of this strategy to the industrial system of prefabricated construction is possible to lead to the creation of new business models that will keep the material value high and prolong building's' life.

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Figure 2.1, Tinggarden plan, https://vandkunsten.com/content//2019/01/Tinggaarden-plan-gallery.jpg

Figure 2.2: Schmidt III, R. Austin, S. and Pinder, J. (2012) Thinking + Talking Adaptability: diagrams for time and change in our built environment, In Schwarz, T. and Lewis, K. (Eds) Diagrammatically (Urban Infill), Cleveland Urban Design Collaborative, Clevelant

Figure 4.3 : LIsbjerg Bakke, https://jv.dk/artikel/p%C3%A5-lisbjerg-bakke-er-en-lille-skov-af-moderne-tr%C3%A6huse-vokset-frem-2019-2-6(6)

Interviews:

Anne-Mette Manelius Greisen, Architect, 17/10/2019

Kim Dalgaard, Architect, 15/10/2019

Joan Thiesen, HSE Manager, 25/10/2019

Mogens Madsen, Sales Manager, 24/10/2019

Den Faber Madsen, Project manager, 24/10/2019