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Feasibility study, screening of trends and predicted future needs

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DTU Construct
Department of Civil and Mechanical Engineering

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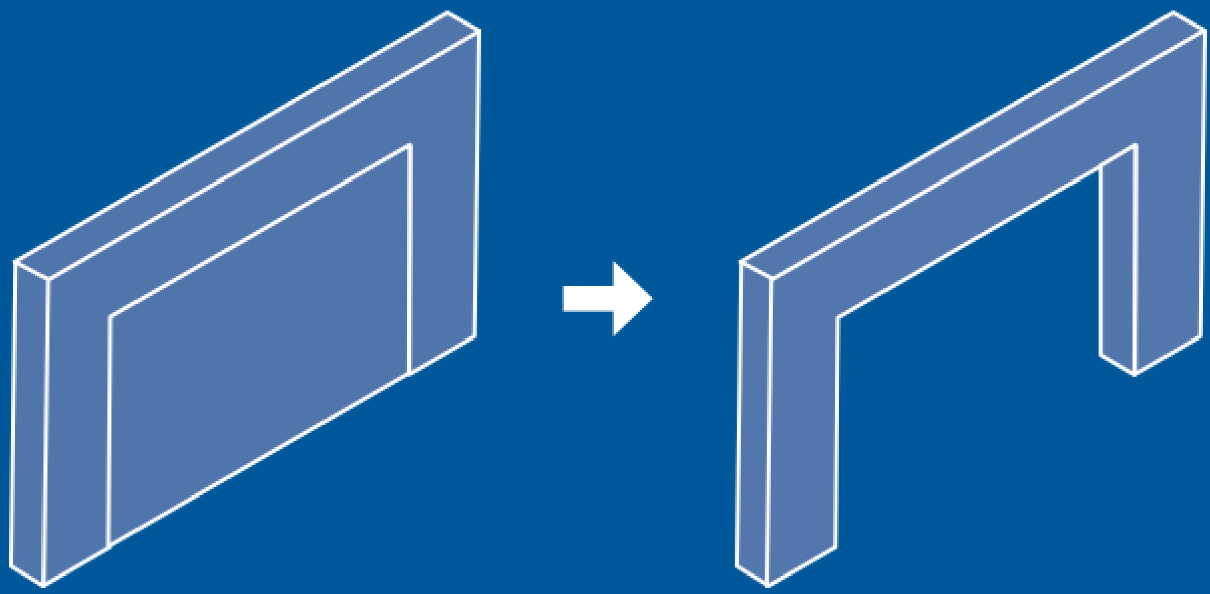
Feasibility study, screening of trends and predicted future needs

Sara Sofie Vestergaard



Report

A modifiable structural system
Feasibility study, screening of trends and predicted future needs

Sara Sofie Vestergaard

June 2022

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By
Sara Sofie Vestergaard

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Preface

This report is written as part of my PhD project: *Design and Analysis of Modifiable Structural Systems for Circular Use of Buildings Made of Precast Concrete Elements.* The PhD project is initiated in October 2020 and is made in corporation with DTU, Rambøll and Contiga. It is funded by Ramboll Foundation, The Innovation Fund Denmark and Realdania, Rambøll and Contiga. The project is part of the Research Network *Circular Built Environment* consisting of 15 PhD's and postdocs, which is facilitated by the Nordic innovation hub for sustainable urbanization, BLOXHUB.

The report is mainly worked out in the period from ultimo 2020 to spring 2021. It acts as an introductory study of the PhD project with the purpose of investigating if there is a need for a modifiable structural system made of precast concrete elements and if the initial idea behind the concept makes sense to further develop, or if some adjustments should be made.

Copenhagen, June 2022

Sara Sofie Vestergaard
Civil Engineer

Content

Summary

The purpose of a modifiable structural system is to make the structure adaptable to future needs of the building. For example, if small apartments are merged into larger apartments, apartments are transformed into office space or other types of transformations that requires new openings in the building structure.
The initial concept of the modifiable structural system in this project is to design prefabricated concrete walls with flexible zones, which can be cut out without or with very little further strengthening of the structure. The wall element consists of concrete and reinforcement, but the production should allow for different types of concrete in the structural zone and the flexible zone to enable the use of low strength concrete in the flexible zone with a lower CO_2 footprint.
The aim of this report is to investigate if there is a need for a modifiable structural system in the market and if the initial concept behind the system makes sense to further develop and analyze throughout the PhD project. If not, adjustments to the concept needs to be made. Furthermore, the report provides some valuable background knowledge about some aspects of the building sector, which helps contextualizing the project. To limit the framework of the report, the focus of the report is on housing in the Danish market.
Throughout the report the following is investigated. The historical development within housing and current trends are outlined, to see if the needs and types of housing has changed over time and to see if there is a clear direction that makes us able to predict the future needs of housing, or if we do need flexible solutions that helps buildings adapt for changes. Furthermore, the development within renovation of buildings is investigated, to see if the tendency for renovation compared to demolish and build new is increasing and which parameters that drives the decision for renovation or transforming a building.
Some of the drivers for using the modifiable system are the short-term and long-term environmental impact and therefore the incentives that makes the construction industry focus on the environment and sustainability is outlined in the report.
An alternative to the use of concrete in the flexible zone could be to make the flexible zone of some sort of lightweight material. Therefore, it is investigated what the technical requirements in terms of sound insulation and fire insulation are for a wall between two dwellings, to see if there are advantages of using concrete compared to a lightweight material.
At the end, the flexibility of building structures is further investigated. This is done by looking at previous industrial building systems that are made with a focus on flexibility, to see if we can learn something from them. Furthermore, some cases of concrete walls that are prepared with flexible zones are shown, and different stakeholders from the industry are interviewed to get their view is on flexibility in buildings and what they think about the concept of the modifiable structural system from this project.

The report and the process that led to the result, supports the need for and the initial ideas behind the concept of the modifiable structural system made of prefabricated concrete elements. It also provides a good background knowledge for why it is needed, which cases it can be used for, how the focus on sustainability in the market can be a driver for implementing the modifiable system, which benefits there are of using concrete in a wall compared to lightweight material, insight in other flexible systems that has been developed through time, and that different stakeholders in general like the concept, both in terms of the flexibility it provides and the potential lower CO_2 footprint.

1. Introduction

Circular economy, sustainability and flexibility are some of the words that are flourishing in the building sector and which many companies attempts to incorporate in their projects. As part of a research network called Circular Build Environment, this PhD project seeks to develop a design concept and conduct structural analyses of a modifiable structural system made of precast concrete elements. The modifiable structural system is designed such that it can be modified to adapt to future needs of the building. For example, if small apartments are merged into larger apartments, apartments are transformed into office space or other types of transformations that requires new openings in the building structure. The initial idea is to make a structural system with modifiable prefabricated concrete walls, which contain a flexible zone. The flexible zone can be cut out without or with very little need of further strengthening of the structural system. This system will create more flexibility in otherwise very fixed concrete structures.

But why is flexibility needed? Do we actually change the use of our buildings? Do we change the way we live, or can sufficient variation in the size and types of dwellings satisfy the needs of the population? Is there a need for renovation and transformation of buildings? What are some of the drivers for the industry to build more sustainable and think in circular solution? Does it make sense to use concrete as material in the flexible zones? Which flexible building structures does already exist? What does some of the stakeholders in the industry actually say about flexibility in the buildings? And are there already cases of concrete buildings prepared for future openings in it the walls?

These are some of the questions that are sought to be answered throughout this report. The overall purpose is to investigate if there is a need for a modifiable structural system made of precast concrete elements and if the initial idea with the flexible zones in the concrete walls does make sense to further develop upon.

1.1 Background

The title of the PhD project is *Design and Analysis of Modifiable Structural Systems for use in Circular Buildings made of Precast Concrete Elements*. It is an industrial PhD made in cooperation between the consultant company Rambøll, Technical University of Copenhagen (DTU), and the concrete element factory Contiga. It is funded by Ramboll Foundation, a co-funding between Innovation Fund Denmark and Realdania, Rambøll and Contiga. As part of the co-funding from Innovation Fund Denmark and Realdania, the project is part of the research network *Circular Build Environment* consisting of 15 Industrial PhD's and postdocs from different professional backgrounds. The PhD researcher Sara Sofie Vestergaard is a Civil Engineer specialized within building structures. The PhD project started in October 2020.

The initial concept of the modifiable structural system is to design prefabricated concrete walls with flexible zones, as illustrated in the example in Figure 1.1. The whole wall consists of concrete and reinforcement, but the production should allow for different types of concrete in

the structural zone and the flexible zone. By allowing two different concrete types in one element, a lower concrete strength can be used in the flexible zone. Concrete with a lower strength emits less CO_2 in the production as it requires less cement. Furthermore, it will be examined how little amount of reinforcement that can be used in the flexible zone.
Thus, the aim of the project is to make a new concept for structural systems made of precast concrete elements, which compared to traditional systems are improved in two ways:

- Enables adaptability of buildings to prolong their lifespan.
- Using less material, measured in CO2-equivalents.

There exist different definitions and descriptions of a circular economy, but in general, the term includes: Use less, use longer, reuse and regenerate. This PhD project is focusing on the two first terms: Use less and use longer.

Figure 1.1: Example of a modifiable concrete wall

This report covers the initial research made in the PhD project, and it is made as a foundation to indicate if the concept is useful, before moving on with more detailed design and analysis. Beside this analysis, the following is to be conducted in the PhD project:

- Development of a numerical finite element program for material optimization of the structure. The aim of the program is to find structural designs with a minimum of CO_2 footprint.
- Fracture mechanical analysis of the modifiable structure with unreinforced and lightly reinforced flexible zones.
- 1:1 test production of concepts with focus on production suitability.
- Mechanical test of the concrete elements, to check the structural behavior found from the analyses.

1.2 Focus and structure of the report

The modifiable structural system is meant to be used for all types of buildings. For office buildings, residential buildings, production facilities, hospitals, cultural buildings, day care centers, ect. The modifiable structural system should enable easier transformations between different types of buildings or transformations within one type. However, to limit the framework the report focus on housing and residential buildings. This is one of the large and important markets in the construction industry (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007), and most literature found in this study is about housing. Furthermore, the focus in the report is limited to the Danish market. This does not mean that the product cannot be scaled and used in other countries, but that is not within the scope of this project.

In Section 2 the historical development in housing and current trends are covered, to see if people do change the way they live, if demand for housing changes over time, and to find out if we can say something about the future by looking at the current trends. Some analysis that tells about the development and prediction for housing in Copenhagen is covered. Furthermore, it is investigated to what extend houses and residential buildings are renovated and some of the factors that determines whether to renovate or demolish a building and build new are outlined.

The sustainable agenda and the circular economy in the building industry are some of the drivers for using a modifiable structural system. In Section 3 it is examined which incentives there exist in the Danish building sector to focus on sustainability.

In Section 4 some of the technical requirements, like sound and fire insulation for walls between two dwelling are outlined. This is done to see if there are advantages of using concrete in the flexible zone compared to some lightweight material.

In Section 5 the flexibility of building structures is further investigated. This is done by looking at previous industrial building systems that are made with a focus on flexibility, to see if we can learn something from them. Furthermore, some cases with concrete walls that are prepared with flexible zones are shown, and different stakeholders from the industry are interviewed to get their view is on flexibility in buildings and what they think about the concept of the modifiable structural system from this project.

Throughout the report many different sources are used, spanning from different literature and reports, talks with different experts from Rambøll and interviews with stakeholders.

2. Development and trends in housing

In this section we investigate if there is a need for flexibility and what causes it. Do people change the way they live, and would it be sufficient to build with a large variation in the sizes and types of housing to meet the demand of the population, or do the demand changes over time?
In Section 2.1 the historical development of the housing market is outlined, to see how it has developed over the last 50-100 years and to give an insight into some of the drivers behind the changes. In Section 2.2 some of the current trends in housing are outlined to give an idea of the current situation and see if we can predict the future needs. It is relevant to see if there is a clear direction for the future needs or if it will be useful to make new buildings adaptable towards future changes. In Section 2.3 we zoom into Copenhagen and use the latest municipal plan to document the development in housing in a specific area of Denmark. In Section 2.4 we investigate renovations and transformations and identify some of the drivers behind the decision of whether to renovate an existing building or demolish and build a new.

The main source behind the historical development and trends in this section is the book *Velkommen hjem*[1] (Bech-Danielsen, Mechlenborg, & Stender, 2018). It describes the historical development in housing from cultural and social perspectives and furthermore outlines the current trends in housing from a 10-year perspective. The book is supplemented with an interview with one of the authors Claus Bech-Danielsen. Claus Bech-Danielsen is an architect and professor at Aalborg University. His work focuses on the development within housing, transformations of housing and in the recent years his focus has been within social housing. The interview is further described in Section 5.3.

2.1 Historical development in housing

Throughout history housing and the way people live in Denmark have developed enormously. Urbanization started back in the 19th century with a very rapid growth in the population of the cities, due to more and more people working at the factories in the cities. The housing market in the cities could not follow the population growth, which resulted in very dense and poor housing conditions. The housing conditions in the cities and the suburbs developed for the better during the 20th century. The average housing area per person in Denmark increased from 12 m^2 in 1910 to 26 m^2 in the middle of the 1950's to 56 m^2 in 2018 (Bech-Danielsen, Mechlenborg, & Stender, 2018). This means more than a factor 4 increase in housing area per person within 100 years.

The following sections describe the development in housing in Denmark from the start of the industrialization of construction, which began in the 1950's. The primary source in this section is the book *Velkommen hjem* (Bech-Danielsen, Mechlenborg, & Stender, 2018). When other sources are used, it is mentioned.

The post-war period

After world war II huge parts of Europe was left in ruins. With economical support from the Marshall-aid in 1948 some big industrialization projects started around in Europe. A growth

[1] The Danish title *Velkommen hjem* means "Welcome home".

period began in the 1950’s, which increased in speed in the 1960’s. In Denmark people still moved from the countryside to the cities and the suburbs. The welfare society in Denmark started developing, which led to more control and planning of the society and the urban development.

In Denmark, as in many western countries, the birth rate was increased during and after the war. The record was set in 1946 with 96.000 births, which we haven’t been any near since (Bech-Danielsen, Mechlenborg, & Stender, 2018).[2]

The destruction of buildings from the war was limited in Denmark, but not much was constructed during the war and with a growing population, there was a huge lack of housing supply. With a growing prosperity in the population, a huge effort was made in increasing the housing standard. The government was supporting the development of the housing standard by encouraging in construction of new buildings. The government gave financial aid in the form of government loan to construction projects of buildings, which lived up to certain standards and requirements.
It was difficult for the construction industry to follow the high demand with only brick constructions. Brick constructions required a skilled working force, which were lacking, and new construction methods were developed.
In the 1950’s different experiments with construction methods and materials were made. Concrete was introduced as a material in construction of housing which also started a new tradition of high-rise residential buildings. An early example of that is *Bellahøjhusene* in Brønshøj, which were constructed from 1951-1957. They consisted of 28 buildings varying from 8 to 13 floors hosting a total of 1300 apartments (Müller, 2016). They were constructed by use of in-situ cast concrete.
Other construction experiments in the 1950’s were made with precast concrete elements, where the elements were assembled by use of special cranes placed on tracks along the construction site. This technique was epoch-making and sat the direction for the industrialized construction of residential buildings in the following decades. The Danish government was very interested in the new experiments with industrialization and standardization of the construction methods and helped pushing the industrial development through different regulations. In 1958 standards for building components were introduced. This included standards for sizes of doors, windows, kitchen closets and concrete elements. In 1960 the so-called *mounting circular* (’montagecirkulære’) was introduced, which meant that in order gain financial support, construction of residential buildings should be made by prefabricated concrete elements. This was part of the reason for a huge change in construction of residential buildings, where the brick constructions in the 1960’s were replaced by large multi-story buildings made of precast concrete elements. The industrialization of constructions had begun.

The middle class was growing and the ideal was an elementary family with two parents and one or more children. In 1950 60% of the households consisted of elementary families.[3] As a consequence, the focus in construction of housing was the elementary family, which continued in the following decades.

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[2] As a reference there were 60.000 births in 2016.

[3] In 2018 the same number was reduced to 18%.

Building boom in the 1960's and 1970's

Despite the many new residential buildings constructed in the 1950's, the increasing demand for housing continued and the largest construction boom in the history of Denmark was seen in the period 1960-1979, where a total of 818,000 new dwellings were constructed in Denmark. As a reference 195,000 dwellings were constructed in the productive years of 2000-2009.

The many new residential buildings consisted of both single-family houses and multi-story residential buildings. In both types of buildings, serial production was in focus. For the single-family houses mass production of standard houses was developed. For the multi-story residential buildings prefabricated concrete elements were used.

Most of the residential buildings in the period were constructed in the suburbs. The ideal of equality in the welfare society had a large role in the design of the apartment blocks. Architects tried to develop one type of apartments that could satisfy the average need of the population. Due to large parts of the households being children families and a low divorce rate, the primary focus in the housing constructions were still the elementary families.

With the youth revolutions, which were peaking in 1968, new trends against the middle-class life were starting. The large generation of young people born during and after world war II was were opposing the ideal of the elementary family and had their own ideals of communities and solidarity. Experiments with new ways of living in communes and cohabitations started.

The large apartment blocks in the suburbs were also criticized. The criticism was not only ideological, but in the beginning of the 70's some of the large housing associations started having difficulties renting out the apartments. In the 70's some of the large apartment blocks started developing concentrations of inhabitants with social problems, and furthermore many of the buildings were experiencing some serious technical issues.

The poor 80's

The 1980's was marked by the economic crises. Furthermore, the population growth was stagnating in the beginning of the decade. In 1986 the Danish government introduced a financial regulation (in Danish called *Kartoffelkuren*). The purpose was to reduce private consumption and increase savings. This meant that loans for housing became more expensive. Demand for new buildings was declining.

The norms for family life were changing. The dream of an elementary family was still dominating, but not actualized as much as before. In the 1970's the divorce rate had substantially increased and kept the same high level throughout the 80's. This meant that more and more families were with joint-custody children. The number of single-person households increased. In 1950 around 13% of Danish households consisted of single-person households. In the 80's this number was more than 30% and it has further increased to around 40% today (Bech-Danielsen, Mechlenborg, & Stender, 2018). Despite of that, new building designs have continued having elementary families as a target group.

Development of the city

Despite the construction boom in the 60's and 70's, the housing conditions in the cities were still very poor with very small and unhealthy apartments. By 1969 a new law for redevelopment of the cities started a more systematical cleaning of the cities and improvement of the living conditions in the old apartment blocks. This meant that many of the old rear buildings in the backyard of the apartment blocks were demolished to provide more daylight and green areas for the surrounding buildings. As a result, throughout the 70's 7,000-9,000 dwellings were demolished each year in Denmark (Bech-Danielsen, Mechlenborg, & Stender, 2018).

The massive development of the suburbs in the 60's and 70's gave some new challenges. One of them were commuting and long tailbacks on the highway. Another drawback was that the landscape full of nature, which originally attracted many people, moved further out in the horizon due to the many new buildings. In the 90's some of the focus moved back to the city center. Some of the arguments to redevelop the city centers was to make the infrastructure and public transport more efficient and sustainable.

With the globalization some of the heavy production industry in the cities had moved to Asia and other parts of the world. This meant that large industrial buildings and harbor areas were emptied, making more room for housing. At the same time the employment in the service and office sector increased. Those industries do not contain the contamination and noise which the production industry did, which has been making more room for housing and offices close to each other.

The development of the cities in the last couple of decades has involved demolishing of old buildings in the backyards and developing of the outdoor areas of the city, making the city more livable. This has attracted many children families.
As part of this development in the city, many of the old small apartments has been combined and many new residential buildings has been constructed in some of the old industrial areas of the cities. Some of the old industrial constructions has been transformed to apartments. In opposition to the very planned areas and apartment blocks in the suburbs in the postwar period, the new areas of the cities were to a much higher degree left for the market forces to develop. To some extent, this has made the city a place for middle class families and pushed the less wealthy people out of the city, making the apartment blocks in the suburbs to the marginalized areas.

Interior design

If looking at development of the interior of housing, a huge development is seen as well. Some of this development involves location and size of the bathroom and the kitchen, which have had a huge impact on the plan arrangement in the homes. As an example, the kitchen has changed from being hidden away to be a very central part of the homes.

Summary and perspectives

Going just 70 years back in history, starting in the post-war period, bear witness of a huge development in the housing stock, the construction methods, the architecture, and the pattern of settlement.
The average housing area per person has increased from 12 m^2 in 1910 to 56 m^2 in 2018 and the family pattern has changed dramatically as well.

Some of the drivers behind the development has been demography, governmental control, trends in society, externally imposed factors like war, epidemics, and globalization. With this historical development in mind, it is difficult to imagine a static need for housing in the future.

2.2 Trends in housing

The last section has described the historical housing development since the post-war period. The primary source has been Claus Bech-Danielsen et al. (Bech-Danielsen, Mechlenborg, & Stender, 2018). The authors have also researched in the housing trends of today from what has been observed in the period 2008-2018. In the following, some of the trends from (Bech-Danielsen, Mechlenborg, & Stender, 2018) are outlined.

In many Danish homes, the way of life and family patterns have changed dramatically over the last couple of decades. The number of single-person households has increased a lot going just 25 years back from 2018 and make up around 40% of the total number of households today. This corresponds well with the fact that 60% of households in 1960 consisted of elementary families with two parents and one or more children, which today is just below 20% (Bech-Danielsen, Mechlenborg, & Stender, 2018). Furthermore, and increasing interest in different communities is observed. Single persons with a higher age than previous starts living together as friends, single parents are seeking others to share the practical burden with, grandparents want to live close to the grandchildren, and some seniors wants a social life with neighbors that are also home during the daytime.

Compared to the previous generations, the interior planning in a family house is very much based on individual needs today with office or hobby spaces for the parents and playroom for the children. These individual needs correspond well with the fact that the housing area per person is increased significantly over the past 100 years.

The demography also develops, and the post-war baby boom generation is around the age of retirement and this changes the housing demand with a large generation of elder people.

We still experience a flow of people moving to the cities in Denmark, and at the same time more people choose to stay in the cities after having kids. This puts a pressure on the housing market in the largest cities. Many housing opportunities in Copenhagen today are for the wealthy, but still the problem of high pricing is not as extreme as in New York, London and Stockholm. Our high number of cooperative dwelling[4] and social housing helps holding the price level down (Bech-Danielsen, Mechlenborg, & Stender, 2018). Different initiatives from the municipality and the housing sector are made to construct more cheap housing, as it is a problem if the low- and middle-income groups are being pushed out of the cities.

As a result of the increased pressure on the housing market in the cities and the high prices for housing, a trend of living in small dwellings has arisen. For some it is for financial reasons, to afford living in the city. But for others it is an ideal that comes as a reaction towards the increasing housing sizes and a way to show that they have non-materialized values. Living smaller can also be a way to accommodate the need of living more sustainable.

Another trend that Claus Bech-Danielsen et al. (Bech-Danielsen, Mechlenborg, & Stender, 2018) is pointing at they call mix an friction. Housing architecture and planning in the decades after world war II was focusing on separating functions, so that homes, work, and spare time activities were in separated areas of the cities. Today the functions are more mixed, and the

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[4] In Danish *"andelsboliger"*.

ideal is to have a mixed city where different people, activities and ideas are meeting. This also applies for the marginalized housing areas. Different initiatives are made to secure a wider mix of social groups. Some of the initiatives are to construct more attractive owner-occupied apartments, to attract people from other classes of society to the area.

Sustainability

According to Claus Bech-Danielsen et al. (Bech-Danielsen, Mechlenborg, & Stender, 2018) there is a wide agreement across the building industry to reduce the environmental and climate impact from our buildings.
One of the trends is to have a cyclic perspective on housing construction. Different experiments with circular economy is made. Cradle to cradle considerations are taking, meaning considerations of how the building material or structures can be reused.

Flexibility

With these different and changing trends Claus Bech-Danielsen et al. (Bech-Danielsen, Mechlenborg, & Stender, 2018) also points out flexibility as a topic that has been in focus for housing for the last many years. The need for flexibility can be for changing phases in the family life, for instance when the kids are moving out of the house. According to (Bech-Danielsen, Mechlenborg, & Stender, 2018) flexibility can also be useful when new people are taking over the house and have other preferences, or flexibility in the use of the of the rooms during a day can be useful. The need for flexibility is also seen due to a huge part of old houses and apartments that have been changed many times. Many places walls are demolished to make the dwellings fit the new needs.

Influence of the Corona epidemic

History has shown how epidemics influences society and the way people live. The cholera epidemic back in 1853 was an eye-opener for the very poor living conditions in the city center of Copenhagen, where people lived extremely dense and in very unhygienic unhealthy housing. The epidemic lead people to move from the city center to the periphery of the city and suburbs arose.

The source (Bech-Danielsen, Mechlenborg, & Stender, 2018) that has been used for this section was published before the Corona epidemic. In the interview in January 2021 with one of the authors, Claus Bech-Danielsen[5], he was asked how he think the Corona epidemic will influence housing in the future. He mentioned that it will create a discussion and a review of the dense city. Maybe it will create a revival of the trend of moving to the suburbs. The trend is already seen in Paris, Claus Bech-Danielsen says. In areas outside of Paris, where many housing have been for sale in the last many years, they are completely sold out now. Claus Bech-Danielsen also mentions that the very dense dwellings with many people in the same home in the marginalized housing areas, has shown to make the people more exposed to the epidemic, and this can be a topic in the future. He also mentions working from home as being in focus now. Working from home has been a topic for the last decades, since the start of the internet, but it has never really had a large effect. But with the Corona epidemic some of the challenges with working from home have been highlighted, especially in the denser areas of

[5] See Section 5.3 for more information on the interview.

the cities with smaller dwellings. Maybe the need for home working space will lead to a change in the housing needs in the future.

The future housing

As seen from this section the trends point in different directions. Some of the trends will lead to changes in construction of housing, whereas some of them will only be temporary.

As seen from the historical development and today's trends in the housing market, society and culture changes over time and with that also the need and demand for housing changes. Many different factors influence the changes. One of the drivers for the changes are reactions against the previous periods ideals and this driver will keep making changes in peoples demand for housing.

Due to the different directions of the trends today and an expectation of changing needs in the future, the future types and sizes of dwellings must be of great varieties and diversity to meet the different needs. To accommodate the future changes, flexibility will also be an advantage.

2.3 Copenhagen

Every fourth year in Copenhagen a plan for the physical development of the city is made, called The Municipal Plan. To develop the plan a lot of background analyses are worked out to make the best strategy for the city. The latest Municipal Plan for Copenhagen from 2019 and the background documents are public at the website www.kp19.kk.dk. In this section some of the relevant results from the background analyses are pointed out to show the development in the demand for housing in Copenhagen.

Housing past

Most of the background material for the Municipal Plan concerns housing. There are some very thorough analyses of the development in the demography, family sizes, size of the housing etc. In general, the analyses show a huge development and variation in the types of families, age of the habitats, size of the housing supply over the years, which shows that the need and demand for housing changes over time. Some examples from the background analyses are pointed out in the following to illustrate this.

In Figure 2.1 the development in the supply of housing in Copenhagen from 2000 until 2018 is illustrated. It shows that the growth in housing supply has been smaller than the growth in number of families[6] since 2008. This is explained with a tendency that an increased number of dwellings are shared by multiple families (Næss-Schmidt, Heebøll, & Kilsdal, 2018), as seen in Figure 2.2. The report (Næss-Schmidt, Heebøll, & Kilsdal, 2018) describes that the increase in number of families living together is mainly a tendency seen for young people. In the report it is assessed that this is mainly because of need, due to the low supply of small apartments.

From Figure 2.1 it is also seen that there has been a decrease in the number of small housing (0-59 m^2) and an increase in the number of large housing (especially 80-119 m^2). In the report (Næss-Schmidt, Heebøll, & Kilsdal, 2018) this is explained mainly from merging of small housing. The report also explains that only relatively few small dwellings have been

[6] A family can also exist of a single person

constructed in the period. This has, amongst other, been due to priorities in the former Municipal Plans in the period, which prioritized larger housing.

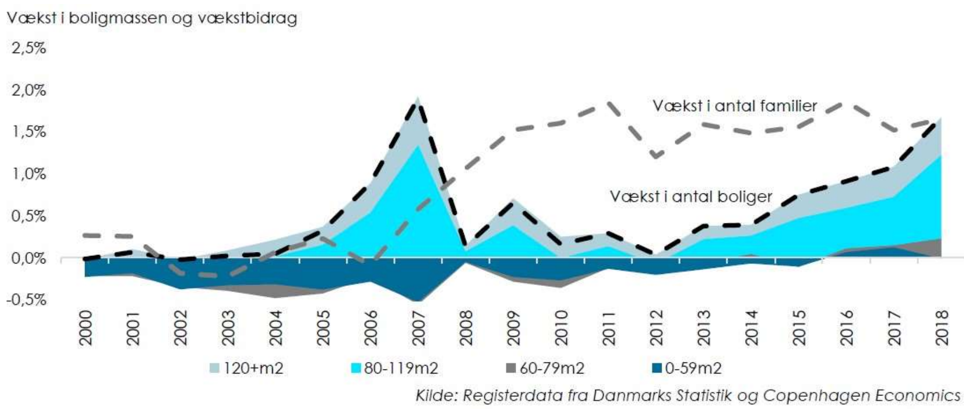

Figure 2.1: Percentage yearly growth in Copenhagen in housing supply (black dotted line, separated by size of housing by the colors), and growth in number of families (grey dotted line). Figure from (Næss-Schmidt, Heebøll, & Kilsdal, 2018).

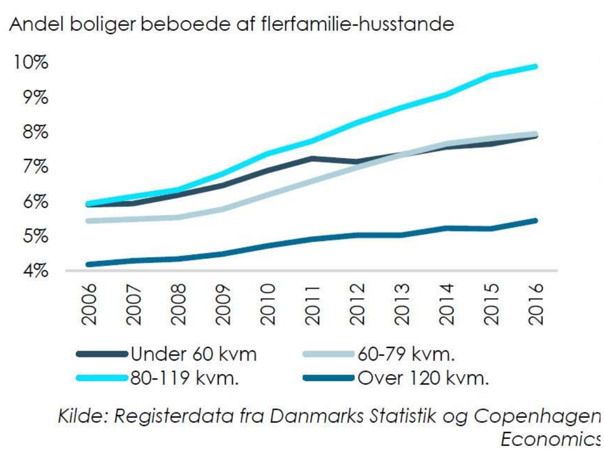

Figure 2.2: Share of dwellings in Copenhagen occupied by multiple families, divided into size of the dwellings. Figure from (Næss-Schmidt, Heebøll, & Kilsdal, 2018).

Housing forecast

According to the Copenhagen Municipal Plan 2019 (City of Copenhagen, 2020) the population in Copenhagen will increase with 100,000 persons from 2019 to 2031, which will result in need for further 60,000 housing in that period. Forecasts for the future predicts a continuing but decreasing growth in the number of families in Copenhagen as seen in Figure 2.3, where the distribution amongst different types of families is also illustrated. It is noted that the forecasts are described as having many uncertainties.

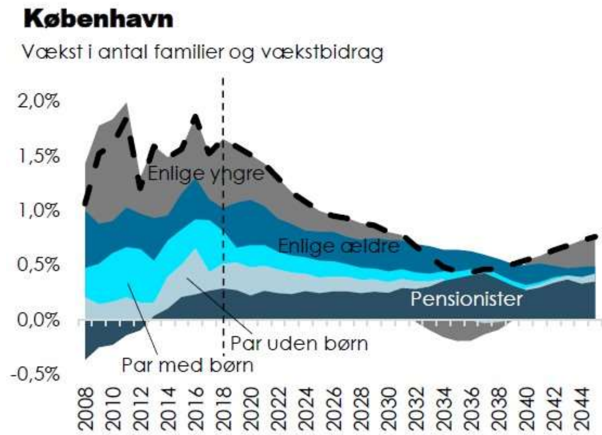

Figure 2.3: Yearly growth in the number of families in Copenhagen. Figure from (Næss-Schmidt, Heebøll, & Kilsdal, 2018). Sources: Statistikbanken and Copenhagen Economics. Translations: "Enlige yngre" = Youth singles, "Enlige ældre" = Elder single, "Par med børn" = Couples with children, "Par uden børn" = Couples without children, "Pensionister" = Retired people.

In Figure 2.4 the predicted future needs for housing is illustrated. It shows that there is a need for different sizes, but the largest group is 80-119 m^2.

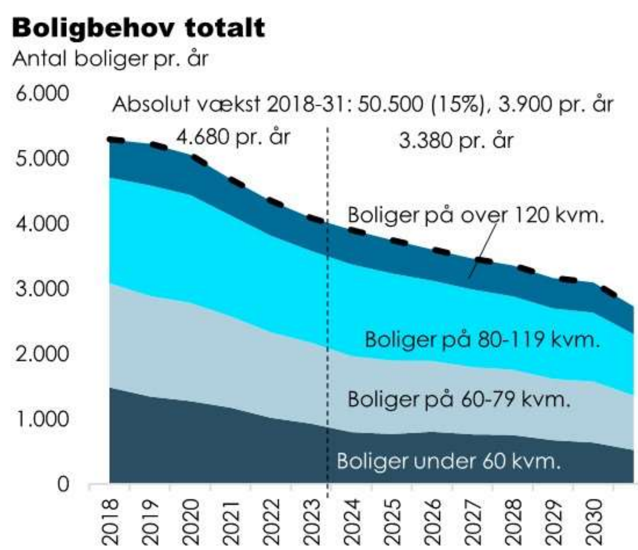

Figure 2.4: The predicted housing needs per year in Copenhagen. Figure from (Næss-Schmidt, Heebøll, & Kilsdal, 2018). Sources: Danmarks Statistik and Copenhagen Economics. Translations: “Antal boliger pr. år” = Number of dwellings per year, “over” = above, “under” = below, “absolut vækst” = absolute growth.

The supply of small housing below 60 m^2 is lagging behind (Næss-Schmidt, Heebøll, & Kilsdal, 2018) and therefore one of the focuses in the Municipal Plan (City of Copenhagen, 2020) is to construct a certain amount of small housing.

Based on the different background analyses the Municipal Plan 2019 has been worked out with different goals, where some of them are (City of Copenhagen, 2020):

- "To ensure room for building up to 60,000 new homes by 2031".
- "To create the framework of 12,000 units of new youth housing, of which 7,500 should be nonprofit, by 2031" (size between 25 - 50 m^2).
- "To build housing for families with children, couples without children, singles and seniors and socially at-risk inhabitants and that variation in housing size and type is ensured in the various neighborhoods".

Beside ensuring 20% of new housing are small youth housing, the municipal plan also focus on creating a variation in the sizes and types of housing in the different areas, which is also suggested by Claus Bach-Danielsen et al. (Bech-Danielsen, Mechlenborg, & Stender, 2018).

Main points

The conclusion and main points that can be drawn from this analysis from Copenhagen is that a change in the size of housing in Copenhagen is seen over the last 20 years. Both a change in supply and demand and that supply and demand does not always fit. For example, a higher demand for larger apartments has resulted in merging of small apartments. This has resulted in fewer small apartments even though demands for small apartments still exist. Because of that, the Municipal Plan for 2019 provides better circumstances for small dwellings to be constructed than the previous Municipal Plans have done. Therefore, it is expected to see an increase in the number of small dwellings in Copenhagen in the near future. But as history describes the need for small and large housing has changed and will probably still do in the future.

2.4 Renovation and transformation

In Denmark around 2.7 mio. housing exists and each year around 1% of our housing stock is renewed (Bech-Danielsen, Mechlenborg, & Stender, 2018). To keep the existing housing stock up to date with our changing needs and requirements and to prolong the lifetime when some of the building parts are worn, a lot of renovations and transformation of existing buildings take place.

In the interview with Claus Bech-Danielsen, he was asked about the development and trends for renovations.[7] According to Claus Bech-Danielsen the existing mass of buildings has changed dramatically over the years, both single-family houses and multi-story residential buildings. As an example, he mentioned an area existing of 120 single-family housing, which he has been following. They were originally constructed completely identical, but today they are very different due to many kinds of renovations and additions to the original buildings. The houses in the area are so different today, so even Claus Bech-Danielsen in the beginning had difficulties realizing that they had once been identical, he said. Claus Bech-Danielsen explained some of the comprehensive renovations in housing with the reason that people to a high extend identify themselves with their homes and many renovations are done due to

[7] The interview is further described in Section 5.3.

lifestyle preferences. With respect to transformations of the rooms, houses typically follows the changes in the family patterns, like having kids, the kids moving out of the house, the parents get divorced, etc. But transformations also take place due to a change in the trends, for example kitchens opening up, bathrooms getting larger and trends of establishing outdoor kitchens.
Claus Bech-Danielsen furthermore talked about the renovations in social housing. Those renovations have gotten more and more comprehensive over the years. The renovations are mainly paid by The National Building Fund and the main reasons for renovations are due to technical issues in the construction and the occupier composition. As part of these renovations dwellings are also combined, as some of the old dwellings are too small for the needs of today.

To quantify some of the statement from Claus Bech-Danielsen about comprehensive renovations in houses and residential buildings, Figure 2.5 from a questionnaire analysis (Realdania & Videncentret Bolius, 2020) is shown. The analysis is based on 7,158 interviews among Danish persons above 25 years. The figure shows that in one year 4.7 % have changed the spatial design of the housing, 4.0 % have removed one or more walls, 4.0 % + 3.7 % have added one or more rooms. However, some of those replies can be from the same person/household, thus they cannot be summarized.

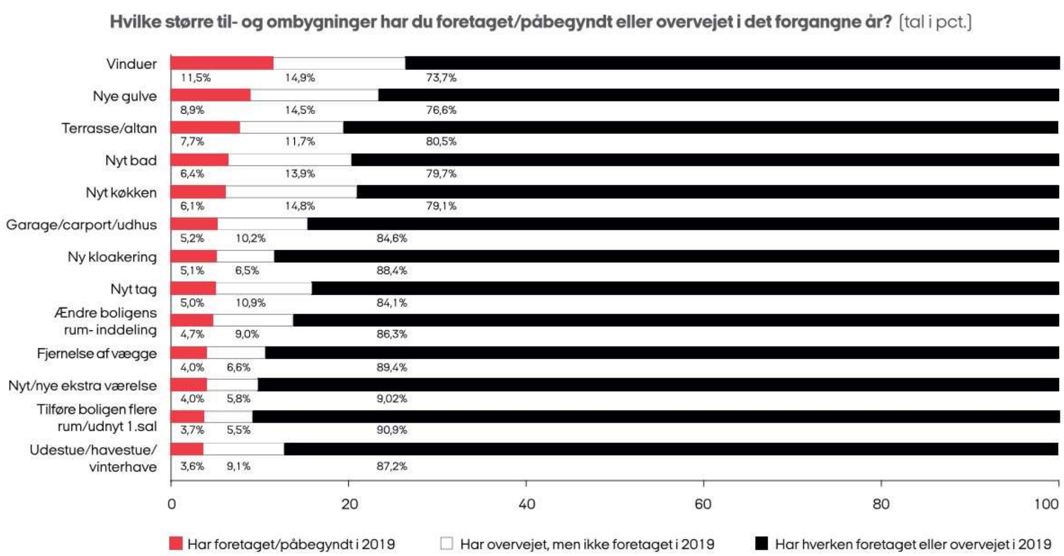

Figure 2.5: Replies for the question "Which larger renovations have you completed/started or considered during the last year?" Red: Have completed/started in 2019, white: Have considered but not begun in 2019, black: Have neither considered nor started in 2019. From (Realdania & Videncentret Bolius, 2020). Translations from the top row in the figure and down: Windows, new floors, terrace/balcony, new bathroom, new kitchen, garage/carport/annex, new drainage, new roof, change in the spatial design, removing walls, new extra rooms, add more rooms to the housing/further use first floor, conservatory/winter garden.

Different reasons for renovation and different types of renovations exists. In this report a distinguish between three main types of renovation is made. One type of renovation does not exclude the other.

- Maintenance renovations - renovation of interior and exterior, which does not affect the energy consumption in the future nor the room division. This can e.g. be renovation of the bathroom, kitchen, facade cladding and so on.
- Energy renovations - renovations of the facades, roof and installations to decrease the energy consumption and improve the indoor environment
- Transformation renovations - renovation of the building to change the use of it. This can e.g. be changing the room number and size, or build additions to the building.

In this project, transformation renovations of buildings are of interest. Transformation of a building can have many different faces. It can be withing the same type of use, but with new use of the rooms, e.g. housing where the number and size of rooms are changed. It can also be a change in the type of use, e.g. if an office building is changed to housing or the opposite.

Renovate or build new

When the use of a building is to be changed, one can chose to demolish the existing building and construct a new one or to renovate the existing building. The main aim of the modifiable structural system in this PhD project is to enable easier transformation of buildings made of concrete, to avoid tearing down the buildings in the future. Other factors, than the structural system, are also driving the decisions of whether to renovate or demolish and build new. Some of those factors are identified in the following.

According to Claus Bech-Danielsen, in single-family houses people's lifestyle preferences are often determining for the choice of tearing down a house. If they find the right construction site but with an old house that does not suit their style or preferences, some people would tear down a building for those reasons and build the exact house that suits their preferences.
In the interviews Claus Bech-Danielsen and the researcher and architect Vibeke Grupe Larsen, both say that architectural quality is one of the most important factors determining the choice of demolishing a building or renovating it. Not only the aesthetic quality is meant, but also the spatial design and the materials. Also, the focus on sustainability, the indoor climate and the economy is mentioned in the interviews as determining parameters. According to the Michael Hansen from PFA real estate, the economy is the main determining factor when deciding whether to renovate an existing building or building a new one.[8]

Renovations and sustainability

One of the factors that can determine the choice of renovation compared to constructing a new building is sustainability. In a report from Rambøll (Sørensen & Mattson, 2020) an analysis of energy renovations is made. In the analysis there are 16 cases of buildings, which each undergoes four scenarios: Three different energy renovations scenarios and one scenario of demolishing the whole building and build a new one. For each scenario an LCA analysis (life cycle analysis - here with CO_2) and an LCC analysis (life cycle costs) are made for a period of 50 years. The three energy renovation scenarios represent three different levels of renovations:

- Level 1: Renovation of the roof.

[8] See the interviews in Section 5.3.

- Level 2: Renovation of the roof and external walls and windows.
- Level 3: Renovation of the roof, external walls and windows, and installations.

The 16 cases represent different types of buildings, including single-family houses, townhouses, multi-story residential buildings, commercial buildings and public buildings.
The analysis shows that for all cases the most optimal scenario both with respect to CO_2-emission and the cost over the 50 years period, is one of the renovation scenarios (in most cases renovation level 2 or 3), (Sørensen & Mattson, 2020).
Figure 2.6 shows an example of a case for a multi-story residential building. The blue part of the columns shows the CO_2-equivalent for operational costs, while the grey part shows the CO_2-equivalent related to the building material. The red triangles show the life cycle costs (LCC) for the scenarios. Both the CO_2-equivalents and the costs are calculated for a period of 50 years.
The figure shows that when constructing a new building the CO_2-emission related to the building materials are substantially higher than for the renovation scenarios and so are the costs. The report illustrates that for many cases it is cheaper both with respect to CO_2 and money to renovate than to build new.

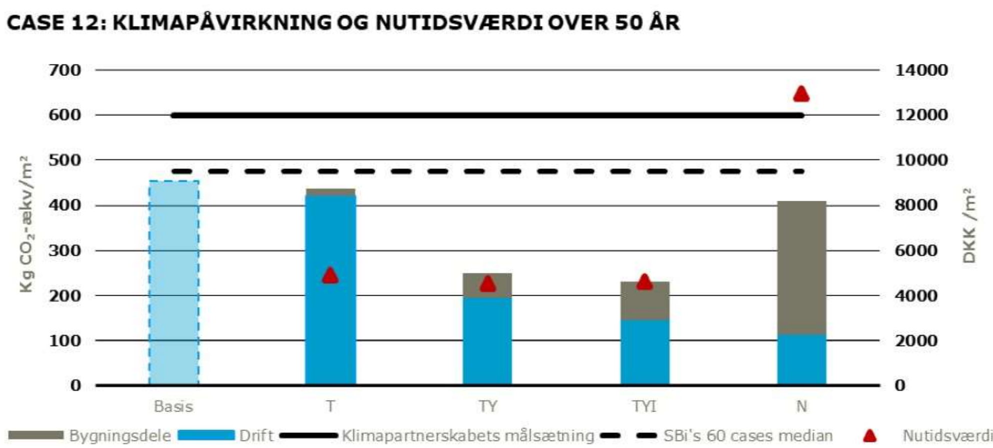

Figure 2.6: Example of a case from (Sørensen & Mattson, 2020) for multi-storey housing. Basis: If nothing is done, T: Level 1 renovation, TY: Level 2 renovation, TYI: Level 3 renovation, N: build new. Figure from (Sørensen & Mattson, 2020). Relevant translations: "Bygningsdele" = building components, "Drift" = operation, "Nutidsværdi" = present value.

The report (Sørensen & Mattson, 2020) only investigate energy renovations, but it helps quantifying the CO_2-emissions and costs in different renovation scenarios compared to building new buildings. It indicates that the costs and CO_2-emissions are substantially higher when building new buildings then when renovating.
This pattern must be the same for transformations. Of course, it depends on the degree of transformation. If only one wall must be removed, it is obvious that it is most optimal to renovate and not tear down the whole building and build everything from new. If the existing

building structure is of very poor condition and the new use requires a substantial change in the existing structures and materials, one can imagine cases where it is more optimal with respect to cost and/or CO_2 to build a new building.

With an increased focus on the sustainable agenda, one might imagine a larger focus on renovation of the buildings in the future. If preparing the buildings with flexible solutions that enables easier transformations, then CO_2 savings, cost saving and thereby incentives to renovate compared to building new must be increased.

3. Sustainability in buildings

The building sector accounts for 38% of the global CO_2-emissions. 28% comes from operation of the buildings and 10% from the materials and construction of the buildings, referred to as embodied carbon (United Nations Environment Program, 2020).
In Denmark, the building sector accounts for 30% of the total CO_2-emissions (DI Dansk Byggeri, 2021). A focus in Denmark the last decades has been on reducing the energy from operation of buildings, for example through the building regulations. Therefore, the embodied carbon accounts for a larger part of the CO_2-emission in the building sector in Denmark than globally. Around half of the carbon emissions from the building sector in Denmark comes from the materials and construction of the buildings (Green Building Council Denmark, 2021).

Production of concrete is very energy demanding due to the content of cement, which emits a significant amount of greenhouse gasses in the production. The cement and concrete industry currently account for approximately 8 % of global CO_2-emissions according to the road map from *Bæredygtig Beton Initiativ*[9] (Thrane, Andersen, & Mathiesen, 2020). According to the road map the Danish concrete industry is committed to halving its CO_2-emissions by 2030 compared to 2019 levels. Different initiatives and tools are implemented in the building industry to help motivate the conversion towards more sustainable buildings. Some of the tools are certification systems for sustainable buildings. Many different sustainability certification systems exist around the world. In Denmark the most used ones are *DGNB* and *Svanemærket* (Dyck-Madsen, Pedersen, & Jarby, 2020) and in 2020 the *Danish Voluntary Sustainability Class* is introduced together with future requirements in the Danish building regulations from 2023. Some of these certification systems are described in the following sections.

3.1 Life Cycle Analysis

In most certification systems it is a requirement to perform a *Life Cycle Analysis* (LCA)[10]. LCA is a method for calculating the environmental impact over the lifetime of a building. Starting from mining of the minerals for the construction materials, including transport, construction, operation, maintenance, and deconstruction of the building, as illustrated in Figure 3.1. To ensure the analyses to be comparable, 50 years is chosen as standard for the analyses in Denmark (Kafani & Birgisdottir, 2021). This does not mean that the building can only last for 50 years, but it is chosen for the calculations to be comparable.

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[9] Sustainable Concrete Initiative, which is an initiative launched in 2019 by the Danish Concrete Industry Association *Dansk Beton.*

[10] It is not a requirement in Svanemærket.

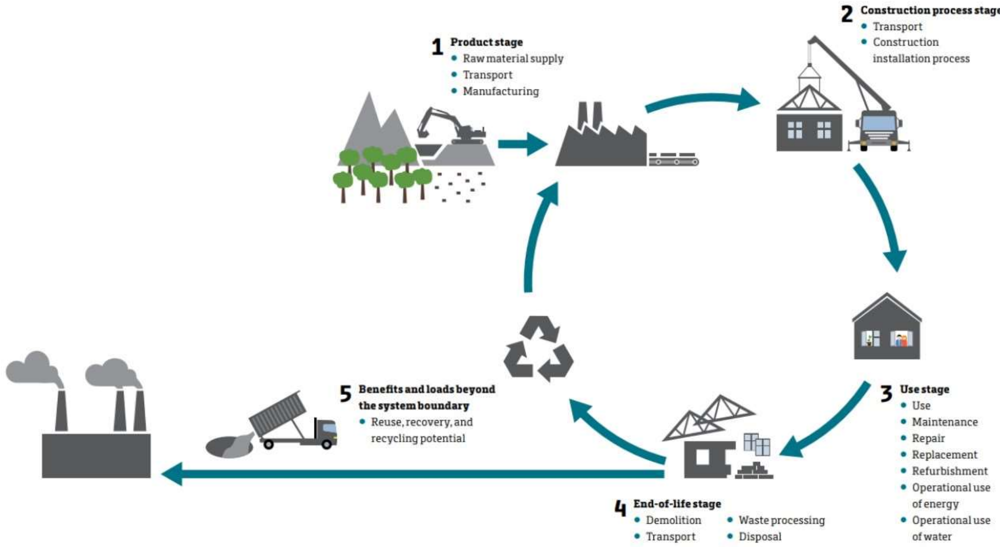

Figure 3.1: Illustration of the life cycle stages. Illustration from (Birgisdottir & Rasmussen, 2016).

The result of a Life Cycle Analysis can be calculated using a selected range of measurable indicators. One of the most used indicators is the Global Warming Potential measured in CO_2-equivalents. CO_2-equivalent is a measure for different greenhouse gasses, which influence the global warming. They are all converted to be comparable to the emission of CO_2 (Birgisdottir & Rasmussen, 2016). In this report, as in most of the industry, CO_2-equivalents are simplified referred to as CO_2. However, one should be aware that there are other indicators that measures the environmental impact of buildings. Thus, initiatives that saves a significant amount of CO_2 can have less or maybe negative impact on other environmental aspects.

In Figure 3.2 a schedule illustrating the stages in LCA, as defined by European standards, is shown. Not all stages are included in LCA analyses. In the DGNB certification system the stages A1, A2, A3, B4, B6, C3 and C4 are included.

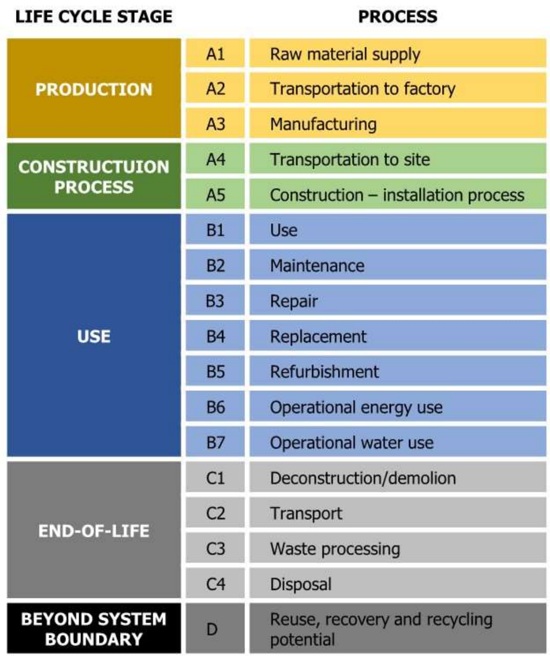

Figure 3.2: Life cycle stages as defined in (Birgisdottir & Rasmussen, 2016), following European standard EN 15978:2011.

A Life Cycle Analysis can be used in e.g. the early design phase of a building project to identify and quantify the impact of each stage of the buildings life cycle and evaluate different solutions. It can also be used to evaluate if the CO_2-emissions for the 50 year period is below a certain target.

3.2 DGNB certification system

DGNB is a German certification system, which has been translated and fitted to the Danish regulations and traditions. The certification system in Denmark is controlled by the non-profit member organization Green Building Council Denmark.
Detailed information about the DGNB certification system in Denmark for new buildings or extensive renovations of buildings is found in the DGNB manual (Green Building Council Denmark, 2020,1) and the DGNB guide (Green Building Council Denmark, 2020,2).
The DGNB certification system evaluates a new building or renovation project within the following 6 topics, with the weights as described:

- Environmental quality - 22.5 %
- Economic quality - 22.5 %
- Sociocultural and functional quality - 22.5 %
- Technical quality - 15 %
- Process quality - 12.5%
- Quality of the area - 5 %

The projects are evaluated with points for different criteria within each main topic. The project ends up with a total score measured as a percentage of the highest possible score. Depending on the score, the project is assigned a silver, gold or platin DGNB certification. To get a balanced project within the 6 main topics, a minimum score for each topic is also required. See the overall requirements for the different DGNB certificates in Table 3.1.

DGNB certificate	Total score	Within each topic
Silver	50 %	35 %
Gold	65 %	50 %
Platinum	80 %	65 %

Table 3.1: DGNB certification minimum requirements

There are 36 different criteria in the certification system distributed amongst the different topics. Few of them are described in the following, as they are relevant for the modifiable structural system.

ENV 1.1 Life Cycle Analysis - 9.5 %

This criterion can obtain a total of 9.5 %. Credits in this criterionare e.g. given for an early inclusion of the LCA results in planning of the project and by comparison of the results with reference values for similar buildings.

ECO 1.1 Life Cycle Cost - 9.6 %

The aim of this criterion is to motivate for a conscious use of economical resources throughout the whole lifetime of the building. The criterion evaluates the life cycle costs (LCC) for the buildings. Credits are given if LCC is performed early in the project and compared with alternative solutions. Furthermore, the LCC result is compared with a reference value.

ECO 2.1 Flexibility and adaptability - 6.4%

The aim of this criterion is to make the building’s design as flexible as possible and creating the greatest possible potential for conversion, to secure the longest possible lifetime of the building.
In the DGNB guide (Green Building Council Denmark, 2020,2) the relevance of the flexibility and adaptability criterion is described by the following[11]: "The technical and social developments means that work, housing and living conditions changes. For the same reason buildings should not only be efficient and flexible now, but they should have the possibility of transformation for another use later in its lifetime to optimize the users accept, the lifetime of the building and life cycle costs. Therefore the criterion is focusing on the effectiveness and flexibility of the building." The criterion is evaluated from different checks, including the geometry of the building such as floor height, the depth of the building, access roads, flexibility of the building structure and flexibility of the mechanical installations such as the ventilation, cooling, heating and water systems.

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[11] Translated from Danish by Sara Sofie Vestergaard

In the DGNB manual (Green Building Council Denmark, 2020,1) the future development of the criterion is described by the following[12]: "There is an increasing attention towards the essentiality of the flexibility and adaptability of a building, and perhaps further and other methods to assess this criterion will come."
The three criteria described above (EVN 1.1, ECO 1.1 and ECO 2.1) can all be affected by the use of the modifiable concrete walls. As seen from the flexibility criterion the overall flexibility of the building is affected by many other parameters than flexibility in the structure and it emphasis the importance of the overall building design to gain as much as possible from the flexibility in the structure.

3.3 Regulations from the Danish government

The Voluntary Sustainability Class[13] is a Danish sustainability class introduced in May 2020. Information about the sustainability class is found in the guide for the class (Trafik-, Bygge- og Boligstyrelsen, 2020), a note about the class (Dyck-Madsen, Pedersen, & Jarby, 2020), and a talk with a sustainability consultant Christine Collin from Rambøll.[14]

The Voluntary Sustainability Class is voluntary in a testing period. It will be evaluated regularly and perhaps introduced as a requirement in the Danish Building Regulations in the future.
The aim of the sustainability class is to include the three sustainable qualities: The environmental and climate qualities, the social qualities and the economical qualities. It is meant to be more simple and cheaper to adapt to than the DGNB system, to appeal to a wider range of building owners and to make it affordable for small buildings as well (Dyck-Madsen, Pedersen, & Jarby, 2020). The sustainability class consist of nine different requirements, which should all be fulfilled in order to comply with the class. The nine requirements are listed in the following:

1. Life Cycle Analysis
2. Documentation of the used resources on the site - such as transport, energy and water consumption
3. Life Cycle Costs
4. Plan for operation and maintenance to sustain a good indoor climate
5. Documentation of materials with problematic chemicals
6. Indoor degasification - requirement for max indoor levels of formaldehyde and TVOC[15] before occupancy
7. Detailed analysis of daylight
8. Noise from ventilation - max requirements in housing
9. Acoustics in housing - requirements for reverberation time in housing

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[12] Translated from Danish by Sara Sofie Vestergaard
[13] *Den frivillige bæredygtighedsklasse* in Danish.
[14] January 2021.
[15] Total Volatile Organic Compounds

The Life Cycle Analysis (LCA) must be performed before application for the building permit and again after completion of the building to assess the total climate impact of the building. The Life Cycle Analysis should include the following processes from Figure 3.2: A1, A2, A3, A4, A5, B4, B6, C3, C4 and D, where A4 and A5 (the construction process) and D (reuse, recovery and recycling potential) are new for the industry and is not included in DGNB system yet.

The sustainability consultant Christine Collin was asked if she believes that the Voluntary Sustainability Class will replace DGNB in Denmark. For that she replied no, because the Voluntary Sustainability Class is not as comprehensive as DGNB, but that it will help more stakeholder to start working with sustainability analysis.

CO_2 requirements

To apply with the Voluntary Sustainability Class there are no requirements for the maximum level of CO_2-equivalents in the LCA yet (it will be introduced from 2023). However, there are some reference levels from 60 building cases analyzed in a report from SBi (Zimmermann, Andersen, Kanafani, & Birgisdottir, 2020). The 60 cases includes different types of buildings, including office building, multi-storey residential buildings, townhouses, single-family houses and other buildings. The (lower quartile/median/upper quartile) for the CO_2-equivalents for a 50 year period for the 60 building cases is found to (8.5/9.5/10.6) kg CO_2e/m^2/year.[16]

In March 2021 the Danish government landed a wide agreement across Danish parties for a national strategy for sustainable buildings (Indenrigs- og Boligministeriet, 2021). They agreed upon introducing a requirement in the Danish Building Regulations for the level of CO_2-equivalents in buildings from 2023.

This means that from 2023 a CO_2 limit for buildings above 1000 m^2 is introduced. The limit will be 12 kg CO_2e/m^2/year and the value will be stepwise decreased in the years 2025, 2027 and 2029.

For buildings below 1000 m^2 a requirement to perform LCA calculations is introduced from 2023, but a CO_2 limit is not introduced until 2025.

For the Voluntary Sustainability Class a CO_2 limit on 8 kg CO_2e/m^2/year is introduced from 2023. This means that the sustainability class will still be voluntary, and the CO_2 limit for this class is lower than in the Danish Building Regulations.

[16] Including the processes A1-A3, B4, B6, C3-C4 from LCA

4. Technical requirements

When developing a flexible structural system an alternative to the modifiable concrete wall could be a frame structure with some kind of lightweight material for separation of the rooms.
Depending on the function of the wall, there are some technical requirements that needs to be fulfilled, like sound insulation and fire insulation.
In this section, the requirements are outlined. The requirements are examined for a wall between two dwellings to keep it simple. It is compared what it takes to fulfill those requirements for a concrete wall and some alternatives.

4.1 Sound insulation

Acoustic requirements are often determining the thickness of the structures used for separation.[17] In this section the requirement for airborne sound insulation in walls between two dwellings and the necessary thickness of the walls to fulfill those requirements are outlined.
This section is primarily based on the following sources:

- Danish Building Regulations, BR18 (Danish housing and planning authority, 2018).
- DS 490: Sound classification of dwellings (Dansk Standard, 2018).
- SBi-instructions 237: Sound insulation between dwellings - new buildings (Rasmussen, Petersen, & Hoffmeyer, 2011)[18].
- Henrik Ravn, Rambøll (a specialist in acoustics and noise in buildings). Conversation in January 2021.

According to the Danish Building Regulations BR18 (§369) dwellings and other buildings used for overnight stays must fulfill class C in DS 490 (Dansk Standard, 2018) for acoustics.
For class C the minimum requirement for airborne sound insulation between two dwellings is:

$$R'_w \geq 55db \tag{4.1}$$

Thus, a wall that separates two dwellings must fulfill this.
For lightweight walls, a supplement for the requirement is recommended (but not a requirement). The reason explained in BR18 is that lightweight walls with the weight below 100 kg/m^2 can have insufficient sound insulation for low frequency sounds, even though the requirements for (4.1) is fulfilled. For lightweight walls it is recommended to fulfill:

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[17] From conversation with Henrik Ravn, specialist in acoustics and noise in buildings, Rambøll

[18] SBi instructions (SBI-anvisninger) are technical building instructions that explains how to build according to applicable laws and regulations.

$$R'_w + C_{50-31} \quad \geq 53db \tag{4.2}$$

where $C_{50-3150}$ is a correction, which in SBi 237 is stated to be around $C_{50-3150} = -10$ dB in many cases. This corresponds to a recommendation for lightweight walls at approximately:

$$R'_w \geq 63db \tag{4.3}$$

According to Henrik Ravn most lightweight walls just fulfills the requirement in (4.1) and not the additional recommendations in (4.2), due to very tight budgets in housing constructions. This results in a worse acoustic for the low frequency sounds and according to Henrik Ravn it makes a difference for the experience of the residents. For example, the noise from a party at the neighbor will sound louder if going through a lightweight wall that meets the requirements in (4.1) than a concrete wall that meets the same requirements.

Wall thickness

According to SBi 237

SBi 237 (Rasmussen, Petersen, & Hoffmeyer, 2011) has got some instructions for how to build to meet the requirements for sound insulation in dwellings. In the instructions, examples for different construction types are analyzed. In Figure 4.1 some of the examples for walls are illustrated.

Figure 4.1 shows that the concrete wall should as minimum be 185 mm thick to fulfill the requirements (4.1) in the example, the lightweight concrete wall should be 220 mm thick, while the plasterboard wall on a steel framework has got the thickness of 265 mm to fulfill the supplements to the requirements in (4.2). The examples are based on certain assumptions for the rooms and the surrounding structures, but they can be used to illustrate a comparison between a concrete wall and a lightweight plasterboard wall. It is noted that there might exist solutions for lightweight walls that fulfills the same sound insulation with a lower total thickness than the examples illustrated in SBi 237.

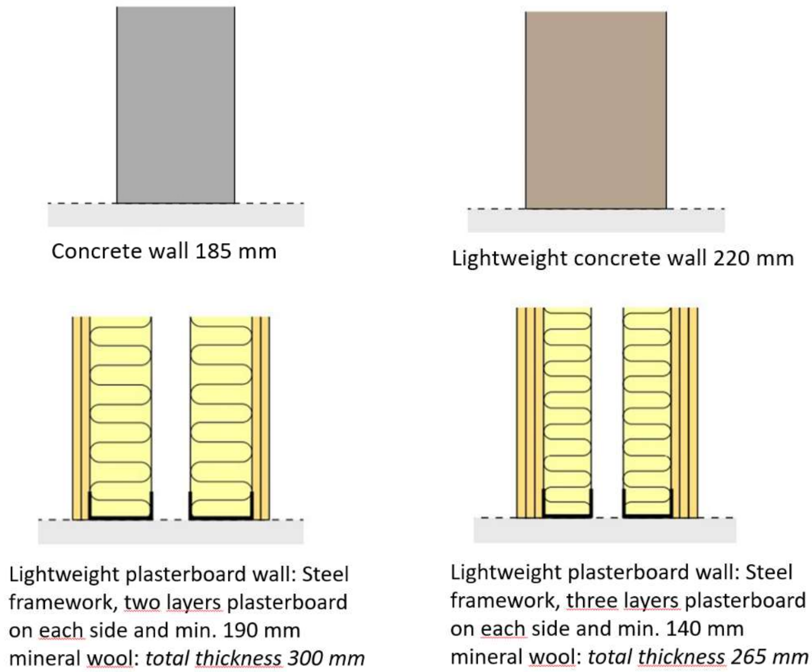


Figure 4.1: Wall types - examples of walls between dwellings that expects to fulfill the requirements and recommendations for sound insulation, according to SBi 237. The wall types are found under certain assumptions for the adjacent walls, floor slabs and room size. Therefore, the examples should not be used without further analysis of the actual rooms. Figures are from SBi 237 (Rasmussen, Petersen, & Hoffmeyer, 2011).

Practical experiences

Henrik Ravn, who is specialized in acoustics in buildings, told about what thicknesses that are used for concrete walls and lightweight walls between two dwellings in practice.
For concrete walls, the thickness used due to sound insulation is 200 mm. This is higher than the 185 mm from the example in SBi 237. He said that the budget for residential buildings are often very tight. Therefore, the budgets do not allow time calculations and optimizations of the wall thickness, to account for different room size and other factors that affects the acoustics. From practical experience, a thickness of 200 mm concrete has proven to meet the requirements in most cases. According to Henrik Ravn, there exist plasterboard walls, which meet the requirements with a total thickness of 230 mm. This however just meets the requirement in (4.1) and not the additional recommendations in (4.2) for lightweight walls. Therefore, the 230 mm plasterboard wall will perform worse than a 200 mm concrete for low frequency sounds.
Some manufacturers state that they can produce lightweight walls with a thickness of 200 mm with a sound insulation of 53 dB. However, there are many uncertainties of those walls, so if using them it is recommended to test the sound insulation of the wall in the actual building before installing all of them.

Development of the acoustic requirements

The requirements for sound insulation between dwellings have developed through the years with an increase in the requirements. The latest adjustments in the regulations were in 1995 where the requirement for airborne sound insulation horizontally between dwellings were set to 52 dB and in the building regulation from 2008 this value was increased to the current at 53 dB.
Henrik Ravn was asked if he expected any further increase in the requirement in the future. He said that with the increased focus on sustainability, an increase in the use of lightweight structures like wood will probably be seen. Therefore, he could imagine that the recommendation in (4.2) for lightweight walls will turn into a requirement, to improve the sound insulation for lightweight walls for low frequency sounds.
He do not expect an increase in the near future for the requirement for heavy walls like concrete, but he sees a trend that some developers wants to live up to higher sound insulation class (like class B) than required. One of the reasons for this is that acoustics also count in the DGNB certification system.

4.2 Fire

In this section it is examined how to meet the fire safety requirements in a wall separating two dwellings. The section is based on the following sources:

- Danish Building Regulations, BR18 (Danish housing and planning authority, 2018).
- Jonathan Dahl Jørgensen, Rambøll (a specialist in fire safety in buildings). Conversation in February 2021.

The fire resistance of a structure can be divided into the following criteria:

- *R*: The load bearing criterion
- *E*: The integrity criterion - whether the fire can penetrate the wall
- *I*: The insulation criterion - heat insulation

As an example R 60 means that the structure should have sufficient load bearing capacity after 60 minutes of fire exposure.

If the wall is a load bearing wall all three requirements *REI* are set, and if the wall is not load bearing, only the requirements for *EI* are set.

The load bearing requirements under fire are not relevant for comparison of the thickness of a concrete wall with a lightweight plasterboard wall, as the lightweight plasterboard wall will not be load bearing in itself. Therefore, only the fire insulation requirements are outlined.

Fire insulation requirements

An apartment in a residential building is typically defined as a fire cell. There are no *EI* requirements for walls internally in a fire cell. For walls between two fire cells in a building (between two dwellings), the requirement are *EI 60* in all cases.

Wall thickness

To fulfill the *EI 60* criterion a concrete wall should have the following minimum thickness (Danish Standards, 2008):

$$80 \text{ mm}$$
$$\text{or } H/40$$

where *H* is the free height of the wall. If for example a wall is 3500 mm high, $H/40 = 88$ mm. Both cases are way below the thickness on 200 mm from to the acoustic requirements.

Most lightweight walls with plasterboards that fulfills the acoustic requirements on 53 dB also fulfills the fire criterion *EI 60*.

Development of the fire requirements

According to Jonathan Dahl Jørgensen the requirement for *EI 60* has been the same since it was first introduced to the Danish Building Regulations. He does not think that they will be more strict in the future, as the requirements has proven to be satisfactory in real fire cases.

4.3 Heat accumulation

Concrete has a good ability to accumulate heat due to its high thermal mass. Compared to a lightweight structure with a lower thermal mass, an advantages of concrete structures is the ability to reduce the variation of room temperatures and create a more uniform indoor climate, but also to reduce the requirements for heating and cooling (Miljøstyrelsen, 2007).
There is no direct requirement for heat accumulation or thermal mass of a building in the Danish Building Regulations, but there are requirements for the energy used to heat and cool buildings.

In a report from the Danish Environmental Protection Agency (Miljøstyrelsen, 2007) it is assessed how the thermal mass of concrete affects the need of energy used for heating. The cases used for calculations are an office building and a single-family house.
The report (Miljøstyrelsen, 2007) shows that using a heavyweight structure of concrete compared to a lightweight structure with wooden floors and plasterboard walls, reduces the energy needed for heating between 11% and 13% for the office building and between 4% and 10% for the single-family house. The span of the results are due to different kinds of calculation methods used.
Besides reducing the energy required for heating, the report (Miljøstyrelsen, 2007) also shows that a heavy structure with a high thermal mass also reduces the overheating issues, which provides more comfort to the user and a lower need for cooling systems.

4.4 Summary

As seen from above, the acoustic requirement for the airborne sound insulation in walls between two dwellings are typically determining for the thickness of the wall, both in the case of a concrete wall and lightweight plasterboard wall. When designing a residential building, the typical thicknesses of walls between two dwellings are:

- Concrete wall: 200 mm
- Lightweight wall[19]: 230 mm

When comparing the concrete wall and the lightweight wall for the above thicknesses, the concrete wall performs better with respect to the sound insulation for low frequency sounds. Perhaps the supplement to the sound insulation requirements for lightweight walls will become a requirement in the future, and if so the thickness of the lightweight plasterboard wall will become thicker to meet the new requirements. In the example in SBi 237 a 265 mm wall is necessary to fulfill the supplemented recommendation for lightweight walls, which might become a requirement in the future.
In the meantime, perhaps technical developments in the future can result in better acoustic solutions for lightweight walls, reducing their thickness.
The thickness of the wall is of course not the only parameter that determines which solution for the structural design that is chosen, but it is a parameter that can influence the choice.

Beside the good acoustic properties of a concrete wall, it has also got a high thermal mass, which at the end can safe some energy for heating when comparing to lightweight structures, and also increases the comfort in the building due to less temperature variations.

This section has shown some benefits of using load bearing concrete walls compared to a load bearing frame structure with lightweight walls. Other considerations also have to be taken into account when choosing the structural system. These are e.g. considerations of the flexibility of the system, the cost, the architecture, lifetime of the materials and the environmental impact in the production of the materials.

[19] Plasterboards covering a steel frame with insulation

5. Flexibility in buildings

Before developing a new flexible structural system, some more background knowledge about the demand for flexible structures and existing solutions are of interest.

It is found from many different sources that it is important to think flexibility into the buildings, to allow the circular use of buildings and saving material in the long run. To further illustrate the wide interest in flexible structures some of the quotes from around the building sector are shown here.

Dan Stubbergaard, architect and founder of Cobe, is interviewed in the Magazine PLATFORM (Plum, 2020) to talk about how they work with sustainability in buildings. In the interview he says:
"A building must be passed on to the future generations. Therefore, it is of high importance, that a house is not a static thing. It must have the ability to be transformed, so you don't have to tear it down to build something new. What must not happen, is that we build something that cannot be transformed or is of such low quality, so that we need to tear it down".[20]

In an interview regarding the recommendations from the climate partnership on how to reduce CO_2 in the construction industry (Hansen, 2020), Michael H. Nielsen, director of *The Danish Construction Federation*[21], is asked about how reuse of construction waste can be optimized. As part of his answer he says:
"But it also addresses to create less construction waste by transforming buildings, so instead of building new and tearing down, we are making building structures which can last longer and change its function; perhaps a school is transformed into a nursing home, which is later transformed into youth housing. If possible, we can use the "body" of the building with its original materials and adjust the interior of the building. Instead of an 80 year lifespan, it can suddenly last for 160 years or more. This provides a significant reduction in the CO_2 footprint".[22]

In an analysis of small housing made for Copenhagen Municipality (Arkitema, 2018) the following is written about flexibility in small housing:
"It is always a challenge to optimize and pack the functions dense and at the same time maintain a certain degree of flexibility in the building structure, so the building in the future can be transformed into larger dwellings. Depending on each project, the future flexibility can be incorporated early in the process, so merging of dwellings is regarded. In that regards especially the shaft and window location is of huge importance, like an increase in the floor height can provide room for installation and thereby open up for other functions than the dwellings are originally designed for".[23]

[20] Translated from Danish by Sara Sofie Vestergaard.

[21] DI Byggeri.

[22] Translated from Danish by Sara Sofie Vestergaard.
[23] Translated from Danish by Sara Sofie Vestergaard.

The above three quotes about flexibility and transformation of buildings illustrates that flexibility is on the agenda in the building sector. The quotes address that flexibility can help reducing the CO_2 footprint, they address some cases for transformation, and that it is important to incorporate the flexibility early in the design phase.

Flexibility in buildings can have many different faces. It can be flexibility in the daily use of the building, where some areas are flexible to use for different purposes during day. This mainly requires architectural quality and flexibility in the interior design or some kind of walls that can be modified from day to day. It can also be flexibility in the building structure, which is of interest in this project, which allows changes in the structure to meet new functional requirements in the future, like openings of the walls or slabs. Flexibility in the building structures can also provide flexibility in the design phases to allow changes in the design before the building is constructed. In a book by CINARK[24] with the title *Three ways of assembling a house* (Beim, Nielsen, & Vibæk, 2010) the types of flexibility in a building are defined by the following:

- *Design flexibility:* Refers to flexibility in the project design phase and is primarily used by professionals.
- *Conversion flexibility:* Refers to the possibility of subsequent conversion or modification of the spatial organisation and is used by professionals as well as the residents.
- *Flexibility of use:* Refers to a 'real time' flexibility integrated in a project by the designer/architect and used by the end user. This is e.g. flexibility in the use during the day.

In this project design flexibility and conversion flexibility are of interest, as the structural system of a building affects those two types of flexibility.
Flexibility can be defined on different levels: housing level, building level and even city level. In this project flexibility on the housing level and building level are of interest. When talking about flexibility, you can also talk about for whom the flexibility is meant. This can for example be the end user or professionals like the architect, engineers or building owners.

To look into different methods of applying flexibility in a building system and learn from previous experience, the following Section 5.1 is outlining different ways of designing flexible systems based on actual cases, and discussing pros and cons of different systems. It furthermore provides a discussion of which parameters that makes a structural system succeed and survive in the market.
Section 5.2 shows three cases where flexibility in the walls has been used, to illustrate cases where the modifiable walls in the PhD project could had been relevant. After that, Section 5.3 provides interviews of stakeholders from the building sector to further examine the focus on flexibility and sustainability, and to get some feedback on the idea of the modifiable walls.

[24] Centre for Industrialised Architecture at Royal Danish Academy

5.1 Industrial building systems

As described in Section 2.1 the industrialized construction technologies that were developed from the 1950s, were developed to rationalize the production and construction methods to enable the construction industry to follow the high demand for housing and to keep the housing affordable. In this section, the development of some of the industrialized building system until today is further described. The description is based on a book by CINARK with the Danish title *Arkitektonisk kvalitet & industrielle byggesystemer* (Beim Anne, Jørgensen, & Vibæk, 2007). The focus of the book is industrial building systems for multi-storey residential buildings in Denmark. It is published in 2007 and the development since then is further described in an interview with one of the authors, Anne Beim. Also the book *Three ways of assembling a house* (Beim, Nielsen, & Vibæk, 2010) from CINARK is used as a foundation. (Beim Anne, Jørgensen, & Vibæk, 2007) and (Beim, Nielsen, & Vibæk, 2010) are made by the same research team with some of the same authors.

Industrialized architecture is a field of architecture that combines technology and architecture and works with the design of the building structures. It acknowledges the importance of the structural design for the architectural opportunities and the potential variation and flexibility of the building.

Principles of the structural design

The structural design for residential building blocks is described through the principles of three primary categories (Beim Anne, Jørgensen, & Vibæk, 2007).

Category of principles:

1. *The structural principle:* Slabs, roof and load bearing elements (walls, columns, beams)
2. *The infrastructural principle:* Internal areas with common access (stairways, balcony, access roads, corridors, ect.)
3. *The principle of installations:* Location and connection of the toilet and kitchen.

For each category different principles can be chosen. In this report the structural principles are outlined, as described the books from CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) and (Beim, Nielsen, & Vibæk, 2010).

The structural principles:

1. *Load bearing partition wall system:* Typical transverse walls separating apartments, but also longitudinal walls.
2. *Column/slab system:* Grids of columns with floor slabs on top.
3. *Frame system (column/beam):* Systems of columns and beams, with slabs put on top.

4. *Load bearing exterior walls:* A system where the facades carry the load and the inner part of the building is left open for choices.
5. *Box combinations:* Volume units put together in different combinations.
6. *Hybrid system:* Different of the above systems combined in the same building.

In Denmark, structural systems made of concrete with load bearing walls (type 1 and 4) are the most common used, primarily due to construction economy (Beim, Nielsen, & Vibæk, 2010). Those systems combine the structural parts and room dividing parts in the same material.
The pillar/slab systems and frame systems (type 2 and 3) provides a distinction between the load bearing and the dividing parts of the building, and are the systems which provides the highest degree of flexibility, both in terms of design flexibility and conversion flexibility.
Box combinations (type 5) have lately become more applied in their light version, especially in residential buildings and even when dealing with multi-storey buildings (Beim, Nielsen, & Vibæk, 2010).[25] Box combinations are volumetric systems that consists of prefabricated boxes. They each have their own sub-system which can consist of some of the other systems, e.g. frame structures or load bearing walls. Examples of heavyweight volumetric systems exists, but seem to fail due to excessive transportation costs (Beim, Nielsen, & Vibæk, 2010). Even for lightweight systems, the transportation causes limitations, as their sizes are limited by the width of the road and vehicles. Due to the limited sizes the volumetric systems are limited to, but suitable for, small and cheap housing, like youth housing.[26] Therefore, they will not be described further in this report and the focus will be on the systems for the structural principles number 1-4.

There are different pros and cons for different structural principles in terms of flexibility, price, production effort, influence on the design of the buildings like floor height ect. In the following section different cases from the CINARK book (Beim Anne, Jørgensen, & Vibæk, 2007), which use the systems 1-4 are outlined and pros and cons for the systems are discussed.

Industrial building systems - cases

All the following cases are from the book (Beim Anne, Jørgensen, & Vibæk, 2007), where the development of the cases and the structural systems are thoroughly described. The design of the structural systems in these cases has been dealing with all three categories of principles: The structural principle, the infrastructural principle, and the principle of installations. All three principles influence each other and the choice and development of the systems, but in this report the focus is on the structural principle. Therefore, not all factors for the development of the

[25] In the interview with Anne Beim in January 2021, she also talks about lightweight volumetric systems that are still more applied. See Section 5.3

[26] From interview with Anne Beim, jan 2021

structural systems will be outlined, but the main the pros and cons of the different structural systems will be outlined and discussed.

***Det nye etagehus/Det fleksible hus*: From column-slab to load bearing walls**

This case is a story of a structural building system from the architects *Arkitema/Arkitektgruppen Århus*[27]*,* which throughout the years developed through many alterations.
The story begins in 1983 when the Danish Ministry of Housing organized a competition under the title *Det Nye Etagehus* meaning '*The new multi-storey house'*. The intention with the competition was to rationality in the production with experiences from the 1960's and 1970's, and to provide some more 'irrational' factors such as variations, to accommodate the new family structures and their demand for flexibility within their apartments.

Structural system I – 'Det nye etagehus'
The architectural company *Arkitektgruppen Århus* won the competition with a new structural system including concepts for the infrastructural principle and principle of installations.
The structural principle for the new system was a column-plate system with fixed connections designed for 3-5 floors. The system consisted of Ø280 columns with 160 mm thick floor slab elements double-reinforced in two directions in the dimension 3,3 x 3,3 m. The stability was secured with some additional concrete walls.
The interior walls and the facades were non-load bearing. The facade cladding was open for opportunities, but for the specific projects, sandwich elements was chosen. In Figure 5.1 a 3D model is illustrating the structural system I.

Figure 5.1: Structural system I - Det nye etagehus. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

[27] Back then Arkitema was called *Arkitektgruppen Århus*

Building cases

In the period of 1986 to 1991 five different buildings were constructed with this system. For the two latest buildings, the distance between the columns was increased to provide a larger freedom between the columns, resulting in thicker dimensions of the slabs and columns. After those buildings the system was not used any further in its original form. There can be different reasons for this, and one of the reasons explained is the fact that it was developed in a period of low economic growth and low degree of construction activity. Because of this there was not enough volume and actual build cases to show its qualities in free competition (Beim Anne, Jørgensen, & Vibæk, 2007). This point on the other hand is counterbalanced with the view that in periods with high economically growth everything goes fast and the construction industry often has not got the incentives to develop new systems.

Some of the advantages of the system are the flexibility on the building level, which enables a high degree of variation, and furthermore the double span of the slabs, which enables holes in the slabs. One of the disadvantages of the system is that it is based on very specific and complex connections and that the elements often needed additional fitting on the site (Beim Anne, Jørgensen, & Vibæk, 2007).

Structural system II - 'Det fleksible etagehus'

In 1998 in a new public competition called *'Fleksible etageboliger i Ørestaden'*, meaning *'Flexible multi-storey residential buildings in Ørestaden'* was proposed. The competition was never completed, but in 2003 the housing fund *Boligfonden Kuben* was financially supporting one of the proposals from Arkitema, with the vision to make multiple-storey residential buildings attractive for families. One of the goals was to make a structural principle that makes it easy to change the layout of the dwellings over time.

The structural system of the proposal was a columns-slab system, which was stabilized by a core in the middle and with cantilevered concrete slabs on both sides of the building, casted in-situ. See Figure 5.2.

The internal walls and the facades were non-load bearing. The idea was to get as open floors as possible to enable a flexible fitting of the dwellings. However, the system with a core in the middle sat a limit to the degree of flexibility, compared to *Structural system I*, but the system kept the flexibility in the facades from the original system.

The system was never built as the centrally located core, was unfit for the size of housing that was needed at the time.

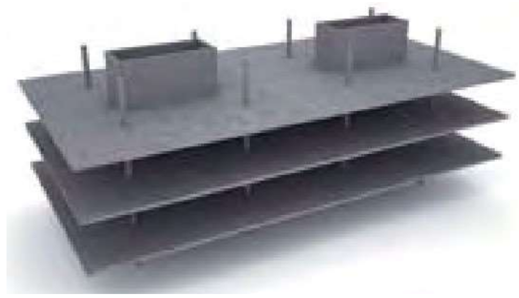


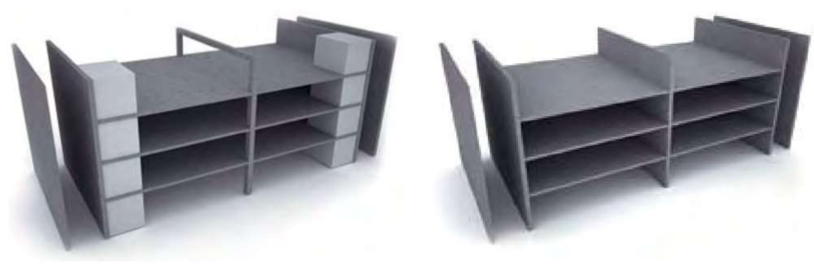
Figure 5.2: Structural system II - Det fleksible etagehus. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

__Structural system III - 'Det fleksible hus'__

After the completion of the idea for *Structural system II*, payed by *Boligfonden Kuben*, another fund *Kuben Byg* wished to build the project in Ørestaden. The planned sizes of the apartments were 85 m^2 and the system with the core in the middle of the dwellings, as seen in Figure 5.2, was not suitable for this size, as the core became to dominant and the spacing around the core was limited. Therefore, Arkitema further developed the system.

The in-situ cast slabs turned out being too expensive and they were replaced by regular hollow core slabs. The infrastructural principle was changed from balcony corridors to traditional staircases in between the dwellings. The cores for baths and kitchen were located close to the staircases but were not fixed to them and the longitudinal stability was taken by crosses in the facades of the staircases. Initially the system was designed as seen in Figure 5.3a, with a column-beam frame for support in the middle between two staircases. With this design the area between two staircases was fully flexible and could be made with two dwelling of equal size, a large and a small, one huge dwelling, or multiple dorm rooms with common facilities.

Late in the project phase, the column-beam support in the middle was replaced by a load bearing wall with two door openings, that could either be chosen to be used or not. See Figure 5.3b for the final structural design. It is not explained why they make this change. The wall in the middle limits the flexibility, but with the potential door openings in the wall it still provides the possibility of having one or two dwellings between the staircases. It also provides the possibility that one of the dwellings can 'borrow' some space from the other side of the wall as described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007).



(a) Structural system III a (b) Structural system III b

Figure 5.3: The structural systems III - Det fleksible hus. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

Building cases
Det flexible hus with *Structural system III b* was constructed in Ørestaden at C.F. Møllers Allé in 2007. The building is seen in Figure 5.4. It was sold as project sale for individual owners. As the book (Beim Anne, Jørgensen, & Vibæk, 2007) was published before the construction was finished, it does not say anything about how the flexibility has been used in the following years. At the website https://www.detflexiblehus.dk/, which is mainly for the owners of the dwellings, the building is described flexible. It says that each dwelling consists of 2 or 3 facade modules with the possibility of expansion or adjustments of the dwellings to fit the individual owners. It does not say anything about how the flexibility is used or how it works if you wish to buy some of the neighboring apartment or selling some of your own.

Figure 5.4: *Det flexible hus* in Ørestaden. Photo: Sara Sofie Vestergaard

Evaluation of the system
The development of the flexible system from Arkitektgruppen Århus/Arkitema, shows a case which was originally developed with an ambition of high flexibility on the building level. The original column-slab system (*Structural system I*) was used for 5 different actual buildings. There is not an exact answer in the book by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) for why it has not been used anymore. There is a doubt if it was because of the low economic growth in the

period, and if a high economic growth would had provided better circumstances for the system. Another possible reason for why it has not been used anymore, is also explained with the chosen distance of the columns on 3,3 m which also puts some limits.
No matter which reason, Arkitema ended up further developing the structural system. What started with a column-slab system which provided flexibility on the building level, ended up with a system with load bearing partition walls with less flexibility.
The final *Structural system III b* which was constructed in Ørestaden is designed with potential door openings in the middle wall between the two staircases. This provides opportunities for combining two apartments or 'borrow' a room from the neighboring apartment. This is the same principle as the principle behind the modifiable wall in the PhD project.

***Comfort House*: From lightweight to heavyweight structures**

This case is another example of a structural system described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007), which starts as a column-slab system and end up with load bearing concrete walls.
In a competition in 1994 about *process- and product development in the construction industry*, a proposal by a consortium consisting of Boje Lundgaard and Lene Tranberg Arkitekter, NCC and Carl Bro was chosen to be build. The system was called *Comfort House*.

<u>*The lightweight version*</u>
Initially the structural system consisted of a column-slab system of steel and plasterboards with prefabricated elements. The building was stabilized by prefabricated concrete cores for staircases and bathrooms. The facades and remaining internal walls were non load bearing. See Figure 5.5 for a 3D illustration. All the columns, except for one in each dwelling, were covered in the facades and the system had a great flexible potential.

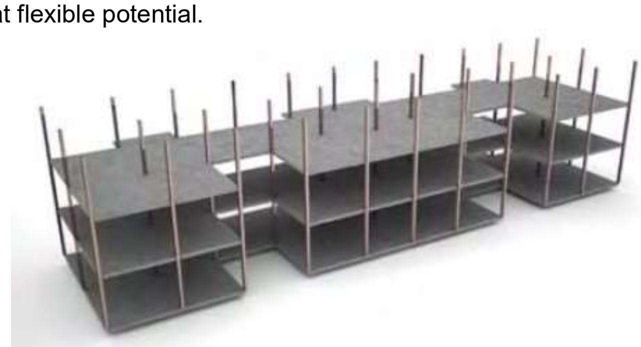


Figure 5.5: Comfort house - light structural system. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

Building cases
The system was constructed in two building projects in Ballerup, called *Egestrædet* and *Egebuen*, which were social housing buildings with 2-3 floors. The prefabricated system made the mounting on the construction site relatively quick compared to similar traditional buildings. The Comfort House consortium had hoped for a 15% reduced construction cost compared to traditional building systems, but this failed to succeed as it would require a minimum of 150 build dwellings a year, which they were not near (Beim Anne, Jørgensen, & Vibæk, 2007).
Some of the disadvantages of the structural system is described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007). It turned out that the system had some challenges with the plasterboard close to the outdoor environment, because of the humidity and temperatures that plasterboards are usually not exposed to. Furthermore, the habitants experienced acoustic problems concerning low frequency sounds. This corresponds with some of the acoustic challenges with lightweight walls described in Section 4.1.

The heavyweight version
In the period of 2000-2006 the consortium behind the Comfort House system changed the system from a lightweight column-slab system made of steel and plasterboards, to a traditional heavy concrete system with transverse load bearing partition walls. Five buildings were constructed with this system. The basic elements of those buildings were almost alike, but the description by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) is using the building called *Blækhuset*, build in Vanløse in 2003. It consists of the total of 24 dwellings, some social housing, and some co-owner housing. The structural system in Blækhuset is illustrated in Figure 5.6. It consists of concrete hollow core slab elements and transverse load bearing concrete walls. It reminds a lot of the structural system in *'Det flexible hus'* in Figure 5.3 b except for having two transverse walls between the staircases instead of one. The space between the two walls is shared by the two adjacent apartments, resulting in one room for each apartment.
The flexibility is limited compared to the light version of the Comfort House system, but the habitats have had a large influence on the interior layout and the non load bearing interior walls. Despite of that, the interior layout of the individual apartments did not end to differ a lot, as described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007). This is explained with the reason that habitants tend to do what they have seen others have done. They do not have sufficient skills or fantasy to make a radical different design.

Figure 5.6: Comfort house - heavy structural system, Blækhuset. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

The advantages of the heavy Comfort House system compared to the light system, is described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) as providing a better indoor climate, better acoustics, and using highly industrialized production methods, which resulted in cheaper buildings.

Evaluation of the system Comfort House
This is another example of an attempt to develop an industrialized flexible building system, which ends up being a system consisting of load bearing concrete walls and with less flexibility than originally thought.
The concrete elements in the Comfort House structural system were chosen as standard sizes. The highly industrialized and cheap concrete products together with the properties of concrete with respect to indoor climate and acoustic, were some of the reasons for choosing this above the initial light system.

Kajplads 24: Utzon building system

In 1986 the architects Kim Utzon and Jørn Utzon developed a structural system made of concrete elements, which is also described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007). The system consisted of column and beams in a frame structure with double-T concrete slabs on top. The system was developed for Paustian furniture house in Nordhavn, Copenhagen. It was based on a former column-beam system by Jørn Utzon, which was developed with the intention of being a flexible and open system.
After the Paustian house was build, plans were made to expand the area in Nordhavn with housing, offices and shops with buildings made of the same structural system. Due to economic recession, the plans were skipped again.
In 1998 the building system was introduced again in a bit modified version in an office house and boat club house next to the Paustian house. Furthermore, offices and cultural buildings followed. Kim Utzon had intentions of using the same system for a residential building. The opportunity came in 2001 when an almost fully designed office building should be redesigned into a residential building.

The project was called Kajplads 24 and located in Islands Brygge, Copenhagen. The original office building was designed with the Utzon element system with concrete columns and beam. When remaking the design into a residential building, the system ended up being modified to include concrete element walls between the dwellings. At the final design columns were only used at the facades. The system for Kajplads 24 is illustrated in Figure 5.7 and the final building in Figure 5.8.

Figure 5.7: Kajplads 24, 3D model. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

Figure 5.8: Kajplads 24. Photo: Sara Sofie Vestergaard

According to Kim Utzon (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007), a reason why the structural system was changed was due to a large building depth of 18 m. The columns inside the building were already skipped, and the large span required additional floor height due to the versed sine of the beams. According to Kim Utzon this provided a bad project finance.

According to CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) another probable reason for introducing concrete walls was due to the fire requirements.
This case is another example of an open and flexible building system, that ends up using separating load bearing concrete walls, which reduces the flexibility of the building.

***Kridthusene:* Load bearing facades**

Dalton Betonelementer has developed a concrete element system with load bearing facades, called *Brik-facade system*. A case which uses this system is described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007). The building, called *Kridthusene*, is a housing project with owner-occupied apartments build in 2005 in Nørresundby, Denmark. The architect was Arkitema, the same who made *Det nye etagehus* and *Det fleksible hus*.
The load bearing facades in the building enabled free and flexible possibilities within the building, as all interior walls were non load bearing. The facade elements are illustrated in Figure 5.9. In Figure 5.10 the floor plan is seen. The outer form of the building is a bit complex, but each floor consists of three almost identical and traditional apartments. Thus, the structural system provides a huge inner flexible potential, which it is not fully used. The building still has the potential of adjusting the size of the apartments over time, but the potential had not yet been used in 2007 when the book (Beim Anne, Jørgensen, & Vibæk, 2007) was published. However, this was also just two years after Kridthusene was built.

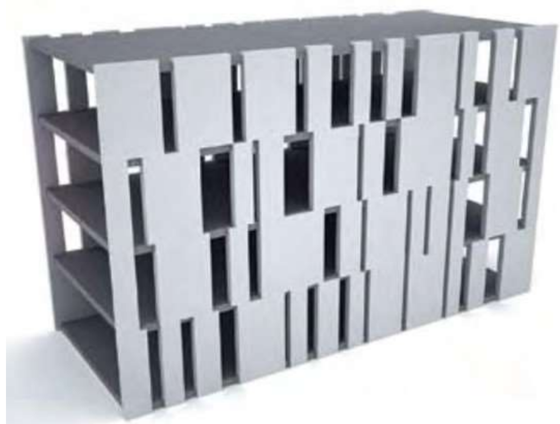


Figure 5.9: Kridthusene facades. © CINARK from (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007)

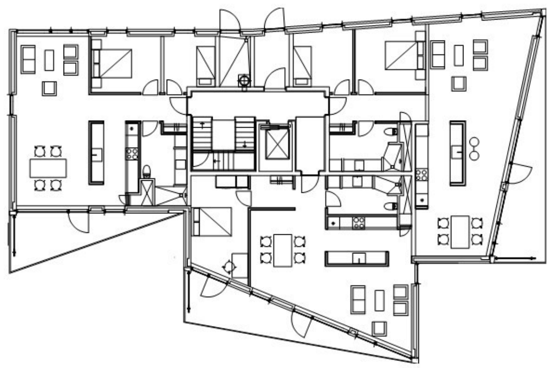


Figure 5.10: Kridthusene floor plan. Drawing by Arkitema from (Beim Anne, Jørgensen, & Vibæk, 2007).

This case is used to show the potential of flexibility inside a building when using load bearing facades. This is possible, as the building units are relatively small. However, having load bearing facades limits the flexibility of opening up in the facades in the future. In such a case the modifiable walls can also play a role, as they can be used as load bearing facades, where the flexible zones can be cut out for a larger windows, balcony or extension of the building.

***VM-husene:* 3D geometric units**

VM-husene were designed by the architects *Plot Arkitekter* and constructed in Ørestaden, Copenhagen in 2005. They consist of two buildings forming a V and an M, when looking from above. This building case is also described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007).

VM-husene mainly consist of housing, but also a little office space and day care center.

The dwellings are fully and partly owner occupied and ranging between 55 m^2 and 130 m^2. The building structure is made of standard concrete elements, using 180 mm hollow core slabs in two different lengths, 3,6 m and 7,2 m, supported by transverse load bearing concrete walls between the dwellings. Some places concrete columns and beams are used as a supplement.

What is noteworthy about this project is the way a traditional structural system is used to create a building with a high degree of variation between the individual dwellings. The buildings are designed from 3D spatial geometries. To generate the 3D units for each dwelling, the initial combinations were designed as seen in Figure 5.11 and Figure 5.12. For the V building, the units were designed with two floors and using balcony corridors as the infrastructural principle. For the M building the units were designed with up to 3 floors, where the infrastructural principle was using internal corridors.

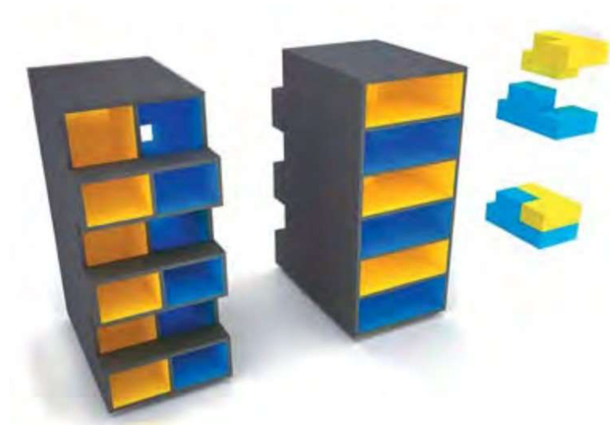


Figure 5.11: V building - 3D design units © CINARK

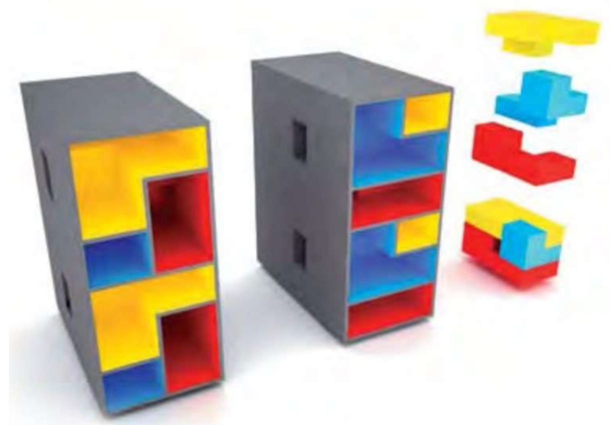


Figure 5.12: M building - 3D design units © CINARK

For both buildings the final design of the 3D units were adjusted to fit the outer V- and M-shape of the buildings.
The final design for the V building ended up with 113 dwellings, consisting of 40 different variants, most of them illustrated in Figure 5.13.

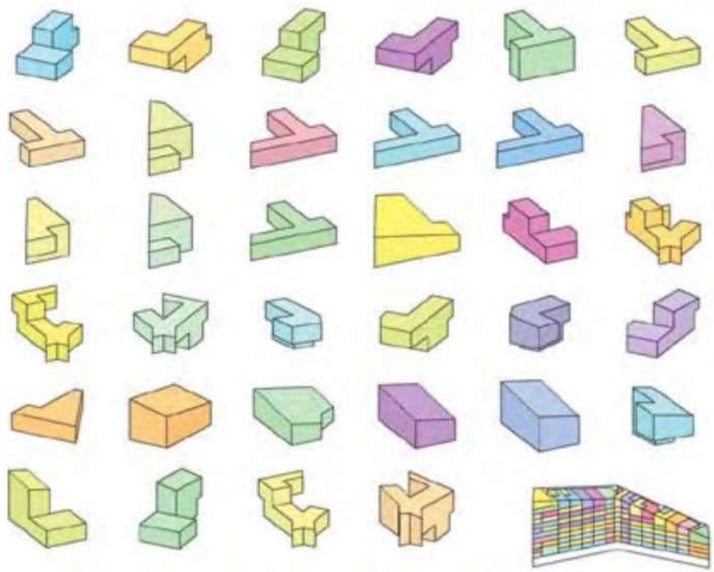


Figure 5.13: V building - 3D units final layout. From (Beim Anne, Jørgensen, & Vibæk, 2007).

For the M building it resulted in 108 dwellings consisting of 36 different variants of 3D units, as illustrated in Figure 5.14.

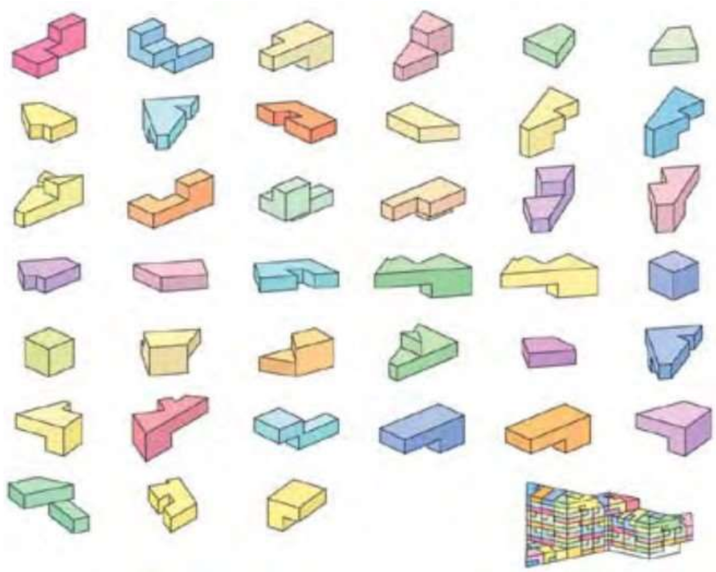


Figure 5.14: M building - 3D units final layout. From (Beim Anne, Jørgensen, & Vibæk, 2007).

As seen from the figures, these buildings provides a very high degree of variation between the individual dwellings. There is a certain degree of conversion flexibility on the housing level as the interior walls are not load bearing, but as the walls between the dwellings are load bearing, there is not a conversion flexibility on the building level. The huge degree of variation makes up for this, as it appeals to many different buyers and the need of having individualized dwellings can be satisfied from the uniqueness of each dwelling. As described, the structure is made of traditional concrete elements and despite the geometric complexity it was not more expensive than comparable traditional residential buildings (Beim Anne, Jørgensen, & Vibæk, 2007). According to Finn Nørkjær from Plot Arkitekter (Beim Anne, Jørgensen, & Vibæk, 2007), the low price for this building was caused by many factors, but he especially outlined the construction management who was very good at controlling the project.

In the book (Beim Anne, Jørgensen, & Vibæk, 2007) this project is described as one of the most successful housing projects and describes that it actually ended up appealing to a wide range of habitats, from young people, children families and elder people.
Thus, VM-husene is a building with traditional concrete elements and a huge variety of dwellings, which can appeal to different individual needs. In such a type of project, the modifiable walls could also be relevant to use for the load bearing walls between the dwellings. This would expand the flexibility from the housing level to the building level.

Discussion of the structural systems
In the previous section different cases of building systems from the book *Arkitektonisk Kvalitet og industrielle byggesystemer* (Beim Anne, Jørgensen, & Vibæk, 2007) are described. The focus has been to describe different structural systems for industrialized production of housing that provides some degree of flexibility or the opportunity to customize the housing to individual needs. The cases show different attempts to develop such structural systems, and they illustrate a tendency that some of the most flexible systems for residential buildings did not survive in their original form. Different reasons for that are mentioned, and in the following some those reasons and pros and cons of different structural systems will be discussed. In the book (Beim Anne, Jørgensen, & Vibæk, 2007) a very thorough discussion of the systems is made. It discusses the benefits and challenges of different systems, but also the surrounding impacts to the success. The surrounding impacts can be the project team, the state of the economy in the society and other subjects. In the book (Beim Anne, Jørgensen, & Vibæk, 2007) the cases and discussions are, amongst other, based on interviews with some of the stakeholders from the different projects, mainly architects, but also stakeholders from the production side. In the following the most relevant points from the discussions in the book (Beim Anne, Jørgensen, & Vibæk, 2007) are outlined.

Two rationales

Two different rationales behind development of industrial building systems are described (Beim Anne, Jørgensen, & Vibæk, 2007).
Some of the drivers behind the development of a new building system are: Rational optimization, the production, its technological possibilities, and the short-term project economy. Those drivers are described as *the technical/economical rationale*.

On the other hand, there are the drivers: architectural qualities, value for the users and the society, and the long-term use of the building. Those drivers are described as *the architectural/total cost rationale*.
There is a certain tension between those two rationales. They do affect each other. In some situations they are opposing each other, and in other situations they have a positive effect on each other. Both rationales need to be included in order to guaranty the quality of the future development of industrialized building systems (Beim Anne, Jørgensen, & Vibæk, 2007).

The structural principles
Throughout the case descriptions different advantages and disadvantages for different structural principles are outlined. In the following some of those points will be summarized and further elaborated on.

A case with box combinations has not been described in this report. As described previously lightweight box combinations are becoming more applied, but due to their limit in the sizing they will not be compared to the other structural systems here.

Structural systems with load bearing facades as used in the case Kridthusene, provides an interior flexibility in the building. However, they put a limit on the flexibility and openness of the facades.

The structural systems from the principles of columns/slabs or columns/beams are referred to as open systems. For the open systems, the interior fittings like the walls are separated from the load bearing system. The structural principle using load bearing walls will be referred to as a closed system.
The open systems provide the highest degree of conversion flexibility and design flexibility compared to using load bearing walls. However, some of the open systems in the described cases were still somehow limited by the short distances between the columns. This was e.g. the case in 'Det nye etagehus' where ø280 mm columns were placed in a 3,3 m x 3,3 m grid. The span can be increased, but it will result in increased dimensions of the columns and slabs.
One of the main disadvantages of the open systems, as outlined are the technical requirements of partition walls between dwellings (Beim Anne, Jørgensen, & Vibæk, 2007). These requirements like acoustic and fire are outlined in Section 4 in this report. According to CINARK (Beim Anne, Jørgensen, & Vibæk, 2007), these requirements makes the solution for the lightweight walls more expensive and has been one of the reasons why the systems in *Det nye etagehus*, *Comfort House* and *Kajplads 24* ended up using load bearing concrete walls.
Another explanation for why the open structural systems in some of the cases ended up using load bearing walls, is the floor height. Poul Erik Hjort, who was the chairman for *Betonelemen-Foreningen*[28], has in an interview (Beim Anne, Jørgensen, & Vibæk, 2007) stated that one of the main reason for load bearing concrete walls being dominating in the residential buildings, is that both column-slab systems and column-beam systems provide a larger floor height, which will

[28] A Danish member union for concrete element manufacturer.

often result in one less floor in the building, which is not good for the economy of the project.
With these advantages and disadvantages of the structural principles, the open structural principles can be said to provide the largest value in the architectural/total cost rationale and the closed structural principle with load bearing walls can be said to provide the largest value for the technical/economical rationale. From that perspective there can be good reasons to choose either of the principles and the choice will often depend on the organizational setup between the different partners in the project, like the client, contractor, architect, developer and end-user.

Concerning the slabs in buildings, the most used concrete element slab in Denmark is the hollow core slab, which is only one-directional. Steel and wood systems often provides slabs which are not directional, which can be an advantage if wanting to make holes in the slab or cantilevers in different directions. For concrete structures, two directional slabs would require in-situ casting if wanting larger spans than the system in *Det nye etagehus* with 3,3 m x 3,3 m prefabricated slab elements. Furthermore, solid concrete slabs would require more concrete than the hollow core slabs.
Peter Thorsen from *Lundgaard og Tranberg Arkitektfirma* is interviewed for the Comfort House case (Beim Anne, Jørgensen, & Vibæk, 2007). He talks about the advantages of hollow core slabs. He says that the hollow core slab is a highly industrialized product that is fast, easy, and cheap to produce, and easy to adjust by cutting of at the ends. He says that it is difficult to make a much more industrialized slab element and that concrete elements in general are very rational and has got a lot of good properties. This is one of the reasons why the Comfort House building system, which started as a lightweight system, ended up consisting of concrete elements.

The continuity of structural systems

The three cases Det Nye Etagehus, Comfort House and Kajplads 24 all describes a longer course of development of structural systems, which ends up very different than the initial systems and ends up almost similar to many of the remaining residential buildings. All three systems are developed in a period with economic recession and low activity in the building industry and this is some of the explanation of why the initial open systems did not survive (Beim Anne, Jørgensen, & Vibæk, 2007).
The development of structural systems and the state of the economy are described as a paradox (Beim Anne, Jørgensen, & Vibæk, 2007). When the industry is experiencing a boom and there are economic resources for development, the time and incentives to think in long term are not present. In periods of recession the time and incentives in terms of new visions are there, but there is not sufficient finance to finalize the development.
Another influence on the development of structural systems is the continuity of the development (Beim Anne, Jørgensen, & Vibæk, 2007). According to Peter Thorsen from Lundgaard and Tranberg Arkiteker[29] (Beim Anne, Jørgensen, & Vibæk, 2007),

[29] Architectural company for the Comfort House system

continuity is an important factor for innovation of the industrialized production. He asks the question if it is realistic with a higher degree of industrialization in a sector that is so unstable and influenced of political trends and the overall economy in the society.
Also, the organizational setup is important for the continuity of a building system. According to CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) the architectural companies experience that the developers and contractors attempts to cut down even further on the budgets to maximize their profit. With the short-term revenue as determining, it can be challenging to develop a structural system which benefits on the longer term. Therefore, the organizational setup for each project that uses a specific building system and the system owner, who are in charge of developing the system, are of importance.
There is no exact answer on how an optimal organizational setup would look like when developing a flexible structural system. However, it is important that the main stakeholders have a long-term view on the investment, or that the system owner or developer ensures the continuity and do not let the system fail because of one or few projects where the short-term view and the technical/economical rationale is dominating. On the other hand, it can be an advantage to have in mind the importance of the system being rational in its production and implementation, so the system can be used when the short-term rationale is dominating. This confirms the need of both the short term technical/economical rationale and the longer term architectural/total cost rationale when developing a building system.

Strategies
When developing a building system, different strategies can be used. The two main strategies can be described as revolutionary and evolutionary (Beim Anne, Jørgensen, & Vibæk, 2007). With the revolutionary strategy one starts from scratch with respect to both architectonics, social aspects, building techniques and production technologies. With the evolutionary strategy one focuses on innovation in one or few aspects and use existing practices for the remaining. The evolutionary strategy often reaches the furthest with respect to the final result, as it is often most fruitful to hold the focus on innovation in one or few aspects (Beim Anne, Jørgensen, & Vibæk, 2007).
As an example of an evolutionary strategy VM-husene is mentioned. In this case a traditional structural system with standard elements of load bearing concrete walls and hollow core slabs. The focus has been to find a systematic way to make new architectural solutions to make a varied supply of dwellings consisting of untraditional floor plans.
On the other hand, ‘Det nye etagehus’ and Comfort House are cases with a more revolutionary strategy. In those cases, the initial ambitions have been a whole new building system, which should provide a high degree of flexibility and industrialization. However, the initial ambitions did not end up being realized.
The boundary between the two strategies is not clear, as both strategies to some degree will always use existing knowledge and experience, but the revolutionary strategy aims at creating new potential through innovation, while the evolutionary seeks to cover untapped potentials in existing systems.

System integration

When talking about a *structural system* or *structural principles,* the following distinction is made. The structural principles refer to whether using e.g. the column/beam or load bearing walls principles and a structural system is a system, that uses one of the structural principles, but with more defined solutions. This can be a system with integrated solutions, such as specific structural dimensions and specific solutions for the connections. A system can have more or less integrated solutions.

There are only few real structural system products with integrated solutions in Denmark and those are not fully developed (Beim Anne, Jørgensen, & Vibæk, 2007).

Throughout the PhD project, it is relevant to discuss to which degree the modifiable structural system should be an integrated system with predefined solutions for e.g. the geometry, connections ect.

According to Erling Holm from Dalton Betonelementer, who developed the load bearing facade system used in Kridthusene, a full integrated building system can be very problematic as there are many different products and situations, which are difficult to consider in a system. He mentions a staircase system, which they have developed, where there are very few parameters to consider. If looking at a whole building instead, there are many different components and different situations from building to building, which adds many different challenges. Therefore, it is difficult to develop a full integrated and parametric building system. He states that it is possible, but one of the drawbacks would be introduction of many limitations (Beim Anne, Jørgensen, & Vibæk, 2007).

An example of an attempt of developing a full integrated building system is the system *NCC Komplett* in Sweden (Beim, Nielsen, & Vibæk, 2010). It was a system that was aiming for a highly automated 90 % prefabricated system for residential buildings. It consisted of concrete elements for load bearing facades and load bearing partition walls and slabs made of steel frames finished with plasterboard, plywood, and parquet. Kitchen and bathroom solutions, doors and windows was also integrated in the system. The system was developed between 2002 and 2006 and a new production facility was made to produce it. After less than two years of production the factory closed due to failing revenue, even though the order book was full. There are different reasons for the failing revenue, but in general the system had more challenges and was more expensive to produce than what was expected in the beginning. Furthermore, the many standards in the system also introduced many limitations (Beim, Nielsen, & Vibæk, 2010).

Potential of the flexibility

As described by CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) the flexibility of the open systems has not shown its full potential.

'Det nye etagehus' and Comfort House are both examples of systems, which are meant to provide a high degree of flexibility on the building level, but through development they end up reducing the flexibility to the housing level, by using the structural principle of load bearing walls. In either case, the flexibility has not really proven to be used, as far as the analysis by CINARK in the book (Beim Anne, Jørgensen, & Vibæk, 2007) goes. However, this is primarily based on the initial

designs of the dwellings and limited access to the user behavior after they were built. Some of the projects were constructed just few years before publishing the book (Beim Anne, Jørgensen, & Vibæk, 2007), and therefore the analysis does not tell about the use of the flexibility on the longer run. However, the flexible possibilities have not been used to a high degree for the initial design of the dwellings.
Studies show that the feeling of the freedom to choose is not directly proportional with the actual opportunities (Beim Anne, Jørgensen, & Vibæk, 2007). If leaving the flexible choices to the user, experiences show that the users to a high extend chooses the same or one of few similar solutions. This was the case with the heavyweight Comfort House system in *Blækhusene*, where the users could design the interior layout of the dwellings themselves, and they ended up being very alike. If the aim is a varied housing and habitat composition, a general and very open flexibility for the user is according to CINARK (Beim Anne, Jørgensen, & Vibæk, 2007) not the best solution. An alternative solution is to combine a specific flexibility, meaning a varied and diverse supply in the design of the dwellings, combined with conversion flexibility (Beim Anne, Jørgensen, & Vibæk, 2007). This would on one side provide individualized options, and on the other side help and qualify the user for further individualization. This is to some degree what was done in VM-husene. In that project a high degree of specific flexibility, by supplying a huge variety of dwellings, was combined with conversion flexibility on the housing level. If modifiable walls had been used between the dwellings in VM-husene, there would also had been conversion flexibility on the building level, by enabling dwellings to be combined.

5.2 Cases with flexible walls

As seen in the previous section, many structural systems, which were developed with focus on industrialization and flexibility of the building, ended up using load bearing walls. This illustrates that the advantages of using load bearing concrete walls outweighs the disadvantage of the system with concrete walls being less flexible than e.g. column/frame systems in the individual projects.

A way to keep the advantages of the concrete wall, but to increase the flexibility of them, is to design the concrete walls with a flexible zone, as the PhD project suggests with the modifiable walls.

This was done in '*Det fleksible hus'*, where the walls between the two dwellings were prepared for potential door openings, as described in Section 5.1.
In this section, three other cases of buildings, where concrete walls are prepared with flexible zones, and future scenarios have been considered in the building design from the beginning, are shown.

Hillerød Markedsplads

Constructed: Under construction
Client: PFA Ejendomme, Momentum+
Architect: Mikkelsen arkitekter
Advisor: Rambøll

The case description is based on project material and an interview with Michael Hansen from PFA Ejendomme.
The project consist of three buildings, where two of them are for housing and one of them a hotel. For the hotel building every second wall between the hotel rooms are designed as non load bearing walls. This is done to have the possibility of removing those walls and potentially transform the hotel rooms into youth housing by combining two hotel rooms into one dwelling. This means that every second wall between the hotel rooms are load bearing concrete walls and every second wall are non-load bearing as illustrated in Figure 5.15. The non-load bearing walls will be made of plasterboard walls with sufficient thickness and material to meet the acoustic requirements and fire requirements.

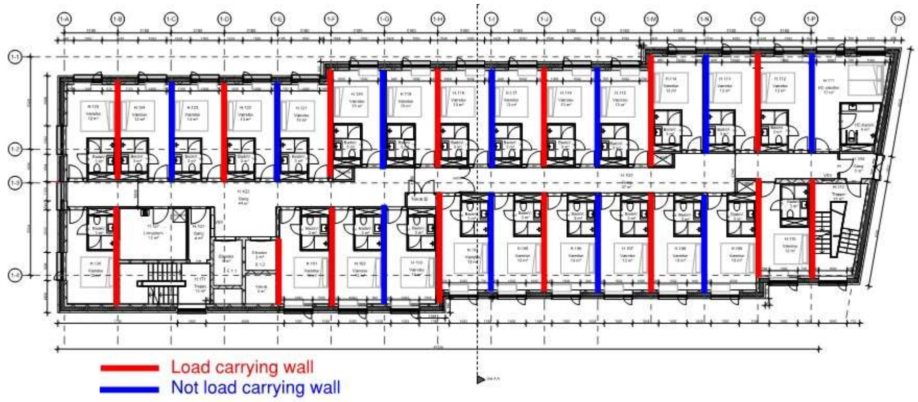


Figure 5.15: Hillerød Markedsplads - 1st floor plan of the hotel building.[30] Illustrating the walls separating the hotel room.

The motivation

In the interview with Michael Hansen[31], he explains the motivation behind the flexibility to meet the uncertainties of the business case with a hotel in Hillerød. In case it turns out that there is not a sufficient demand for the hotel rooms within the first three years, they have got the permission from the municipality to transform the hotel into youth housing. In the interview Michael Hansen could see the potential of using the modifiable concrete walls in a similar case, as he could see the advantage of enabling more than two hotel room to be combined and have even further flexibility in a potential transformation from hotel into housing. He was asked whether it was important that the whole wall could be removed or if it could also be relevant with large door openings. He said that it was not crucial that the whole wall could be removed if it enabled more than two hotel rooms to be combined.

[30] Plan from drawing number HMP_B1_K01_H1_E1_N101 draft version from 08-01-2021. The red and blue lines are inserted by Sara Sofie Vestergaard to illustrate the difference of the walls.
[31] Interview from 17-12-2020. The remaining interview described in Section 5.3

This case is a good example of the need and willingness to build flexible due to uncertainties in the market.

Kanalfronten Vejle

Constructed: 2013
Client: Pension Danmark Ejendomme A/S
Advisor: Rambøll

The project consists of three buildings for housing along the harbor side in Vejle. The building structure was made of prefabricated concrete elements, consisting of load bearing walls between the dwellings and load bearing facade elements. The buildings varies between 3 and 5 floors. In one of the buildings, a part of the ground floor was prepared for offices. The initial size of the rooms were the same as the dwellings on top of them, thus the load bearing walls continued all the way down. The load bearing walls on the ground floor was prepared for future openings in case the rooms needed to be combined. With this structural design, different renting possibilities were kept open. The rooms could be combined for larger offices, and in case it could not be rented out for offices there were a possibility of making dwellings instead. The description of this case is based on the project material from Rambøll and a talk with Carsten Rune Ellendersen from Rambøll, who worked as project manager on the project when the offices were combined in 2020.
In Figure 5.16 a plan drawing for the four offices on the ground floor of the building and the potential future door openings in the concrete walls are illustrated.

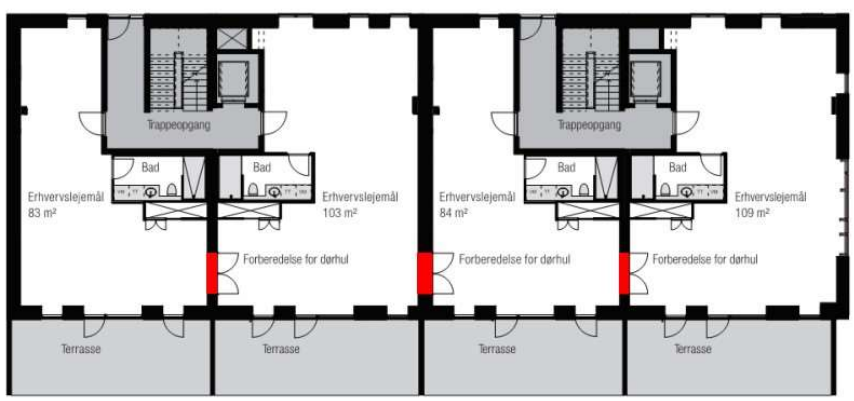


Figure 5.16: Kanalfronten, office plan[32]. Red illustrates the part of the walls that are prepared for door openings.

[32] The figure is from Kanalfrontens sales brochure from http://www.kanalfronten.dk/Files/Media/Kanalfronten_erhverv.pdf

Combining the offices in 2020
In 2020 Rambøll got involved in the project again, when two openings were to be made in the walls to combine three of the offices. Se Figure 5.17 for the location of the openings. As seen from Figure 5.17, opening 1 were wider than the prepared door hole.

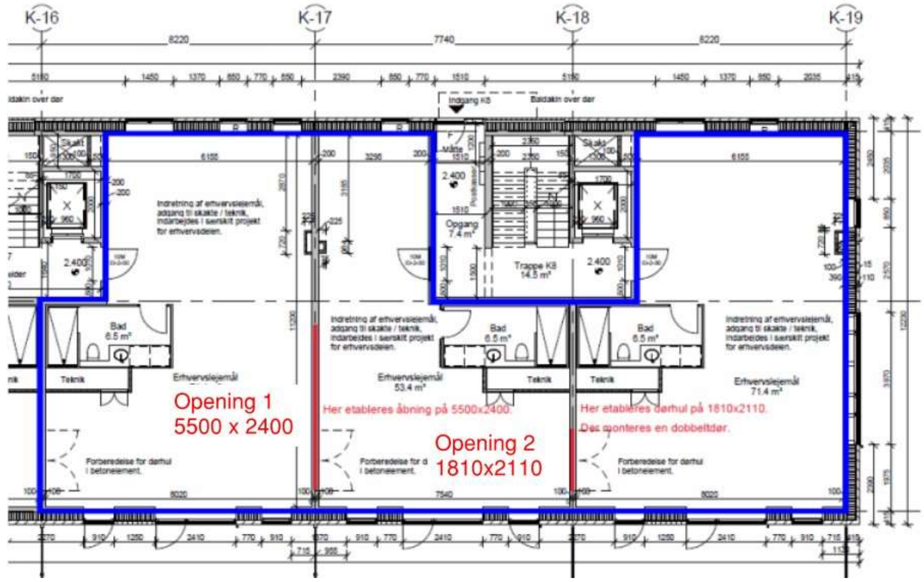
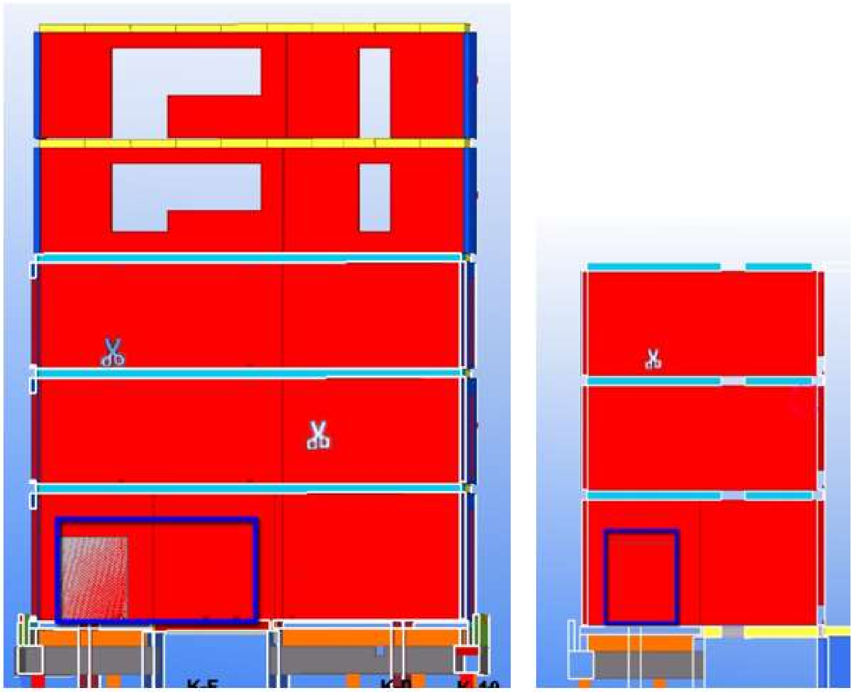


Figure 5.17: Kanalfronten, actual openings in 2020. Red marks illustrates the new openings. Figure from the project material (Gabrielsen, 2020).

In Figure 5.18 the size of the actual openings compared to the prepared openings are illustrated. For both openings, it is seen that the openings needed to be larger than prepared for. One of the reasons was that there had not been taken consideration of the floor height in the prepared door opening.



(a) Opening 1 (b) Opening 2

Figure 5.18: Wall openings illustrated in the 3D model. Blue frame illustrates the actual openings. Figures from the project material (Gabrielsen, 2020).

To illustrate the reinforcement design in one of the walls prepared for an opening, part of the technical drawing of the element at opening 2 is shown in Figure 5.19. It is seen that there is column and beam reinforcement around the prepared door opening. Beside that, there is the same amount of net reinforcement in the whole wall, including the potential door opening.
Because the actual door hole had to be higher than the prepared one, the beam reinforcement above the opening were cut off. Therefore, the wall needed to be strengthened with new beam reinforcement.

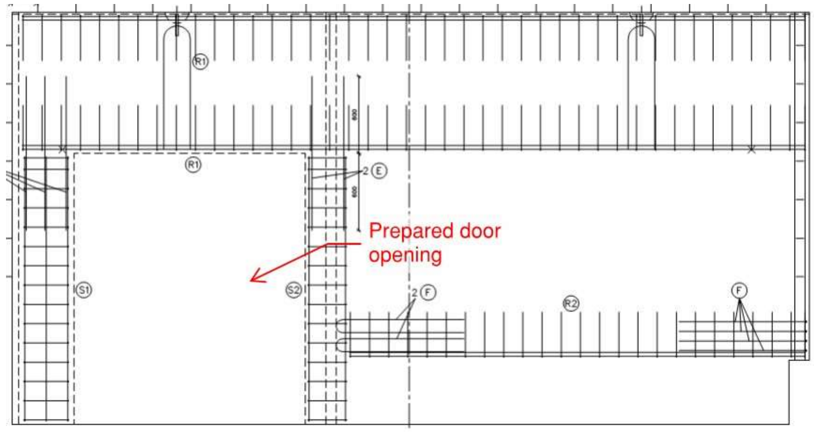


Figure 5.19: Kanalfronten, reinforcement design in wall element. Part of the technical drawing of the original element prepared for door opening (opening 2). Beside the reinforcement illustrated in the figure, there is a net reinforcement in the whole wall (including the potential door opening) of Ø8/150 in both sides and both directions.[33]

In opening 1 additional columns and a beam were constructed around the opening because the opening was both to wide and to high. In Figure 5.20 and Figure 5.21 photos on the site during construction of the holes are shown. They illustrate the additional beam reinforcement inserted after opening of the walls, and before new concrete in the beams was cast.

Figure 5.20: Opening 1 in the construction phase. Illustrates the new beam reinforcement inserted before casting of the concrete in the top of the openings.

[33] The technical drawing is made by Spæncom and is part of the project material.

Figure 5.21: Opening 2 in the construction phase. Illustrates the new beam reinforcement inserted before casting of the concrete in the top of the openings.

Modifiable wall perspective

This case illustrates an example of an existing building where some of the walls were prepared for future openings, to allow different kinds of use. The case shows that some of the openings were actually needed, but that the prepared zones did not have the sufficient sizes. Therefore, this is also an example of the importance of the design and size of the flexible zones in the walls, to avoid additional calculations and strengthening of the structure.
In this case the flexible zones used the same concrete and net reinforcement as the remaining part of the wall even though it was probably not necessary, as the load bearing capacity was calculated with an opening. In the PhD project, the modifiable wall structure will be optimized, so less reinforcement and lower concrete strength can be used in the flexible zone.

Pharma Building Case

Buildings for pharmaceutical production (referred to as pharma buildings) often need transformations in the walls and the decks in order to apply for the changes in the production facilities.
This case description is based on experiences in Rambøll from a talk with a pharma building specialist and project manager Kristian Mads Arounsack-Jørgensen from Rambøll. He has helped with a talk about the need for and advantages of flexible building structures in pharma buildings.

In pharma buildings it is an advantage with flexibility in the building structures for several reasons. One of the reasons is that a critical factor in the design phase of pharma buildings is the timeline. Enabling the structural design phases to be made before and independently of the mechanical design[34] has proven to shorten down the time for the design phase significantly. To enable the design of the structure to

[34] Mechanical design is for example design of the pipelines for the machinery, ventilation, water ect.

be prepared, without knowing the mechanical design, it is a huge advantage if the walls in the structural design are prepared with zones that potentially can be cut out without further needs of calculations or strengthening of the structure.
Another reason to make flexible structures in pharma buildings is that the production facilities changes often. In many cases it changes every fifth year, which often requires new holes in the walls and the decks for the new piping. If the structures are not prepared for this it requires new calculations of the walls and probably extra strengthening of the structure, which is costly and requires extra time and materials. In some cases, it is not possible to meet the new requirements from the client. Kristian Mads Arounsack-Jørgensen tells that he has also seen cases of old production buildings with a huge amount of holes in the walls, which have not been prepared from the beginning, but added over time. In such cases it would be very costly to add any further holes.

The building case

Rambøll has designed the structures for several pharma buildings with walls that have been prepared for future holes. The case showed here, referred to as the Pharma Building Case, is a project designed in Rambøll, with an extensive use of flexible zones, called boreholes in the case project. The description of the case is based on the talk with Kristian Mads Arounsack-Jørgensen and the project material.
In Figure 5.22 one of the elevations for the concrete walls are shown. The red hatched areas marks the boreholes. As seen from the figure, most of the bore holes are located in the top of the wall as that pipes are usually guided below the ceiling. Most of the boreholes are 1.0 m x 1.2 m in size. In two of the walls, potential door openings have also been made. The element marked with blue is shown in Figure 5.23.

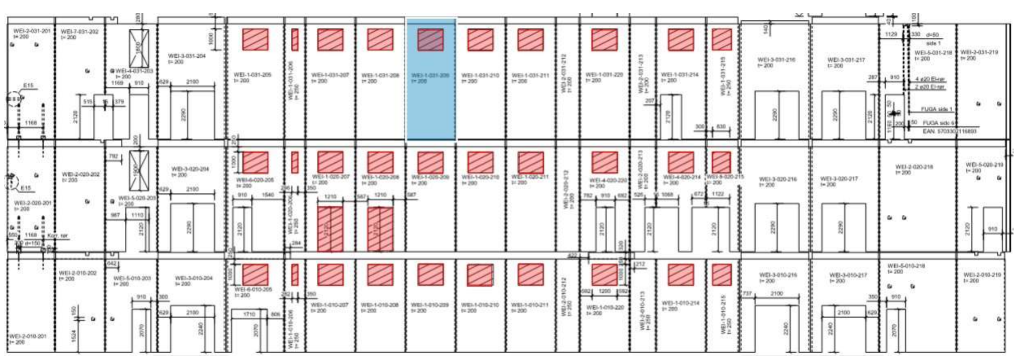


Figure 5.22: Pharma Building Case. Wall elevation from the Rambøll project material. The red hatched areas marks the boreholes.

The walls with the boreholes are designed and calculated as if the holes were cut out. The walls are produced with the same concrete and net reinforcement in the whole wall including in the boreholes, but with additional reinforcement around the holes as seen from the element drawing in Figure 5.23.

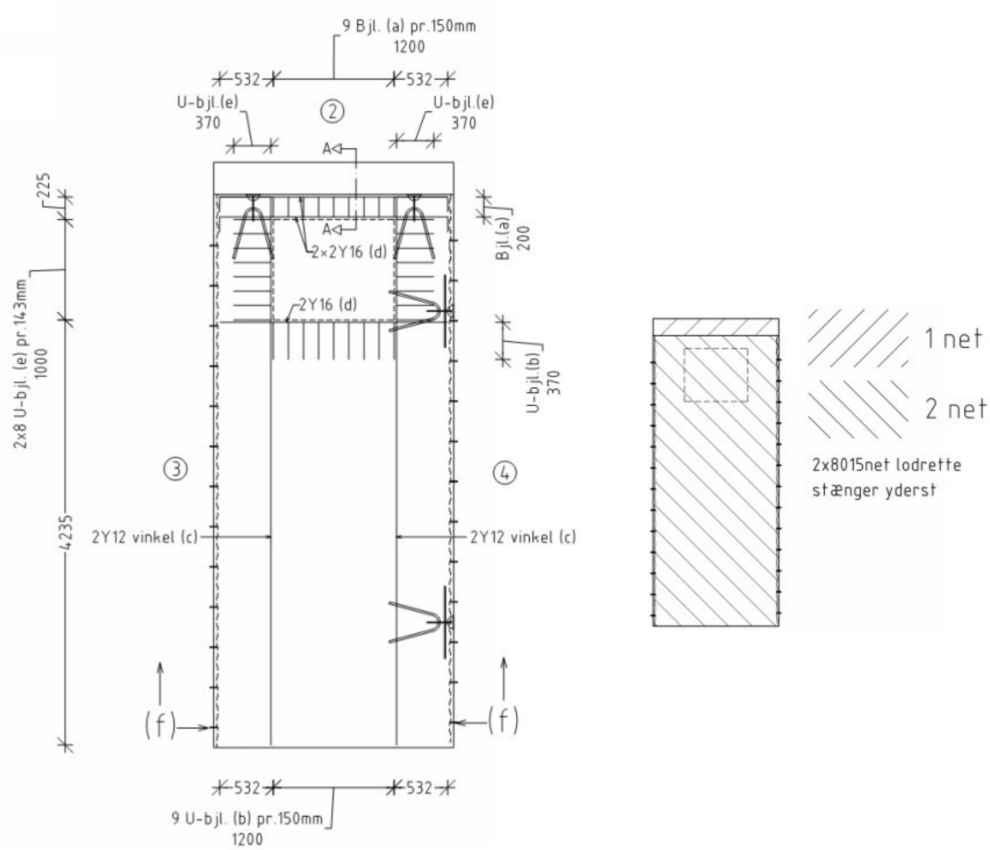


Figure 5.23: Pharma Building Case. Example of an element with a bore hole. Part of the element drawing from the manufacture.

According to Kristian Mads Arounsack-Jørgensen, the boreholes in this project have proven to be very useful as the project succeeded to reduce the timeline for the design phases of the building significantly compared to similar projects, and it has proven to be very valuable in transformations of the production facilities.

Modifiable wall in pharma buildings

The Pharma Building Case has shown that it is valuable to use walls that are prepared for holes in pharma buildings. In this case, the boreholes have not been optimized with respect to material. In the PhD project the modifiable walls are optimized with respect to the material usage, thus seeking to minimize the amount of reinforcement and the concrete strength in the flexible zones.
In this pharma case the boreholes are not that large, and minimizing the reinforcement and concrete strength in the holes will maybe not have a significant contribution to the total material usage. However, this case and the talk with the Rambøll pharma specialist Kristian Mads Arounsack-Jørgensen shows the potential of using modifiable walls in pharma buildings or other production facilities.

5.3 Interviews

To support the analyses of the need for modifiable walls in the market, interviews with some stakeholders within the building sector have been made.
People from two different stakeholder groups were invited for interviews. A researcher/architect group and a group of clients/building owners. Three stakeholders from each group have been interviewed.
The interviews were qualitative and semi-structured. This means, that some of the questions were the same in all interviews, but that some of the questions were adjusted for the individual interview. In general, the agenda of the interviews has followed these subjects:

1. Renovation and transformation of buildings
2. Flexibility of buildings
3. The modifiable concrete wall

Different focuses for each subjects have been made for the two stakeholder groups, and furthermore some of the questions have been made specifically for the individual interviews. This has for example been the case for questions referring to a book written by the stakeholder or a specific construction project that a stakeholder were involved in.
Some of the questions were adjusted or left out during the interviews, depended on the answers and the proceeding of the interview. However, the questionnaires were used as a basis to check if some subjects were left out. Due to the different turns the interviews took, the questionnaires will not be attached, but the focus for each subject in each stakeholder group will be outlined.
The interviews were conducted in the period of December 2020 and January 2021. They were all made by online video calls in Danish language within the duration of 30-60 minutes.
Each interview are described in the following. Some of the statements from the stakeholders are quoted directly, but the remaining description of the interviews and the stakeholders perspectives are interpretations from the author with the attempt of describing as precise as possible what was said in the interviews.

Researchers/architects

In the category of researches/architects, the following stakeholders were interviewed:

- Anne Beim, CINARK, Royal Danish Academy if Fine Arts School of Architecture.
- Claus Bech-Danielsen, BUILD, Aalborg University.
- Vibeke Grupe Larsen, Danish Association of Architectural Firms and Southern University of Denmark, SDU.

All three stakeholders are both researchers and architects. Anne Beim is a researcher in the field of industrial architecture. She has made a lot of research within industrial building systems. Claus Bech-Danielsen is a researcher in the field of housing and transformations. Vibeke Grupe Larsen is doing research in sustainability and circular transition of social housing.

The questions within the three main subjects were constructed like the following, with some variations:

1. Renovations and transformations: Have you observed any specific development within renovations and transformations? Do you see any trends in renovations and transformations for the future?
2. Flexibility of buildings: What does flexibility in a building mean to you? Is there a need for flexibility and what kind? Do you know any cases with flexible building structures?
3. The modifiable concrete wall: Can you see a need and use cases for a system with modifiable concrete walls? For which cases? Can you think of a specific focus I need to take into account when designing the wall? Do you think there would be a demand for the modifiable walls?

Furthermore, some specific questions were made for Anne Beim with respect to building systems and for Claus Bech-Danielsen with respect to the themes in the book about the development within housing (Bech-Danielsen, Mechlenborg, & Stender, 2018). In the following the most relevant points and stories from each interview are outlined. It is noted that the replies regarding renovations have been outlined in Section 2.4 and therefore left out in this section.

Anne Beim
Interviewed in January 2021.

Background
Anne Beim is a professor and head of Center for Industrialised Architecture (CINARK) in the Royal Danish Academy of Fine Arts School of Architecture. She is an architect educated in the field of applied building techniques. This means that her architectural background combines the technical aspects of a building with the architectural aspects. She has a PhD degree in architecture within the subject of tectonics[35], where she wrote about flexibility of building.
Anne Beim is also working with sustainability of the buildings with the approach of gaining more and using less, by using the materials and systems in the most clever way for the given context.
Anne Beim is one of the authors of the books *Arkitektonisk kvalitet og industrielle byggesystemer* (Beim Anne, Jørgensen, & Vibæk, 2007) and *Three ways of assembling a house* (Beim, Nielsen, & Vibæk, 2010) used in Section 5.1.

[35] Tectonics is, amongst other, describing the relation between the construction technology, form of the building, and the principles behind the project decisions.

Building systems
In the interview, Anne Beim describes some of the historical building techniques, such as buildings systems of brick structures, as being more flexible than many of the system and techniques used today. As example, she mentions *Kartoffelrækkerne*, which are townhouses in three stories, constructed in the end of 1800, by use of brick structures. The buildings have gone through multiple transformations, and e.g. the walls between dwellings have been opened[36].
Anne Beim tells about some of the reasons for the difference in some of the historical building systems and techniques and the systems used today. One of the reasons is that the requirements are changed, such as the safety within the production, the lifespan of the building, transportation of the elements and many different circumstances that determines the way we build today.

The use of concrete
When talking about the use of materials in buildings Anne Beim acknowledge the good properties of concrete, but she hopes that concrete will be used less in buildings in the future, or used in a more clever way. The reason is the massive CO_2 emissions that comes from concrete production. According to Anne Beim concrete should mainly be used for structures with large span such as bridges, train stations, sport buildings, airport ect. She says, *"we don't want to see large and heavy concrete elements used for miles of housing facades. That time is over"* and *"Perhaps we can have some very clever concrete structures for buildings, that can be dressed with all sorts of envelopes and closings. We should not use concrete in a stupid way".*[37] Anne Beim also states that wood structures of CLT is being more and more used and hopefully continues the development, but she also says that CLT has its limitations and should not be used at any price. If for example constructing a high-rise building concrete or steel is still probably the best material for that.

The modifiable concrete wall
In the interview, Anne Beim was asked whether she think the modifiable concrete walls could be useful. For that, she said that it would definitely be preferable when using concrete walls, if the reinforcement is designed in a way that enables flexibility of the wall. She mentioned a case of a building with concrete elements in the facade with small and centralized openings for windows. She thought it would be nice with a flexibility in the facade elements, such that you could open them further in the future to e.g. build a French balcony.
For other purposes, Anne Beim said that she could see the modifiable wall useful for building that often needs to adapt to changes, like hospitals, institutions like nursing homes and day care centers. Anne Beim was asked if she could imagine situations where the modifiable wall could be useful for combining dwellings. She definitely could see that, and she said that currently there is a huge focus on

[36] In the interview, Anne Beim does not talk about the technical aspects of opening the walls, but probably some kind of reinforcement is needed when opening the walls between the dwellings.

[37] Quotes translated from Danish by Sara Sofie Vestergaard.

building more youth housing and senior housing, which are small. Perhaps over time they would need to be merged.
Anne Beim was also asked if she think there will be a demand for the modifiable wall. She replied that she could see a demand for some situations. She also said that probably there would be an even larger perspective for the modifiable wall internationally.
When talking about the development of the concept of the modifiable wall system, she said that it is important that there is something new that has not been seen in the systems already known. She agreed the flexible zones in the concrete walls she had not seen a lot, but she referred to a system in the southern part of Europe, where they use concrete frames, that they fill in with bricks or porous concrete. Probably with the aim of flexibility to combine dwellings. Furthermore, she said that it is important to be visionary and challenge the current production methods and not being locked by the current production facilities.
As a concluding remark in the interview Anne Beim emphasized that she thinks it is a very interesting and relevant project, and in the context of sustainable and circular buildings, there is a need for researchers and engineers to look into the actual building systems.

Claus Bech-Danielsen
Interviewed in January 2021.

Background
Claus Bech-Danielsen is an architect and professor at Aalborg University at the Department of the Build Environment, BUILD. His field of research is housing with a focus on transformations of housing. In recent years, his research has been focusing on social housing.
Claus Bech-Danielsen is one of the authors of the book *Velkommen hjem* (Bech-Danielsen, Mechlenborg, & Stender, 2018), which describes the development and trends in housing used in Section 2.

Flexibility in buildings
In the book (Bech-Danielsen, Mechlenborg, & Stender, 2018) some of the suggestions to meet the many different trends and demands for housing is to build more varied housing. Therefore, Claus Bech-Danielsen was asked if he believes that we will see the same amount of transformations in the future, even if it succeeds to build a larger variety of housing. He replied "*yes*". He believed that people would still like to adjust internally in their housing to meet their own personal preferences, but maybe we would see a little less merging of dwellings. However, that would require that there is a sufficient movement in the housing market in the respective areas, so people can move to another dwelling in the same area when their needs are changing. He stated that no matter how much the types and sizes of housing would vary in the future, the need to merge dwellings would still exist.

For the need of flexibility in the building structures, Claus Bech-Danielsen said, "w*e don't know anything about the future, so the more flexibility in any kind of buildings, the better*".[38]
Claus Bech-Danielsen was asked whether he thought flexibility is relevant both vertically across floors and horizontally in walls. He said that both cases are relevant, but if looking at history, most merging have been horizontally.

The modifiable concrete wall
Claus Bech-Danielsen could see the usefulness of the modifiable walls. He mentioned that when combining the small dwellings in social housing it is very expensive because concrete walls needs to be demolished, and for such cases it would had been relevant with the modifiable wall.
Besides merging dwellings, Claus Bech-Danielsen could see other useful cases for the modifiable wall. He talked about transformation of housing to offices, nursing homes or other building types. He also said it would be useful internally in housing when the family wants to transform the rooms. He said that in some single-family houses load bearing walls are also used internally. He also mentioned that large dwellings could be transformed to even larger ones for housing communities, as housing communities is one of the current trends. Claus Bech-Danielsen also mentioned that there could be a need for flexible solutions in the facades.
In general Claus Bech-Danielsen said that it is difficult to know the exact needs of the future, so what is important is to make the buildings as flexible as possible to whatever needs that are in the future. For the modifiable wall, the larger the flexible zone is the better.
Claus Bech-Danielsen was asked if he believed there would be a demand for the modifiable wall. He replied *"yes"*, as long as it is not too expensive, as many developers only have a short-term view for the revenue.
A last point from Claus Bech-Danielsen was that the knowledge about the flexibility of a building is important. He said that there are many flexible buildings, which for some reasons are never changed. Therefore, it is important to think about how this knowledge survives when developing the modifiable walls.

Vibeke Grupe Larsen
Interviewed in December 2020.

Background
Vibeke Grupe Larsen is an architect who has been working with sustainability in buildings for many years. Recently she started a PhD project with the title *Circular transistion of social housing: generating environmental, economic and social co-benefits by design*, where she will develop a method for integrating life cycle analysis LCA, life cycle cost LCC and social value. The PhD project is made in

[38] Translated from Danish by Sara Sofie Vestergaard.

cooperation with Danish Association of Architectural Firms and University of Southern Denmark, SDU.

Renovation of buildings
Vibeke Grupe Larsen could see a tendency that more building are renovated instead of demolished. One of the reasons is, as more reports are pointing out, that you save CO_2 emission when renovating instead of building new.

Flexibility of buildings
When asked what flexibility in a building means to her, she said it means a freedom. It is a huge quality to have the possibility to stay in the same house even though your needs changes in the future.
Vibeke Grupe Larsen talked about demographic changes, which changes the need for buildings over time. She also mentioned the trend of people working more from home, which can cause some of the office building being transformed to e.g. housing in the future.

Modifiable concrete walls
Vibeke Grupe Larsen thinks, from the sustainable perspective, that the project on modifiable concrete walls has a very interesting angle of avoiding tearing down buildings in the future. Some of the cases where she could see the modifiable wall useful, could be when building new dwellings, where the structures could be prepared to make larger dwellings in the future. She also suggested that they can be used for facade elements, enabling further openings in the facades for larger windows or French balconies.
Vibeke Grupe Larsen suggested getting some architects to make some actual suggestions of how a case with the modifiable walls could look like, to get an idea of the needed size for openings in a facade to improve the daylight, and to get some scenarios of the use. Another use of the wall she could see, was in the design phase. She had been in situations herself, where she would have loved to be able to make changes after a wall was installed.
With respect to the demand of the wall, Vibeke Grupe Larsen pointed out the importance of architects knowing about the opportunity of the modifiable wall. If people know the opportunity exist, she is sure that some would like to use it.
As a last comment, she pointed out the relevance of using reusable concrete. That it would provide a more integrated sustainability of the product, if the zones that are cut out in the future can be reused.

Clients

One of the stakeholder groups that has the largest influence on what is built are the clients/building owners. Therefore, stakeholders from the real estate departments of three large Danish pension funds were interviewed to get their view on flexibility in building structures and to see if they would potentially like to implement the modifiable concrete walls in one of their projects. The following three stakeholders were interviewed:

- Morten Leen, AP Pension
- Jens Breinholt, Pension Danmark
- Michael Hansen, PFA

The questions within the three main subjects were the following with some variations:

1. Renovations and transformations: Do you have experience in renovations and transformations of buildings? If yes, do you see any development or trends within renovations and transformations?
2. Flexibility of buildings: When you start a new building project, do you have any considerations of other use cases in the future?
3. The modifiable concrete wall: Can you see a need and use cases for a system with modifiable concrete walls? For which cases? Do you think there will be a demand for the modifiable walls? How important would the price be? If the CO_2 footprint is reduced compared to a traditional concrete element wall, would you be willing to pay extra? Can you think of a specific focus I need to take into account when designing the wall?

In the interview with Michael Hansen some questions was also asked about the project *Hillerød Markedsplads*, which was used as case in Section 5.2, as PFA is one of the clients of the project.

Morten Leen - AP Pension
Interviewed in December 2020.

Background
Morten Leen is a project chief in AP Ejendomme, which is a subsidiary company to AP Pension. According to Morten Leen, AP Pension accounts for around 500,000 customers. The ambition for AP Pension is that a specific part of the investments is allocated in alternative investments (alternatives to stocks and bonds), where a part of this is real estates. Currently AP Ejemdomme has got assets in real estate for around 6-7 billion DKK. In the beginning of 2020, AP Pension bought the Danish part of Skandia Pension, which gained 100,000 new customers to AP Pension. As Skandia had no real estate in their portofolio, and the ambition in AP Pension is to keep the same percentage of total investments in real estates, AP Ejendomme are heavily increasing their investments at the moment, according to Morten Leen. According to Morten Leen, AP Ejendomme are basing their investments in development of real estates, meaning that their aim is to join the projects from very early state, to gain from the developing profit. They have projects all over Denmark, but focus on cities under huge development. AP Ejendomme have expertise in development of whole city areas and according to Morten Leen they are very qualified in creating areas with focus on inclusion and mixed districts.

Morten Leen himself is working with buildings for business, but AP Ejendomme invests in all sorts of buildings, though very little involved in shopping malls and hotels. Their portofolio exist of 65-66 properties, where the oldest one was constructed in 2002. Therefore, they have done small renovations to optimize the building physics, but not any large renovation projects.

Flexibility in buildings

Morten Leen was asked whether AP Ejendomme considers a possible transformation of the buildings in the future when they start developing a new project. He said that in the subject of office buildings, they are looking into flexibility in the fitting of the rooms and the concepts. He stated that the concepts for the offices changes approximately every 15 years, where companies changes from cell offices, to open offices, project offices, activity based layout and so on. For these changes, it is mostly concerning non load bearing walls, but there could be cases where opening or closures in load bearing or stabilizing walls could be relevant. This could be when changing an office building from a domicile to multiple companies or the other way around.

Morten Leen was also asked if he could see the case of a residential building transformed to an office building, but he thought that such a transformation would be more difficult. With respect to flexibility in residential buildings, Morten Leen talked about an analysis from Realdania, which investigated family typologies and found that there existed around 37 different family constellations and there are still more to come. With that in mind, he finds it relevant to build varied housing with respect to room arrangements and sizes.

He could see use cases of the modifiable concrete walls in some cases. He stated though that their approach to accommodate the varying demand for housing is to build a larger variety of housing. Furthermore, they will try out new concepts for residential buildings, where the concept of the design, ownership, ect. accommodate that families can interchange dwellings and move to a new one when the family situation changes.

Morten Leen could see the use of the modifiable wall to combine two dwellings, but said that there are different challenges that needs to be dealt with. One of them is public regulations, which regulates the sizes of the dwellings in a city and if wanting to transform from e.g., small student dwelling to larger ones it needs the approval from the municipality. Furthermore, he talked about the importance of the right design if combining two dwellings, as that will include two core modules with kitchen, bathroom, ect., which can be a challenge. Another point from Morten Leen is that there can be some challenges if transforming from cheap youth housing to larger and more attractive dwellings, as the building for youth housing is constructed on a tighter budget.

With respect to a possible demand for the modifiable walls, Morten Leen said that the demand would depend on the price and the buildability. With buildability, he means that it is important that it does not make each wall even more individualized, than if using traditional concrete element walls. It should not be of more trouble to the contractor on the construction site.

Sustainability

Morten Leen was asked if they could be willing to pay extra for the modifiable walls and he had a clear statement about the focus in AP Ejendomme. He did not refuse that they could have an interest in the walls because of their flexibility, but he said that their focus is much more on the CO_2 footprint of the building, and it would be of very high interest if the CO_2 footprint of the walls can be reduced. If it succeeds to reduce with e.g. 15 % we have gotten really far, he said. If the CO_2 footprint is reduced, they would therefore be willing to pay extra for the elements. AP Pension, together with the other pension funds, has agreed to UN to invest a certain amount of money in green investments together as an industry. As part of this all investments in AP Ejendomme should be sustainable from now on. Therefore, it is the ambition in AP Ejendomme to get all their buildings sustainability certified. All residential buildings are certified with Svanemærket and all office buildings are DGNB certified with minimum DGNB gold.

Morten Leen told about EU taxonomy regulations, which is a new classification system in EU, which will define what is needed to call an investment sustainable. According to Morten Leen it will probably be a demand from around 2023 for sustainable investments. Those regulations can lead to new demands for the green investments. In AP Ejendomme they are still about to figure out what is needed to live up to the taxonomy regulations and whether e.g. their platinum DGNB certified real estates will fulfill those requirements.

Jens Breinholt - Pension Danmark

Interviewed in December 2020.

Background

Jens Breinholt is a project director in the real estate department of the pension fund Pension Danmark. He works with sustainable solutions and is responsible for their sustainability program.

Ultimo 2019 Pension Danmark had a real estate portfolio on 23,4 billion DKK.[39] They invest in many different types of buildings, housing, offices, court buildings, buildings for healthcare services, ect. They both invest in buildings for rental and for project sale. For some buildings they are part of the develop themselves and others they just invest in. So, they have a very varied real estate investment profile.

Sustainability

In Pension Danmark they construct all buildings for minimum DGNB gold certification, and city areas for DGNB platinum. As part of this, they have made their own sustainability program, which defines how they work with DGNB certifications. In their sustainability program they also state that from now on they will comply with *The Voluntary Sustainability Class*[40] with the aim of a maximum

[39] https://www.pensiondanmark.com/investeringer/

[40] *"Den frivillige bæredygtighedsklasse",* as described in Section 3.

CO_2 emission on 8,5 kg CO_2/m^2/year. They both work with sustainability in the operations of the buildings, but also the building parts and the material. They try to reduce the amount of concrete spend and to use the most sustainable products. They e.g. require that the steel in their buildings, as far as possible, comes from Celsa or similar, which produces steel from water power. They aim to construct less in concrete, but as he said, they cannot avoid it completely. Therefore, he agreed that it is good to challenge the concrete standards.

Flexibility in buildings

In the DGNB certification system credits are given to flexible solutions. Therefore, Pension Danmark is thinking flexibility into the buildings from the beginning. As Jens Breinholt states, they do not construct the buildings with the purpose of transforming them in the future, but they do some initial thoughts and designs to make transformation possible in case it becomes necessary. This includes considerations of different transformation scenarios, so when they build e.g. a cultural center, they consider if it can be transformed into a hotel, youth housing or rental housing. The transformation scenarios are considered in the design of the floor heights, depths of the building, ventilation systems, fire safety exits, ect. During Jens Breinholts years in Pension Danmark they have not been transforming any of the buildings yet though.

When talking about the use of the modifiable concrete walls, Jens Breinholt said that he could imagine some cases where it could be useful. A case he mentioned could be the need for larger door openings when transforming a building into a hotel, to comply with different requirements due to fire or handicap access. Or the possibility of making larger window openings in the facade.

Jens Breinholt stated that the modifiable wall element is not only relevant in case of future transformations, but it can also be useful in the design and construction phase. He said that it is an obstacle that the element design is locked very early on in the project, as it is not rare that they experience the tenants or themselves changes their wishes, or function of the building during the design and construction phase. For that the flexibility of the modifiable concrete walls can be useful.

Another case Jens Breinholt mentioned is a property they build in Virum with different kinds of housing and a Lidl supermarket on the ground floor. The building was prepared for a shop on the ground floor, but Lidl had extra requirements for the size of the door openings due to their logistics and the use of a pallet truck of a certain height, which had to enter through some of the door openings. Because of that, they spend more than 400,000 DKK and a lot of time on increasing the size of the door holes and making different sorts of strengthening, as the walls with the openings were used for the transverse stability of the building. In that case it would had been very useful if the walls had been prepared for larger openings, Jens Breinholt said.

Jens Breinholt was asked about how much the price matters if buying a modifiable concrete element. He replied that the price is always important as they must manage their investors money as good as possible. If they see a value in the flexibility, they could pay a little extra, but if it is of the amount 10-30% they will probably not be interested. Jens Breinholt was asked the same question about the price if the concrete elements had a reduced CO_2 footprint compared to traditional concrete elements. For that he said they are more willing to pay a little extra for. The reason is that sustainability is a good business, and they are able to increase the rent for sustainable buildings. This is because of lower operational costs, but also customers, like companies and tenants, are seeking buildings with low CO_2 footprint. At the end of the interview, he said that the sustainability development within the building sector has an extreme speed of growth, meaning that it cannot go to fast with development of the material optimized modifiable walls.

Jens Breinholt was asked if he had inputs for special considerations when developing the concept of the modifiable concrete walls. He had some different points. He talked about considering embedment of sockets of the walls when designing the wall. Furthermore, he mentioned material passports, which makes building elements useful for recycling. They can be made in form of a chip, a QR code, or other digital solutions, that can be read in e.g. 100 years. The material passport includes all sorts of information about the material and properties of the building element. It is often used for the purpose of reuse of the elements in the future. Jens Breinholt meant that it could be useful for the modifiable wall to store the information about the flexible zone, like the geometry.

Michael Hansen - PFA

Interviewed in December 2020.

Background

Michael Hansen is a senior portfolio manager in the Nordic part of PFA Ejendomme called Nordic Real Estate. He has a financial background and is responsible for the strategy of residential buildings. He has also been leading several building projects during his 6 years in PFA, including *Markedspladsen Hillerød* one of the cases in Section 5.2. PFA Ejendomme's portfolio includes business properties, primarily used for office and administration, and rental housing. The investments are made in both new construction projects and existing properties.[41]

Transformations of buildings

Michael Hansen was asked if they have experience in transformation of existing buildings. He said that some places they have transformed business properties into housing. He was further asked how he saw the development in building transformations. He replied that transformations are often done for financial reasons. If, for example, the housing market is in growth, there can be financial reasons to transform business properties into housing. Also deciding whether to tear down or transforming a building depends on what is best financially. But he stated that today the agenda starts to focus more on recycling and use existing material, so he did imagine more buildings to be transformed in the future.

[41] https://pfaejendomme.dk/in-english/

Flexibility in buildings

In general Michael Hansen sees a huge need and advantages of building flexible building structures. He said: *"I really believe there is a future in flexibility".*

One project where they have considered the uncertaincy of the future and made flexible solutions from the beginning is in the hotel building in Hillerød Markedsplads, which is further described in Section 5.2. In that case they have considered a future scenario of transforming the hotel rooms into youth housing in case the hotel is not financially profitable.

Michael Hansen said that it is very relevant with flexibility of residential buildings to enable dwellings to be combined. He talked about the uncertainties of e.g. choosing the appropriate size of dwellings when building a new residential building. He said that they use real estate agents to help predict the need for sizes and types of housing before they start a project. But sometimes when the project is done, the demand for housing looks different and the customers e.g. wants more space or a different fitting of the rooms. If it is not possible to rent out the dwellings there are two opportunities he said. Either you can lower the price or you need to do changes in the building. Sometimes it is enough to change the interior walls in the dwellings, to increase the interest, but for the cases when people are interested in larger dwellings, it could be useful to make openings in the load bearing walls between two dwellings.

Michael Hansen talked about that the wall between two dwellings locks the dwellings. In general in PFA they do not make changes in those walls. He said that of course it is possible, but it is a very difficult and expensive process to do. Therefore, he could see the use of the modifiable walls and stated that all future changes that are prepared for, makes it cheaper when making the changes. He said that having flexibility in the load bearing walls between two dwellings, would enable them to make smaller dwellings, that can be transformed into larger if needed.

Beside the uncertainties, from the project is initiated until it is constructed, Michael Hansen also talked about the development in an area over time. As an example, a location with many young people can be changed to consist of children families during 10-15 years of time, and for such cases it would also be good with the possibility of transforming the dwellings into larger ones.

In general, he stated that flexibility in a building is a large plus to him and he also mentioned the fact that flexibility provides credits in the DGNB certifications.

Michael Hansen was also asked about the importance of the price of the modifiable walls if using them to enable flexibility. He said that of course the price is important, and if something becomes more expensive it has to pay off at the end. He told that when they build, they usually expect to own the building for 100 years, and therefore it can pay off to future proof the building from the beginning. Therefore, they are willing to spend a little extra in the beginning in cases where it makes sense.

5.4 Use case sum up

Throughout this report and especially throughout Section 5, different use cases for the modifiable concrete wall have come up. In the following the different cases are summarized and elaborated upon.

Design flexibility

In the Pharma Building case and in some of the interviews with the stakeholders, the advantage of having flexibility in the design phase came up. When the concrete element designs are locked, it can be difficult or costly to make changes. Sometimes clients or the tenants changes their wishes during the design or construction phase and having zones that can be cut out of the concrete walls for a very low cost can be an advantage. Especially for pharma buildings the concrete element design is very dependent on the mechanical design. Thus, if preparing the walls with zones that can be cut out without further need of calculations or strengthening of the structure, the structural design can be made independently of the mechanical design, which in some pharma building cases has proven to shorten down the time for the design phase significantly.

Conversion flexibility

For conversion flexibility the modifiable structural system can be used for many different types of buildings. For housing, history has shown that many small dwellings have been merged into larger ones. Today in Copenhagen, there is a lack of small housing and therefore there is an increased focus on building small affordable housing for e.g. students. Probably in the future there will be a need for merging of these small dwellings into larger ones, and therefore the modifiable concrete wall is very relevant for new small dwellings. Beside merging of housing, other cases have been seeing, where e.g. a hotel has been prepared for transformation into youth housing in case the hotel do not prove to be a good business case, and in a residential building the walls on the ground floor have been prepared for transformation into office space. In the interviews, the stakeholders mention many other use cases, such as day care centers, nursing homes, hospitals, cultural buildings, ect. In principle the system can be used for all types of buildings, but of course only when it makes sense to use a structural system with load bearing concrete walls.
Beside using the modifiable walls for interior walls, the use in facades has also been mentioned from some of the stakeholders. This can be useful for preparing small windows to be transformed into larger openings for e.g. balconies. Or if wanting to prepare for an extension of the building, the exterior wall can be prepared for a door opening where the building is supposed to be extended.

It is worth noting, that no matter which case the modifiable structural system is used for, it is important to make a proper geometry of the flexible zones for them to be useful in the future. Besides, many other parameters in the building design are important to consider to make the flexibility useful. These are parameters like the floor height, the mechanical system, location of the stairways, and so on.

6. Conclusion

Different aspects concerning the need and demand in the market for a modifiable structural system made of concrete elements, has been covered throughout this report. The aim has been to gain some background knowledge about the market for buildings within subjects that are relevant for flexibility of the building structure. The background knowledge is used to predict the future needs for a modifiable structural system and assess whether the initial concept behind the system makes sense to further develop throughout the PhD project, or whether it should be adjusted to another kind of modifiable system. The focus in the report has been on housing and residential buildings in the Danish market, to limit the framework. However, other types of buildings have been included when it has been relevant.

In general, the knowledge gained throughout the report supports the need for and the concept behind the modifiable structural system. The reasons behind this statement are covered in the following, by summarizing the main takeaways from the different sections.

In Section 2 the historical development and current trends in housing in Denmark has been covered. The historical perspective illustrates a huge development in the housing stock going just 70 years back in time from the 1950's. Many factors have influenced this development, such as demography, trends in society and family pattern, technological development, governmental control, and externally imposed factors such as war, epidemic and globalization.
The current trends for housing point in different directions and makes it difficult to predict the needs for housing in the future. As the future needs can be hard to predict and as the needs will probably also vary a lot in the future, it will be an advantage to incorporate flexibility in the building structures to allow easier transformations. By enabling easier transformation and thereby support circular use of the buildings, the buildings will have better conditions of lasting longer, and fewer of them will be demolished when the functional needs of the buildings are changed. As Claus Bech-Danielsen said in the interview: *"We don't know anything about the future, so the more flexibility in any kind of buildings, the better."*

Section 2 also covers some analyses for the Municipal Plan of Copenhagen. The background documents for the Municipal Plan show some very thorough analysis that are made to predict the future needs for buildings in Copenhagen. The analyses show that supply and demand for housing in Copenhagen have changed a lot through the years and that there has been a gap between the supply and demand. The high demand for larger apartments has resulted in merging of small apartments throughout the years. However, today there is a lack of small housing in Copenhagen and therefore the Municipal Plan for 2019 provides better circumstances for building small housing. If a larger amount of small housing is constructed in the near future, there is a possibility that some of them will need to be merged or transformed in the longer run. Therefore, it would be an advantage to include flexibility in the walls between the dwellings to allow an easier transformation into larger dwellings in case that is needed in the future. For those buildings, the modifiable walls could be useful.

Some of the advantages of using a modifiable structural system are lower costs and lower environmental impact when transforming a building in the future. The economic incentive to use a modifiable structural system depends on the price of the system and the probability that the building needs to be transformed in the future. The environmental footprint of buildings has gained more focus over time and if the modifiable system can prove to lower the environmental footprint both in the short run and long run, this can be a huge incentive to use the system. Therefore, in Section 3 some of the drivers for considering sustainability and the environmental impact of buildings has been covered. The section describes some of the tools and certification systems used in Denmark to measure and document sustainability of a building. In the DGNB system, one of the most used sustainability certification systems in Denmark, flexibility and adaptability of a building also provide some score. Furthermore, the Danish government has introduced the Voluntary Sustainability Class. The Danish government also introduces regulations in terms of an upper limit for the CO_2 footprint of buildings from 2023. Therefore, the sustainability and environmental impact will be in focus in most of the industry in the near future, which can provide incentives to use the modifiable structural system.

When developing a new concept for a structural system that includes concrete walls, it is relevant to find out what the technical requirements in terms of sound insulation and fire are. This has been done in Section 4 for housing, to investigate if there are advantages of using concrete in the whole wall or if an alternative such as a frame structure with some sort of lightweight material in the flexible zone is just as good. The requirements have been found for walls that are separating two dwellings. It is found that the acoustic requirement for airborne sound insulation are typically determining for the thickness of walls between dwellings. It is also found that a lightweight wall will typically need a little more thickness than a concrete wall to fulfill the acoustic requirements. Furthermore, a concrete wall that fulfills the requirements performs better for low frequency sounds than a lightweight wall that fulfills the requirements. Thus, the technical requirements for a wall separating two apartments have shown that there are advantages of using concrete compared to lightweight material. In Section 4 it is also found that there is another advantage of using a concrete structure compared to a lightweight structure, in terms of heat accumulation. Concrete has a high thermal mass, and using a concrete structure compared to a lightweight structure can reduce the heating requirements with a significant amount and it can also reduce overheating issues. This shows that there can be advantages of using concrete in the flexible zone compared to lightweight material. Another argument of using concrete in the flexible zone can be the construction process. A flexible zone of concrete is casted together with the remaining element at the factory, which can be easier and simpler than installing e.g. wood or plasterboard and insulation afterwards. Having a simpler construction process, can help scale the use of the product, which can also be an advantage. It should be mentioned that the advantages found in this report of using concrete in structural systems, are not covering all aspect that has to be taken into account when choosing a structural system, but they are used in the context of the modifiable concrete walls, to consider if it makes sense to use concrete in the flexible zone. The advantages of using concrete in the flexible zone supports the initial idea of the concept, and as mentioned it will be investigated how little cement and reinforcement that can be used in this zone, to minimize the CO_2 footprint.
In Section 5 the concept of flexibility has been further investigated. Different types of flexibility have been defined and the modifiable structural system concerns the two of them: Design flexibility and conversion flexibility. The Section looks into previous industrial building systems, that are developed with an eye of flexibility. It covers some cases, where walls have been prepared for future openings, and it provides interviews with some stakeholder, to find out what their view is on flexibility and the concept of the modifiable structural system.

For industrial building systems some very thorough analyses of different systems have been found in the book *Arkitektonisk Kvalitet og industrielle byggesystemer* (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007). The analyses cover different cases of development of industrial building systems for housing, where industrialization and flexibility have been in focus. The cases in the book illustrate a tendency that some of the most flexible systems consisting of columns/slab or frames did not survive in their original forms for residential buildings and ended up consisting of load bearing walls instead. Different reasons for that are discussed, and one of the main reasons explained are the technical requirements such as acoustics and fire, which makes the lightweight walls more expensive (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007). Other reasons are also explained such as exterior factors like the economy of the society and the organizational setup of the team developing the system, such as the client, contractor, architect, developer and end-user.
Other parameters that are good to have in mind when developing an industrial building system are also discussed. It is found that it is important to include both the long term *architectural/total cost rationale* that ensures the long term perspective of a project, and the *technical/economical rationale* that ensures the system being rational in its production and implementation, to develop a system that can survive in the market. Furthermore, two different strategies are mentioned: Revolutionary strategy and evolutionary strategy. According to the book from CINARK (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007), the evolutionary strategy, which focuses on innovation in just one or few aspects, often reaches the furthest with respect to the final results. This also supports the concept of the modifiable structural system, which can be said to be evolutionary as it takes its basis in well-known production techniques for concrete elements, and do not start completely from scratch. Furthermore, considerations of whether the system should have more or less integrated or predefined solutions, such as predefined geometries or specific solutions for the connections has also been discussed. A drawback of a system being very integrated/predefined is that it provides many limitations (Beim, Jørgensen, & Vibæk, Arkitektonisk kvalitet & industrielle byggesystemer, 2007).
The experience from the cases of industrial building systems (Beim Anne, Jørgensen, & Vibæk, 2007), where the most flexible and open systems end up using load bearing concrete walls, is very interesting when developing a new system consisting of load bearing concrete walls. The cases support the statement that there are advantages of using concrete wall elements. A disadvantage of using concrete walls is that they are not very flexible, and therefore it makes sense to make the concrete walls modifiable to increase their flexibility. Thus, the modifiable concrete walls both use the long term *architectural/total cost rationale* in terms of the flexibility and the short term *technical/economical rationale* as it is based on well-known industrialized production techniques. However, as Anne Beim also mentions in the interview, it is also important to challenge current production techniques. From that it can be concluded that it is good to take the basis in the current techniques and use them whenever it is optimal, but the solution for the walls should not be limited by them.

In Section 5.2 examples are shown, where future openings of the walls have been considered from the beginning. The case Kanalfronten Vejle with walls on the ground floor that was prepared for openings, illustrated the importance of having a sufficient size of the prepared opening, as it turned out that they had to be larger than prepared for. The Pharma building case shows that there are huge advantages of ensuring flexibility in the walls of buildings used for production facilities as there are frequent changes in those.

The interviews with the stakeholders have in general supported the idea behind the modifiable structural system. All stakeholders said that there is a need for flexibility in buildings, and they could also see the advantage of a flexible zone in the concrete walls. Different ideas for the use of it came up, such as merging of housing, transformation of housing, offices, nursing homes, hotels ect. Several stakeholders also mentioned flexibility in the facades as being useful and the advantage of having flexibility in the design phase. For the clients, they could all see the usefulness of the modifiable wall for some cases. However, a different approach to the flexibility in residential buildings was mentioned, which were to focus on building a varied supply of housing in an area. One of the clients said that the modifiable wall could be very useful for housing, as it is very hard to predict the demand for sizes of housing when starting a new project and it often turns out to be other demands than predicted. All clients said that the demand for the modifiable concrete wall would depend on the price. In general, they said that if they could see a value of the flexibility, they could pay a little extra, but not much. Some of the clients valued a reduced CO_2 footprint higher than the flexibility as they have a huge focus on that. One of them said that it would be of very high interest if the CO_2 footprint of the walls could be reduced and for that they were willing to pay extra. Thus, in general the sustainability is in very high focus for the clients, especially the CO_2 footprint. The need for the flexibility would depend on the specific case.

Some challenges were also mentioned in the interviews. These were challenges like preparing a proper design that makes the building fit for transformation. Another challenge that were mentioned were the quality of the building if transforming from youth housing constructed on a tight budget into larger more expensive housing. Some of the stakeholders also mentioned the importance that the knowledge about the flexibility survives. For that the material passport was mentioned as a solution, to save information about the flexible zone.

As a concluding remark, this report and the research process behind the report, has left the author with a confidence that the initial ideas for the concept of the modifiable structural system made of prefabricated concrete elements, are worth following throughout the PhD project. It also provides a good background knowledge for why it is needed, which cases it can be used for and how the focus on sustainability in the market can be a driver for using the modifiable system. Furthermore, it provides knowledge on which benefits there are of using concrete in a wall compared to lightweight material, insight in other flexible systems that has been developed through time, and what different stakeholders think about the concept.

The concept of the modifiable concrete walls seeks to be an alternative to traditional way of designing concrete elements that are used a lot in the industry. The project aims at finding a way to use the concrete smarter and push the boundaries for the codes and standard ways of producing concrete elements, and thereby contributing to the reduction of the environmental impact from buildings and concrete structures on the short run and long run. With this report in mind and the knowledge gained throughout the research, the PhD project will continue the structural analyses and develop the technical knowledge and the framework that is needed to find an optimal structural design for the modifiable concrete walls.

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