FLEXIBLE PREFABRICATED COMPONENTS

Modular and flexible housing components
for the Circular economy

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God bless.

ABSTRACT

With the country's expanding population comes the need for more homes to accommodate its residents. In the Netherlands, there is a growing housing shortage. Fast construction techniques of prefabricated dwellings erected on existing flat roof tops may be a solution for saving land and resources in and around urban areas. Flexible solutions with sustainable design techniques that cater to the masses are essential for the Circular economy.

The research topic is presented, and the research questions are framed in terms of technique and relevance to the construction sector. Flexibility issues with contemporary house designs are highlighted in the literature review, and circular building concepts are discussed in order to develop design requirements for building components. The many types of prefabrication are identified, and a system is chosen for the design concept. Building physics strategies relating to steel's thermal and acoustic qualities are examined, and these strategies are noted for prospective integration into the design.

A design suggestion for modular housing top-up units is presented. Different options for internal partition walls and façade architectural components are presented, all of which are modular and designed to extend the life of the components through reuse. The modular components are used in a top-up situation to validate the architectural quality of the design.

The design criteria given out in the research are used to evaluate the building components. Finally, conclusions are drawn and research questions are addressed.

Keywords:
Flexible, circularity, prefabrication, design for disassembly, lightweight steel frame

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1. RESEARCH FRAMEWORK

1.1 BACKGROUND - KLOCKNER METALS ODS

This sustainable design graduation research involves the company Klöckner Metals ODS Nederland (ODS NL), who is a multi-metal distributor located in the Netherlands and Belgium. ODS is a subsidiary company of the German Klöckner & Co SE, who holds a world wide trading market and is the largest independent steel and metal distributor in Europe and North America combined. Both ODS NL and Klockner & Co SE have the ambition to keep growing and with the emergence of circular economy playing a prime role in the construction industry, the company seeks to implement circular approaches into their building products.

The company played a prominent role in the realisation of the first GTB (Green transformable building) lab circular module in 2019 with Ar. Elma Durmisevic and other industry partners. The circular module was designed with complete reversibility in consideration, with the goal of maximizing the reuse of all building components. The company recently in 2020 equipped a pavilion designed by Pompa ter Steege Architecten at The Field, a hotspot for circular buildings in Leiden with a façade system recovered from the scale model it built for Gare Maritime in Brussels. The company wishes to explore more future possibilities in the housing sector with their current steel profiles as a part of their circular construction ambitions.

The scope of this research is limited to steel prefabricated systems with Light steel framed (LSF) for houses. For the design of this new system, the Jansen VISS Quattro profile developed by the company is taken for the research. Further, circular building materials such as bio-based products will also be considered to be integrated with the Jansen VISS profiles for the façade or the wall module.

1.2 CONTEXT OF THE RESEARCH

For the ever growing population of the world, there are not enough resources on our planet to provide for everyone, which is why a different approach is required. To ensure that there are enough resources for all, we must switch from a linear economy where waste products are discarded, to a circular economy where waste is avoided by producing and reusing products and materials effectively. If new materials are required, they must be sourced in a sustainable manner to avoid harming the environment. This implies to the construction industry as well, as it is one of the largest consumers of raw materials and energy. In the Netherlands, the building industry is expected to account for 50% of raw material consumption, 40% of total energy consumption, and 30% of total water consumption. Furthermore, construction and demolition waste accounts for a significant portion of waste in the Netherlands (about 40%), and the industry is accountable for roughly 35% of CO2 emissions (Circular economy, 2016).

With the growing population of the country also comes the housing problem to accommodate its inhabitants. There is a huge housing crisis in the Netherlands. According to Bouwinvest, the condition is much more critical today, considering that the national housing deficit is expected to have doubled since 2008, reaching around 300,000 homes in 2020, with some estimates predicting that the supply/demand gap could widen to around one million homes by 2035. With the shortage of housing in major cities, finding a place to live has also become expensive and difficult. When the Minister for Home Affairs, Kasja Ollongren delivered the 2020 report on the condition of the housing sector to the parliament in June 2020, she stated that 845,000 homes must be constructed by 2030. (NL times, 2020). Therefore the Netherlands needs to keep building to avoid this crisis, but also in a circular manner to address the global sustainablity issues.

One may suggest that prefabricated housing solutions could solve the housing crisis since it has several advantages over conventional construction methods. It's fast construction time could help the country achieve its housing number targets. It's cost effective solutions could address the affordability issues. Construction waste can be reduced since products can be mass produced in the factory and a higher quality of construction could be achieved because of better working conditions. These are some of the benefits that prefab homes can have over conventional construction systems.

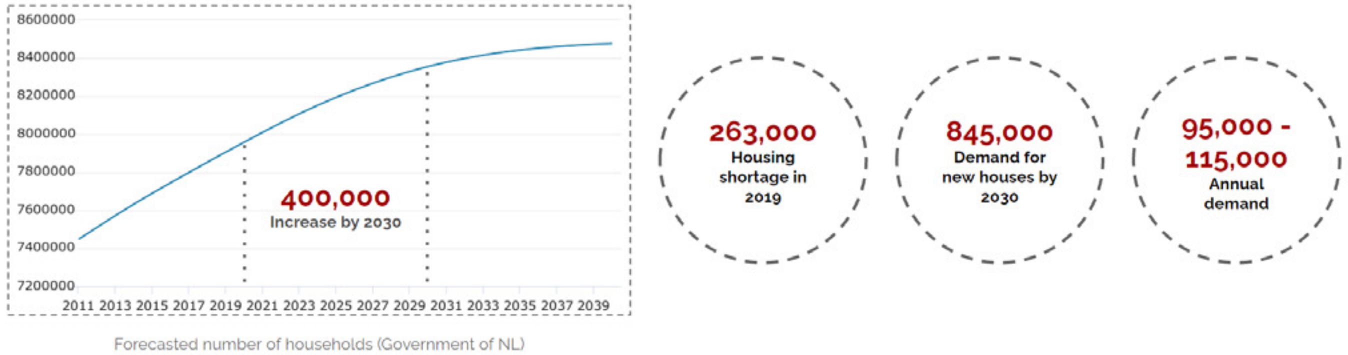


Figure 1.1: Housing numbers (Source: government.nl)

A solution could also be to create houses on top of existing flat rooftops (Top-up housing), instead of building them on vacant plots in order to save land in and around cities in Netherlands. These vacant flat roofs are many in number across cities such as in the case of Rotterdam, with over 18 km2 flat roof areas (Gemeente Rotterdam, 2019). One could exploit these spaces to help overcome some of the housing crises in Netherlands. Building Top-up houses would also depend on the structural capabilities of the existing building. Since the structural aspects are beyond the scope of this research, it has been assumed that two storied houses with lightweight building components with a standard storey height of approximately 3 meters have been considered.

1.3 PROBLEM STATEMENT

While prefabricated houses can have certain advantages over conventional houses and its construction methods, it is not admired by many home owners for reasons. One major reason is its inability to adapt to different customer choices, since it comes with limited choices or no choices at all. Owners do not want their ability to personalize or change the look of their home restricted (Friedman & Cammalleri, 1993), with others go so far as to say that if buyers are to be attracted by the modern methods, prefabricated houses must be unrecognizable from traditionally built methods of construction (Gann & Senker, 1993). The vision of the Transition agenda Circular construction economy also states that, Sustainable materials will be used in the construction process, and designs will be geared to the dynamic wishes of the users (Transition agenda Circular construction economy, 2018).

In order to accomodate the home owner's wishes, some degree of flexibility in the design of prefabricated parts are desired. This flexibility can be in terms of design related choices like size, layout and orientation etc., aesthetic appeal like materials and finishes, technical aspects such as durability, acoustics and thermal performance and building service related aspects like electrical, plumbing and accomodation for new mechanical equipments etc. The more flexible the system, the more choices a home owner can have and a way to achieve a more flexible and circular system.

In order to move to a sustainable built environment, aspects of circularity need to be incorporated in the design. The design for disassembly (DFD) can be seen as the master strategy for circular design approach. It allows reuse, repair, remanufacturing and recycling. A usual building will last from 30 to 50 years and sometimes even longer. A good design will already allow to transform the function of a building by incorporating adaptable building components. Thus, the longer a building components will serve their purpose, the lower the impact on the environment. Therefore, the design must be robust with flexible components to ensure its parts can be reused in the same or different buildings. This approach implies to prefabricated houses as well where the user or their lifestyles can change, which would mean a need for renovation to a certain degree. By considering design approaches for DFD and flexibility, the reuse potential of a building product can be higher. However, achieving this can be a challenge with regards to function, aesthetics, technicality and services of the building as previously mentioned. How is flexibility related to circularity and upto what extent can flexibility of building products influence its circular characteristics?

1.4 OBJECTIVES

Following from the problem statement the main objective of this research is:

- Analise the feasibility and influence of flexibility on Light steel framed (LSF) prefabricated top-up houses for achieving a circular design approach.

The sub-objectives are:

- Finding the relationship between flexibile and circular design.
- Identify and address acoustic and thermal problems for steel prefabricated components.
- Identify problems and opportunities with existing houses with respect to flexibility.
- Find ways to use Klöckner Metals ODS steel profiles in building components in a flexible and circular manner.
- To propose a design for a building component (façade or partition wall) that supports flexibility and disassembly while addressing the technical facet (acoustic and thermal).

1.5 RESEARCH QUESTION

Related to the main objective the following research question is:

- **How can flexibility of Lightweight steel framed (LSF) construction in prefabricated top-up houses help improve its potential towards circularity with added benefits?**

Further, the sub-questions have been derived:

- What is the relationship between flexible and circular design?
- What are the acoustic and thermal problems for steel prefabricated components and how can we address them?
- What are the problems and opportunties of existing houses that affect flexibility?
- How can Klöckner Metals ODS steel profiles be used in a flexible and circular manner?

1.6 METHODOLOGY

Based on the main objective and research questions the research is structured as shown in figure 1.2. The first step is the literature study of two aspects. The first one is to get a basic understanding of circular design and flexibility. Flexibility and circularity of buildings components will be defined and a clear relationship between them must be identified to answer the research question. Further, problems and opportunities related to flexible building components will be studied particularly in the housing sector through literature study and case studies. Through these approaches, a set of criteria for a circular design would be formed either for building components.

The second one to be studied alongside is prefabrication systems in building construction. Types of prefabrication will be classified and be looked into to get a good understanding of the system. The problems of Lightweight steel framing construction with respect to thermal and acoustic perfomance will be studied through literature and case studies. Since steel would be the main supporting structure for components, ways to find solutions in a circular manner for them would be determined.

A brief study of the company Klöckner Metals ODS will be carried out. However, a thorough analysis on their steel profiles, Jansen VISS in particular, will be done in terms of design, production, assembly and disassembly sequences, and flexibility. The products would be assessed according to the set of criteria and problems and opportunities will be identified. The problems would be addressed and the opportunities would be evaluated to make use of it for the new system. This new system could be generated for a building component like façade, indoor partition wall module or both depending on the study and the time constraints of this research. Accordingly other circular materials to go with it depending on the building component type will be identified and applied in the process.

The context of the prefabricated top-up housing unit will briefly be looked into. The prefabrication type and the way it is assembled on site will be addressed conceptually. Depending on the design requirements, variants of design will be proposed and would be further evaluated according to the set of design criteria. The research paper would be concluded by answering the research questions and further research and reflection on the topic will be put forward.

1.7 RELEVANCE

Designing of building components in a sustainable and circular way has to be thought about in a detailed manner to save resources using the current technology available to us. This research focuses on using building technology (Steel prefabrication technology in this case) in a circular way to have a positive effect on the larger architecture realm and propose a solution to the housing crisis in Netherlands. In order to achieve circular goals set by the Dutch government by 2050, mass production and application of circular building components must be realised. Prefabrication of building products is one of the most effective ways to achieve this. However, with prefabrication of products, flexibility is an issue due to diverse user demands and the changing economic and technological trends. If flexibility of prefabricated building products can be addressed in a circular way, it could cater to a larger audience within a short frame of time, thus paving the way to reach circular building goals by 2050.

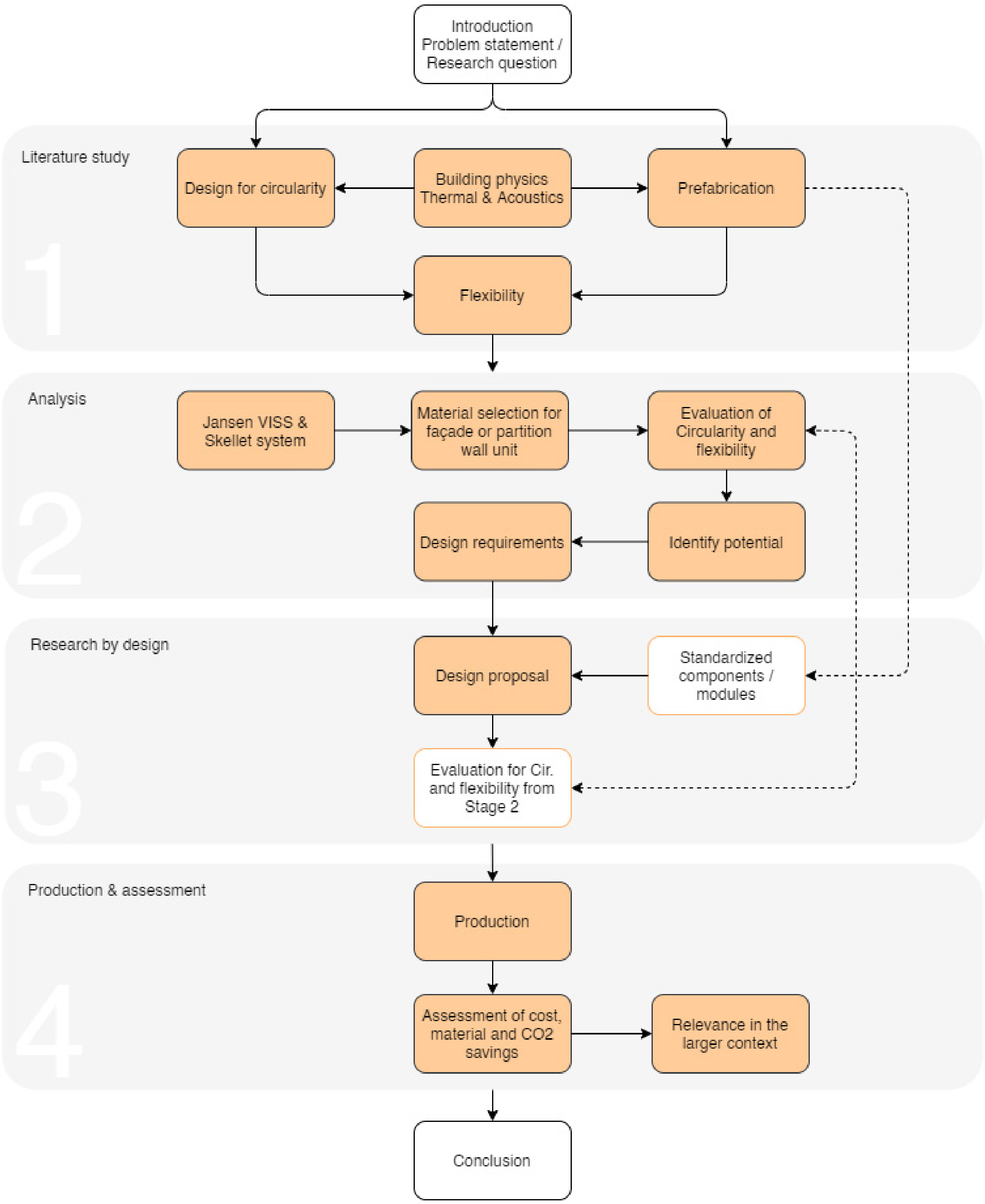


Figure 1.2: Methodology (Source: author)

2. CIRCULARITY AND FLEXIBILITY

2.1 INTRODUCTION

Circular building is an integral part of the Circular Economy (CE) concept and in the past decade it gained momentum in the Netherlands since its inception. The construction industry is recognized by the Dutch Ministry of Infrastructure and the Environment as one the five sectors that can play a key role in achieving a circular economy by 2050 (Circular economy, 2016). In order to facilitate circular flows of building materials and products, segregating the building layers as emphasized in Stewart Brand's shearing layers diagram (Brand, 1995) as seen in Figure 2.1 and eventually leading to the segregation of detailed building parts is important. This would enable easy disassembly, reusability and recyclability of building products. One approach to achieve this is by creating a clear separation between structural and non-structural elements, which promotes circular flows of materials and products and adheres to the core principles of flexible building (Geldermans et al. 2020). Flexible building components allow for change of parts and reconfiguration of spaces according to the changing occupant lifestyle, different users, function and potential upgrades to a system (Geldermans et al. 2020). As a result, a clear relationship between the concepts of Flexible building (FB) and Circular building (CB) can be established.

A flexible building component and circular building component can be defined as follow:

- Flexible building components are building parts which have the capability to adapt functionally or aesthetically to constant change in user and strategy demands to address social, sustainable and economic issues.

- Circular building components are building parts that concur to circular design approaches such as Open building concept, Design for disassembly, reusability and recyclability etc. and are built out of sustainable materials.

To achieve circular building objectives by 2050, the emphasis must change from small scale pilot projects to mass customization projects affecting a larger scale. Prefabrication principles such as modularization and standardization of components and mass production can help aid this cause. However, this is made possible by working together closely with key stakeholders and the end user of buildings. For a fruitful, meaningful design a comprehensive user-centric approach is required. It is important to identify, apply, and evaluate parameters for measuring user benefits for flexibility and circularity. This study looks at the potential of flexible and circular design concepts in terms of user benefits, such as increased control and comfort for residents. The chapter is structured around these points:

- Housing flexibility problem
- Housing flexibility opportunities
- Identifying the relationship between flexible and circular building components

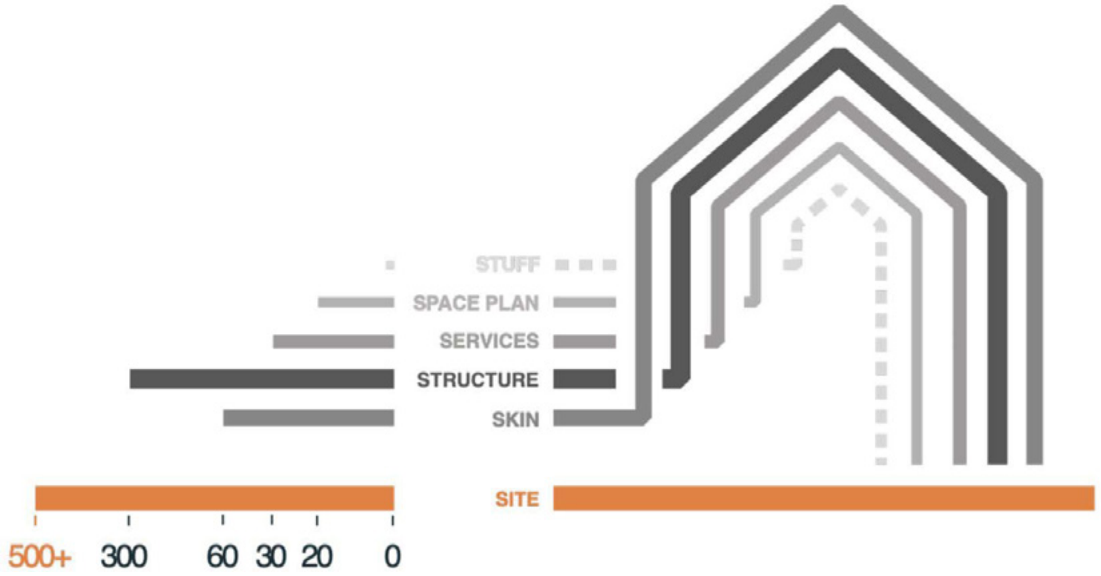


Figure 2.1: Stewart Brand's shearing layers (Source: Circular economy for a sustainable built environment, TU Delft)

2.2 HOUSING FLEXIBILITY PROBLEM

The numerous levels of economic, technological, and cultural developments in our society have an impact on our daily experiences. Changes in the user, changes within the family structure, and the activities done within are all examples of changes in housing. Housing flexibility aims to cater to the needs of different people by altering their living spaces and functions. It was a vital source of mass social housing, which provided shelter to the majority of working people and their families (Leupen, 2004). It allows buildings to be modified spatially or structurally to meet user needs, while also accommodating economic, technical, and cultural changes that occur over time. It could be based on extending the lifespan of building products by using circular design approaches through sustainable material choices and reusability of building parts.

Flexibility refers to a space's ability to provide a variety of options, configurations, and modifications (Groak,1992; Rabeneck et al.,1973); or the polyvalence of a space to perform multiple functions without changing its shape, resulting in an optimal answer (Hertzberger,1991). Structure, construction methods, in-built furniture, partitions, materials, and building facilities are all variables it incorporates. It can exist in the detail to a large scale building unit as a whole. Further, some case studies from literature research are given below which shows the need for flexibility in housing.

Slaughter (2001) studied into 48 projects in the US, looking at the structures, external wall, utilities, and interior finish. The survey found that, in order to meet new uses, buildings need more renovations than initially assumed. Even though most buildings are independent and continue to function, changes within the enclosure and in the performance of building components can occur. Systems, components, and processes will all change as a result of the new functions. Slaughter (2001) implemented the most widely used design techniques for flexibility and grouped them into ten groups to avoid certain situations (Table 2.1). Since they concentrate on the autonomy of elements, easy access, and emphasis of technical areas, these methods can easily be integrated into the design of living spaces. The implementation of flexibility in buildings, according to the report, has a small effect on the initial cost but produces savings during the first renovation, resulting in a positive investment return. Despite the fact that they extend construction time, the techniques reduce renewal time and make maintenance easier.

Design Strategies	
Reduce inter-system interactions	Dedicate specific area/volume for system zone
Reduce intra-system interactions	Enhance system access proximity
Use interchangeable system components	Improve flow
Increase layout predictability	Phase system installation
Improve physical access	Simplify partial/phased demolition

Table 2.1: Flexible design strategies (Source: Slaughter, 2001)

Dhar et al. (2013) assessed 15 families in Khulna, Bangladesh, consisting of 12 multifamily and 3 single-family dwellings. According to the study, middle and lower-middle-income residents change their homes more often than high-income residents, every 5-10 years. The common reasons for change were due to the rental market, lifestyle transformations, family structure and technological update. The highest percentage of changes (Figure 2.2) was the accommodation of extra people and in function (business or otherwise not specified in the study). It was determined and stressed that in developing countries, flexibility should be recognized because it extends the life of buildings and decreases necessity for demolition.

According to a research by Montellano (2015), 18 of the 28 apartments were studied in Casa de Las Flores (fig 2.3), which was built in 1931 by Secundino Zuazo in Madrid. He discovered

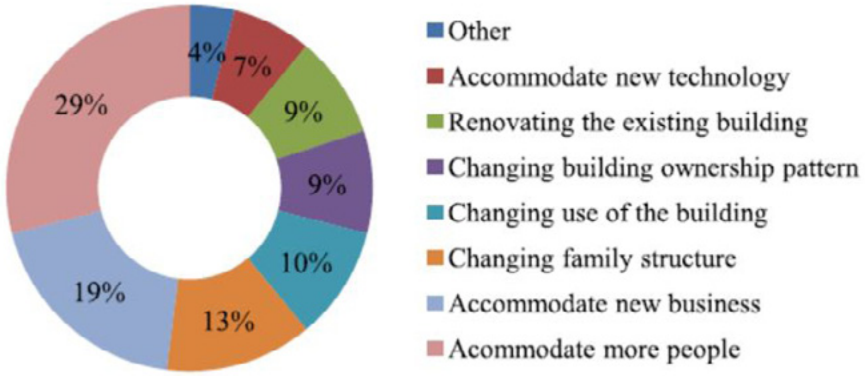


Figure 2.2 Reasons for layout adaptations in Khulna housing (Source: Dhar et al., 2013)

12 separate domestic arrangement types and 21 apartment setups, as well as previous configurations and ongoing modifications. In 14 of the 18 apartments, alterations in function were discovered, as well as the division of rooms in 15. Changes in the family structure, domestic dynamics, and resident demands all contributed to the changes in the configurations. Even though the walls were load bearing, the inhabitants managed to make these changes, which could have been more if they were not. The study concluded that due to load-bearing walls, it was impossible to have transversal connections between rooms.

Figure 2.3: Casa de Las Flores block and several apartments from the survey (Source: Montellano, 2015)

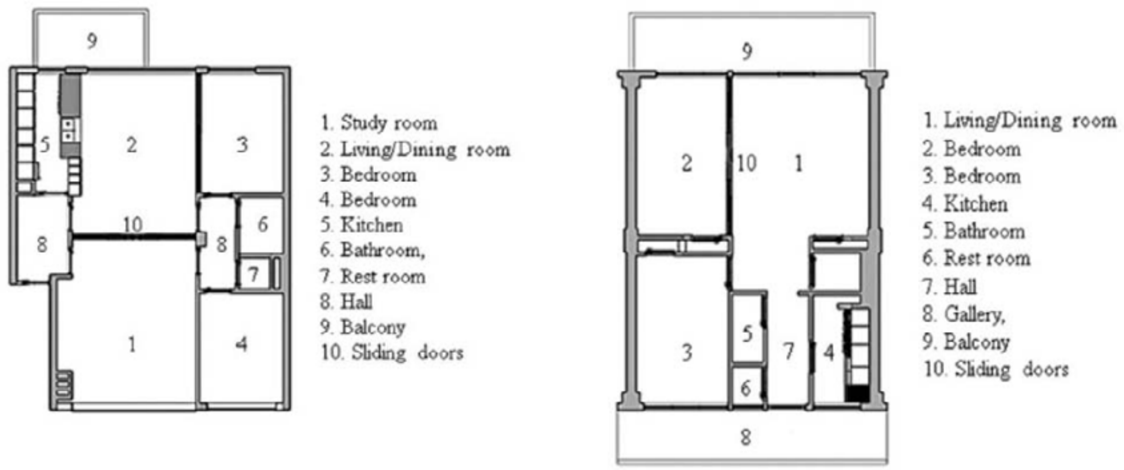


Figure 2.4 Vroesenlaan apartment left, Bergpolder apartment right (Source: Raviz et al., 2015)

Two case studies on Dutch housing in Rotterdam (Figure 2.4) were done by Raviz et al. (2015). The first one was the Vroesenlaan apartment block designed by Van den Broek in 1935 and the second one was the Bergpolder apartment building designed by Willem can Tijen in1934. The apartment was structured as per the day/night cycle in both cases, which included a multipurpose room with indirect access that could be used for a variety of uses. As per the user's needs, the living/dining room and single bedrooms were designated as multipurpose areas. The apartments were able to integrate different activities by using sliding doors, walls, and other flexible components, demonstrating how flexibility can provide layout configuration options.

From these case studies it is imperative that flexibility in housing is a problem in the long term. Slaughter (2001) also highlights design strategies to overcome flexibility issues, while the two case studies by Raviz et al. (2015) in Dutch housing showcases some promising solutions by using flexible building elements. The problems arise mainly due to constant change in users and their changing demands. According to Geldermans et al. (2020), the degree to which multi-family housing in the Dutch context incorporates changes with time was the subject of three conclusions. These were:

- Housing quality demands vary by individual or target group, as well as by time period; current stock will often need adaptations.
- Inflexibility of housing remains the norm; the vast number of multi-family housing is built in view of no or only one sort of occupant/occupancy.
- More than once in the last few decades, paradigm changes based on a desire for greater versatility have been pointed at.

User demands will always change and differ from person to person, while technological advancements will also contribute for the need to change. However, the only way to tackle flexibility in buildings is to predict and take into consideration these changes and accordingly design flexible components that can adhere to these changes.

2.3 HOUSING FLEXIBILITY OPPORTUNITIES

Some studies and efforts have been made in the past to make housing more flexible due to an understanding that it is not only a problem in terms of changing user demands, but also a sustainable and circular issue. Whenever a change or renovation of a building component is made, the used product is usually dumped as waste and discarded which in turn loses its value. The principles of Open Building (OB), Industrial, flexible and demountable (IFD) and Design for disassembly (DFD) will be studied along with other case studies to give an insight of possible flexible design strategies.

2.3.1 OPEN BUILDING (OB)

Open building is a design approach for architecture and buildings that allows adaptation of buildings during its life time to social or technological change. In expectation of complex, ever-changing user activity, it accommodates changing layouts (Geldermans et al. 2020). The concept was founded by Dutch architect, John Habraken in his book Supports: An alternative to mass housing in 1961, however the term was coined in the mid-1980's in the Netherlands (Council of open building). One of John Habraken's best quotes sums up the roots of the idea of Open Building: "We should not forecast what will happen, but try to make provisions for the unforeseen" (Habraken, 1961). He proposed introducing various stages of decision making in the construction process to accommodate unknown potential change: tissue, support, and infill, respectively referring to the urban fabric, which contains the structural element of the building with their fit-outs.

Open building provides the foundation for a well-organized construction process with clearly defined interfaces by enabling the construction process to be partially transferred from building to production. It is seen as an answer to eliminating waste by arranging measurements and roles rather than cutting to scale on the site. This is a necessary condition for reusing building pieces, thus extending their lifespan without the waste of dumping and recycling, which occurs simultaneously as deterioration and the use of resources (Cuperus, 2001).

In this building concept, to create an atmosphere that can adapt to individual needs of the dweller, the support and infill were viewed as separate entities with different life cycles. It is a multi-faceted philosophy that includes technological, financial and organizational solutions for a flexible built environment. It encourages user participation, industrialization, and reorganization of the construction process.

Principles of Open building
Open building advocates for a strong distinction between support and infill, emphasizing that this is about more than just technological capacity, but also about the ability to facilitate personal control. The supports are permanent and belong to the public domain, while the infill belongs to the individual owner/user and can be changed. The user's participation and freedom of choice are the primary goals. It works with Stewart Brand's shearing layers of change concept where the faster layers should not be hampered by the slower layers in order for a building to have a long lifespan. The principles have been categorized according to the Brand's system of layers for buildings (Open building, 2021).

Site: The first layer is the building site which has an infinite lifespan, where property rights and freedom to accommodate a function is open. It should have access to centralized connection to utilities such water, electricity etc. These aspects are not studied in detail in this research since it falls more on the urban, city level scope.

Structure: This layer should robust enough to be able to withstand more than 200 years and should be oversized to meet both residential and non-residential requirements. Free layout spaces should be encouraged with open floor spans and possibility of vertical ex-

Building Layers	Design Principle	Solution / Strategy
Site (Infinite)	Property rights	-
	Maximize amount of apartment rights	-
	Freedom of function assignment	-
	Centralised connection to utilities	-
Structure (>200 years)	Robust	Higher safety factors could be considered
	Oversized	Higher margins can be incorporated
	Meets residential and non-residential requirements	Larger grid spans for more flexibility
	Free layout	Open floor plan
		More vertical connections rather than horizontal
	Partition walls disconnected from supports	Dry, accessible and demountable connections
Skin (=50 years)	Demountable	Dry and accessible connections
	Adaptable	Modular panel sizes
	Freedom of appearance	Flexible and adjustable framing system
Systems (=25 years)	Demountable	Dry and accessible connections
	Independent from support	Integration within flooring or ceiling system
	Maximise free layout of floors	Raised floor or suspended ceiling system
	Centralised cabinets	Consolidating MEP systems into building core
	Shared facilities	Common extraction points
Space Plan (=15 years)	Demountable	Dry and accessible connections
	Flexible	Open floor plan with movable partition walls
	Property of inhabitant	Interior space without walls and finishes
	Circular materials and systems	Sustainable products with leasing possibility
	Customized manufacturing	Flexibility in design phase

Table 2.2: Open building design principles (Source: Author)

pansion for the future. The partition walls (infill) should be disconnected from the supports.

Skin: The building façade should be able to fulfill approximately 50 years of life and be demountable when the need arises. Freedom of layout behind the uniform appearance of the façade can be ensured by standardizing grid sizes.

Systems (Services): Building services and installations should have a use lifespan of at least 25 years. They should be demountable and independent of the other layers. These can be achieved by using raised floor systems or suspended ceilings. These facilities should be shared while maximizing free layout of floors.

Space plan: This layer has the lowest use lifespan of 15 years but more is encouraged. They should be demountable, flexible and adjustable and falls under the property of the inhabitant. Partition walls, furniture and cabinets etc fall under this category. Circular materials and circular trading systems should be encouraged to reduce waste due to its shorter lifespan.

The basic design principles and strategies for Open building system have been listed (Table 2.2). These design strategies will be used as a guiding principle in this research paper to come up with a design solution.

It is evident from the literature that OB principles emphasize on flexible design strategy mainly on the infill partitioning system. A study was conducted by Geldermans et al., (2020) with Open building experts to look into the connections between circularity, flexibility, and residential usage gains in greater depth. The expert consulted here was architect Frans van der Werf, who since the 1970s has used open building concepts in his own work and has gotten a lot of attention recently also in relation to circular building goals. The addition and removal of indoor partitioning walls are among the most significant

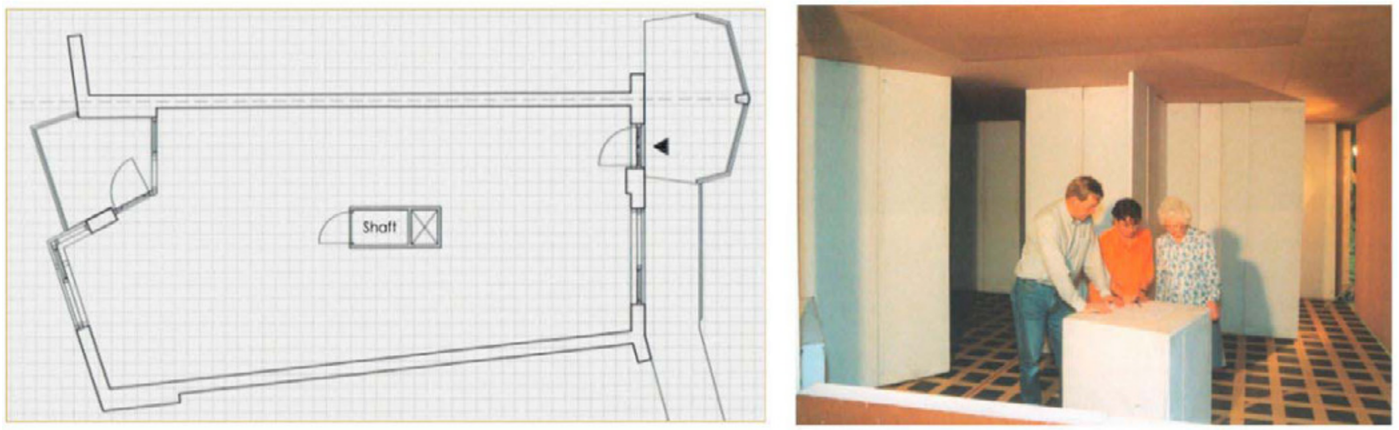


Figure 2.5 (a) Open plan design (b) User consultation (Source: Geldermans et al., 2020)

improvements to the interior layout, according to Frans. In a number of projects, Van der Werf built housing structures with versatile layout capability, such as the Pelgromhof project in Zevenaar (1999–2001), as shown in Figures 2.5 (a, b). According to the consultation with Van der Werf it was found that infill components could be placed on a modular 30 cm grid, and contact with residents is labor-intensive in the initial stage but rewarding. It recognizes that all households are unique, and that customization must be valued in the design and construction of individual housing units (Geldermans et al., 2020).

The OB principle focuses on having a clear distinction between the support and the infill components which is also in relation with flexible and circular building principles. General aspects regarding the distinction between the support and infill domain is shown in table 2.3. Recommendation for the need for adaptability notably lies on the infill side (Geldermans et al., 2020). Here, one can see that there is a clear distinction between the interests of the investor and the user and how the user predominantly reveals itself on the infill side. It also shows that the characteristics of these two components differ. The shorter lifespan of the infill components demands more change therefore it should be demountable and flexible. This could facilitate circularity of building components that can adapt to change and ensure less waste by reusing them.

The open building concept garnered attention worldwide and is still a popular concept among many architects and designers. Figure 2.6 showcases CiWoCo, in Amsterdam by Gaaga, where open building principles have been utilized. With the advent of circular economy, OB has gained more momentum since it supports circular building approaches.

	SUPPORT	INFILL
Characteristics	Long lifespan Fixed Architecturally strong	Short lifespan Variable Demountable
Scope	Main structure Collective spaces	Partitioning walls Kitchen, bathroom Mechanical, Electric, and Plumbing services Possibly façade elements
Decision Sphere	Investor	User
Circularity Relation	Retained or increased value Long lifespan	Adapts to change Less waste Facilitates circular reuse

Table 2.3 General aspects regarding the distinction between support and infill domains. (Source: Geldermans et al., 2020)

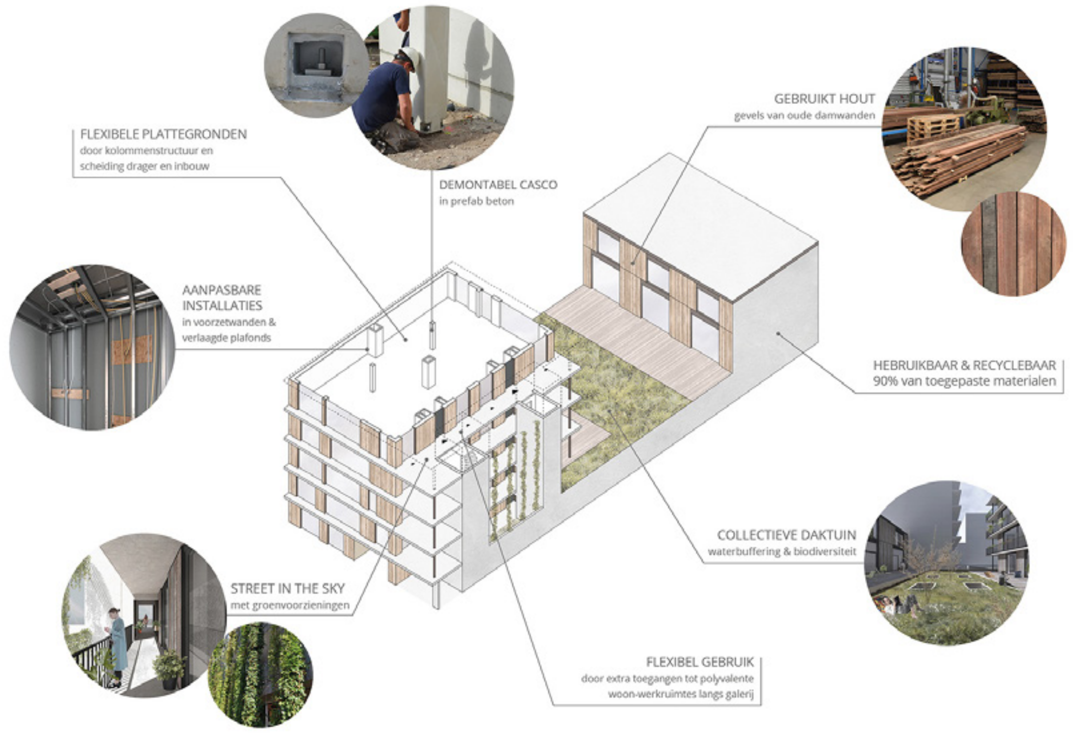


Figure 2.6 CiWoCo, Amsterdam by Gaaga (Source: gaaga.nl, 2020)

2.3.2 INDUSTRIAL, FLEXIBLE AND DEMOUNTABLE (IFD)

In 1999, the Ministry of Economic Affairs and the Ministry of Housing, Spatial Planning and the Environment in the Netherlands created a program called "Industrial, Flexible and Demountable Construction Demonstration Projects." The aim of this program is to promote the use of industrially built and manufactured construction components in the construction and renovation of residential and public utility structures (Gassel, 2003). IFD design is a method of constructing flexible housing in which the user has complete control over the size of the home, as well as the layout, built-in features, and finishing. Furthermore, such dwellings may be modified to meet changing housing demands while their occupants are still living there (Geraedts, 2011). IFD follows an integrated approach to the inception, design, production and the use phase of buildings. It promotes an early dialogue between various stakeholders in the building which enables an extensive coordination of the concept, design and implementation of the project. The client (flexible), the manufacturer (industrial), and society (demountable) are all involved in IFD building as a three-pronged approach to improve the construction procedure (Van den Brand, 1999).

In IFD, parts are produced on an industrial scale which reduces costs and production time. The deployments of the parts are flexible because the connections between elements are standardized and replacement is efficient as everything is demountable which also allows parts to be reused. The IFD building concept is based on six core values of a building (Gassel, 2003):

1. Basic value: Obtaining a degree of building physics that exceeds existing requirements.
2. Use value: aiming for maximum layout flexibility at the house, story, and apartment levels, as well as installations that are individually customizable and measurable.
3. Local value: establishing a building system that allows for distinction based on form, surface, layout, fixtures, and architecture
4. Ecological value: the significance of using light structures and reusing foundations.
5. Economic value: Creating a commodity that meets the needs of the market.
6. Strategic value: constructing a flexible structure that can be altered over time.

The salient features of IFD building system comprises of the following (Hendriks et al.,1999):

1. Prefabrication in industrial building, where waste is reduced and production recycling is possible.
2. On the construction site, no waste is generated.
3. Completely dry building method.
4. Materials that are flexible and changeable are used, resulting in less waste.
5. Flexibility in the design phase.
6. Reusable and recyclable demountable parts.

Considering these salient features of IFD system, a building that is demountable can be achieved where its components and parts can either be reused, refurbished and recyclable for the circular economy. It is noticeable that IFD technology stresses on flexible and demountable components. To ensure this, the following design criteria for changeability or flexibility were developed (Hendriks et al.,1999):

1. Integration and independency: Installation, load bearing structure, outer skin (Façade), and interior finishing are both integrated and independent disciplines.
2. Dry building method: There is no concrete, mortar joints, screeds, stuccowork, sealant, or PUR (polyurethane) spray used in this process.
3. Perfect modular measuring: Attention to drawing, prototype testing on functionality, mountability and demountability, assembly instructions.
4. Adjustable components: Structure (limited), installations (unlimited), outer shell (limited and modular), interior finishing (unlimited and modular).

Here in point no. 1 (Integration and independency of disciplines), one can draw parallels with Stewart Brand's shearing layers concept. This concept forms a base platform for ideas of flexible and demountable components to spring from and will be used as a rule of thumb in this research. The dry building method is essential for demountable parts and will be used wherever possible. The other important aspect that needs to be considered in design is the modularity concept in point no. 3 and 4. With a modular design approach, standardization of component sizes can be achieved which in turn can make adjustability of components easier to deal with. These design guidelines and set of criteria will be briefly concluded at the end of the chapter and the results will be carefully considered in this research.

Case studies
To further gain knowledge and understand the IFD building system, literature related to building projects that have used this technology in the past have been studied below. They showcase some of the practical problems and opportunities that arrive using this system.

Trial module, Dubo park, Eindhoven University of Technology
A trial module was installed on the DUBO (Sustainable Construction) park on the Eindhoven University of Technology campus to obtain experience with the IFD construction method. A two-story trial module of 14 meters wide and 11 meters deep (Figure 2.7) was built which had the following characteristics (Gassel, 2003):

- An 11 m span and a 7.2 m grid.
- Support structure made of hot-rolled standard I-profile steel with L-supports at the corners and joists on the grid line.
- The joists are fixed to the carriers in a way that vibration is reduced, and the supports provide stability. The floor panels were mounted on the joists.
- The floor panels are unfilled so that technical equipment can be installed.
- Non-bearing walls are used to divide rooms which ensured free space providing various layout possibilities.
- Option of having free exterior wall was considered.
- The roof does not have a specific design. As a result, the conventional warm roof solution was chosen.

Figure 2.7: IFD trial module, Eindhoven University of Technology (Source: Gassel, 2003)

- Flexibility in terms of vertical and horizontal piping, allowing for a variety of toilet, kitchen, and bathroom locations.

The design and the manufacturing process were both accessed for its IFD capability. Designers from different fields such as architectural, structural, building physics, construction, electrical, mechanical, construction designers and other stakeholders were involved in designing from an early stage. The incorporation of functions and components required a high level of focus during the construction of the building in the factory.

From the trial module in Dubo park the following findings were found as per their respective aspects (Gassel, 2003) given in the table 2.4. Alongside it the corresponding recommendations have been listed by Gassel (2003) or by the author. These set of findings and recommendations would be concluded as a whole at the end of the chapter.

Apart from the trial module in Dubo park, a national experimental program was organized in 1999 to encourage the market to adopt the IFD building system in the Netherlands by Public housing sector (SEV). These projects were funded by the Ministry of Housing, Spatial Planning and Environment (VROM) and the Ministry of Economic Affairs (EZ) (Geraedts, 2011). Even though there was a positive response from clients to participate due to flexibility and sustainability concept, the projects failed to meet the original goals that guided them in the first place (Crone, 2007). Obstacles in the construction phase forced projects to be halted halfway through, caused construction delays, or resulted in a different end-result than anticipated. These were due to the following reasons.

Lack of familiarity with the IFD concept:
Even though the main clients are well educated with IFD construction, it continues to be unfamiliar to a large number of people. Furthermore, the limited use of IFD construction makes it more difficult to embrace, especially among small businesses and construction companies.

Technical aspects
The experimental IFD house-building projects heavily emphasized the use of smart design techniques. Obstacles arose because groundbreaking systems at the building component level (floor, wall, construction, and façade systems) were either immature in some cases, or because there was a lack of creativity at the main concept level. "Nevertheless, these obstacles to IFD building and to innovations in construction also represent challenges for the future" (Decisio BV, 2006).

Organizational aspects
Although building technology is unquestionably important in achieving a versatile dwelling that can satisfy the user's needs and demands, the related organizational aspects are equally important. The structure of the building process was influenced by consumer-ori-

Aspects	Findings	Recommendations
Design	The design process necessitates collaboration and a multidisciplinary approach.	Use of BIM and related software could help aid this up to a certain extent (author).
	Traditional design solutions are often chosen due to a lack of a suitable model for calculating costs, as well as the absence of a marketing strategy.	Prior planning and detailed market analysis should be carried out (author).
	In the implementation process, design issues were still being resolved, typically on the construction site.	Proper and accurate design documentation is needed (author).
	Since reference points and proportions were not specified on the drawings submitted, mechanics had to figure them out on their own.	It is necessary to create specific assembly drawings.
Prooduction	To connect technical installations into the steel construction, more production space was needed at the plant.	
	The construction of large elements was approached as a project rather than a mass production.	
	Small materials were shipped in bulk, unsorted. Therefore, a lot of sorting out was required, and some materials were damaged.	Materials should be delivered in crates and by alternate modes of transportation.
Assembly	Mechanics also attempted to install equipment on the job site rather than at the factory.	Strict instructions should be followed.
	At the construction site, parts were chosen and the assembly order was decided.	Special assembly drawings should be made.
	The steel structure and floor panels are easily dismantled in comparison to the exterior walls, roof, fixtures, and finishing elements.	Components that change frequently should be designed for quick disassembly (author).
Management	Every vendor submits its own set of drawings. Connections between the different suppliers' construction components were not given, so a solution had to be found on the job.	The connections between the building elements should be drawn out. Specifications should be of such high quality that they do away with the need for drawings and instructions.
		Entrusting one organization with a variety of development activities, such as preparing and reviewing drawings, as well as allocating labor resources for transportation and safety.
Resources	Scaffolding of various types was erected for various aspects of the project.	One type of scaffolding should be used.
	Cranes of various types were used, often as many as four at once.	During the execution process, only one form of crane should be used.
	For the project, special labor services were created and deployed on the construction site.	Specific labor resources should be designed.
Waste	During the fitting-out process, a lot of waste was produced.	Packaging that can be returned should be used.
	Waste was not collected separately.	Work on the construction site should be kept to a bare minimum. Government rules should be followed when it comes to waste separation.
Technical	Measurements of building physics revealed that a variety of details had not been completed properly, resulting in noise leaks, air leaks, and other issues.	It's important to pay attention to the details.

Table 2.4 Findings and recommendations (Source: Gassel, 2003)

Figure 2.8: Seven Heavens (Source: Hoyt architects)

ented construction and the use of advanced construction systems which was heavily influenced by the organizational aspects of IFD construction (Geraedts, 2011). Hindrance in the development and construction process and the inability to provide assurances due to a lack of teamwork and cohesion among parties involved were among the reasons given. For instance, from a survey that was conducted (Geraedts, 2011) on two projects, The Mask (Het Masker) and Seven Heavens (Zeven Hemels) which demanded close cooperation among the various disciplines involved, there was a lack of coordination between architects and other groups. The latter project involved 8 different architects simultaneously on the design and was considered too ambitious (Figure 2.8). There was also a lack of communication to be found from the consumers or users end in 2 projects (A+ dwellings and Terbregse.nl). The tenants and buyers were not interested until after the project was completed (A+ dwellings) or some users delayed to communicate their choices, which meant that the flooring system could not be customized to meet individual needs in the Terbregse.nl project (Geraedts, 2011).

However there were some positives to be taken from one of the projects. The Terbregse.nl project drew on previous experience of designing flexible houses in a prefabricated and demountable way. The most critical phase in the construction process, integrated design, was already well thought of. As a result of this, the parties involved were able to establish a strong working relationship, and the implementation stage went off without a hitch.

From the survey and case studies done by Geraedts (2011) with real estate developers, architects, and construction firms participating in 12 IFD housing projects, technical, financial, and organizational issues were the three most common explanations for failure to meet objectives. From his research he concluded that these following aspects should be addressed to optimize the IFD system (Geraedts, 2011):

- Understanding the demands and requirements of the target group which entails market analysis.
- Goals are established based on the target group, which are to be tracked during the process.
- Consumers have conventional views and are skeptical therefore a building prototype can help
- The degree of user involvement should be determined which will influence the end result (Regarding the house size, layout, built-in facilities, finishing and aesthetics).
- Lack of experience with innovative products and processes lead to many problems.
- Integrated approach with expertise of various parties and coordination between various disciplines

- It will be necessary to translate the desired degree of flexibility into a design. This opens up possibilities for the technological aspects of construction.
- When the dwelling is in use, the full capacity of product flexibility can be used to meet evolving housing needs. However, these must be closely controlled and supervised to prevent awareness of what is and is not possible from weakening over time.

From this chapter a comprehensive knowledge of IFD system was obtained through thorough literature research. It lays down a basic platform to design Industrial, flexible and demountable building components but also makes one aware of the drawbacks in the system. Even though the problems using this system arise mainly due to organizational aspects which are not in the scope of this research, one should be aware of these shortcomings. From the literature study (Geraedts, Hendriks, Gassel), a set of guidelines defining the process of IFD system has been laid.

1. Defining target group: The IFD system clearly relies on industrial fabrication, which means mass production of building components is necessary for this system to be economically feasible. Therefore, a larger audience should be targeted. This can be suitable for the social housing sector and not for the niche consumer. Younger generation who are looking to buy their first homes or housing corporations that build and rent out homes could benefit from this system due to changing users.
2. Formulating requirements: A thorough market research is necessary to understand the needs and requirements of the target group. A wide variety of special requirements should be neglected and the few basic set of options should be presented to the consumers. This will help to streamline the design, production and assembly process.
3. Draft guiding principles: The concepts to be developed include a specification for the IFD building concept, the modular housing development concept, and the approach to potential users. All stakeholders should be familiar with the IFD concept. This could be made more transparent by building a prototype and by making users experience this space.
4. Objectives of the system: Develop objectives in the initiation stage that can be divided into a core goal of providing value (or added value) to the customer, as well as peripheral goals geared toward manufacturing, flexible, and demountable structures. These goals should be monitored throughout the entire building process while not straying away from it.
5. Selection of method and product: During the planning stage, residents should have a certain amount of freedom of choice, and during the usage process, they should have some degree of flexibility. Select an innovative construction method and product capable of providing the required flexibility.
6. Flexibility in the design stage: During the design phase, assurances must be provided about the freedom of choice available in terms of house size, layout, installation, built-in facilities, and finishing. Scenarios of change when the dwelling is in use, such as adding or removing different parts of the building, or changing the layout or appearance should be informed.
7. Cooperative organization during the construction phase: Organize the construction phase such that the building can be constructed quickly without facing problems. This necessitates collaboration between the contractor, subcontractors, and suppliers. It could be fruitful to entrust one organization with a variety of development activities, such as preparing and reviewing drawings, as well as allocating labor resources for transportation and safety.
8. Monitoring flexibility during the use phase: Create flexibility options when the home is being used, and make sure they can be applied if the need arises. If a building is still owned by a housing corporation, they are responsible for making adaptation and transition options as transparent as possible. While when a user owns a home, the latter must be provided with an instruction manual that describes and explains the various modification options.

As mentioned earlier in the chapter, the design principles and strategies for IFD building system have been listed in a nutshell (Table 2.5). These design strategies will be used as a guiding principle in this research paper to come up with a design solution.

Design Principle	Description
Prefabrication	Waste is reduced
	Production recycling is possible
Integration and independency	Installations, load bearing structure, facade and interior finishings are both integrated and independent
Dry building method	Elimination of chemical connections
	No concrete, mortar, screeds or stuccowork
	No PUR spray used in the process
Perfect modular measuring	Attention to drawing
	Prototype testing
	Assembly instructions
Adjustable components	Structure (limited)
	Instalations (unlimited)
	Facade (limited and modular)
	Interior elements (Unlimited and modular)
Materials	Flexible and changeable resulting in less waste
	Reusable and demountable parts
Design	Flexibility in design phase

Table 2.5 IFD Principles (Source: Author)

Figure 4 Nakagin-Capsule-Tower-3.jpg

2.4 DESIGN FOR DISASSEMBLY (DFD)

The design for disassembly can be seen as the master strategy of circular design. It allows for reuse, repair, remanufacturing and recycling of products and buildings as a whole. It is described by Morgan et. al (2005), as "DfD is the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials. This design process includes developing the assemblies, components, materials, construction techniques, and information and management systems to accomplish this goal." Material recovery aims to increase economic value by reuse, repair, remanufacture, and recycling. Energy recovery from products and healthy biodegradation are the last resorts. DfD allows for whole-building versatility, convertibility, addition, and subtraction. Reusable materials, materials intended as recycling feedstock, and natural materials that may be completely biodegradable are all included in DfD (Morgan et. al, 2005).
The flexibility of building components is presumed in this study to be dependent on the building's disassembly potential, which has a direct relationship with the sustainability level of a building. A higher disassembly potential means a lower negative environmental impact and vice-versa. To step toward such scenarios, we must shift our understanding of a building's technological composition from one that is permanent and set to one that is changeable and open (Durmisevic, 2006).

The following are the Principles of DFD listed according to literature research (Morgan et al., Guy et al., 2005):

1. Documentation: Disassembly and deconstruction drawings should be made with specifications and proper labeling of connections and materials.
2. Selection of materials: Materials that are selected with future impacts in mind and are of good quality will maintain their value and be easier to reuse and recycle. Use of binders, sealants, and adhesives in products make it impossible to separate and recycle them, and they raise the risk of harmful human and environmental health effects.
3. Standardization and modularity: Construction and deconstruction would be easy with open-span structural structures, simple shapes, and standard dimensional grids. It would be easier to reuse products and structures that follow the ideals of modularity, independence and standardization.
4. Separation of building components: A clear distinction between non-structural and structural components by separating the structure from the skin would allow better flexibility. Separating MEP (Mechanical, electrical and plumbing) systems from the components that house them make it simpler to fix, replace, reuse, and recycle components and materials.
5. Standard (Bolted, screwed and nailed) connections: Using regular and restricted connector types reduces the number of tools required, as well as the time and effort required to move between them. Connectors should be designed to withstand repeated assembly and disassembly to allow for adaptation and reuse.
6. Accessibility: Connections that are visually, functionally, and ergonomically accessible with adequate tolerances can improve efficiency while avoiding the need for costly equipment or stringent environmental health and safety standards for workers.
7. Design for the worker: Human-scale parts, or components that are designed to be easily removed by standard mechanical equipment, can minimize labor work and improve the ability to integrate a diversity of skill levels. Allowing for safe worker movement, building equipment and ease of material flow would save money and reduce risk during renovation and disassembly.
8. Assembly and disassembly process: Preference for parallel disassembly to speed up the disassembly process on-site. Using prefabricated subassemblies that can be disassembled and reused as modular units or separated off-site efficiently.

A comprehensive list has been prepared (Table 2.6) with the principles of DFD and the design strategies to achieve it from the literature study. Also given are the benefits that can be achieved with each strategy.

Design Principle	Solution / Strategy	Benefits
Documentation	Assembly / Disassembly instructions	Ease of disassembly
	Labeling of components and materials	Easy to identify for future use
Selection of materials	High-quality durable materials	Encourages market reclamation
	Minimise material types	Reduces complexity and separation process
	Avoid toxic and hazardous materials	Decreases human and environmental health impact
	Avoid composite materials	Same material is easier to recycle
	Eliminate chemical connections	Difficult to separate and recycle them
Standardisation and modularity	Simple forms	Allows easy construction and deconstruction
	Use a standard structural grid	Allows standard sizes of recoverable materials
	Use a wide structural grid as possible	Maximizes the non-structural wall elements
	Minimize types of components	Increases the quantity of recoverable parts and interchangeability among them
Separation of building components	Separate the structure from the skin	increased adaptability and separation of non-structural deconstruction from structural
	Consolidate MEP systems into core units	Minimizes runs and unnecessary entanglement
Standard connections	Using regular and standard connector types	Reduces the number of tools, time and effort
	Minimize numbers of fasteners and connectors	Increases speed of disassembly
	Design connections to withstand repeated assembly and disassembly	Allows for adaptation and for the connectors to be reused
Accessibility	Accessible connections	Improves efficiency avoiding the need for costly equipment
	Adequate tolerances to allow for disassembly	minimizes the need for destructive methods
	Avoid secondary finishes	Easier to access and find connection points
Design for the worker	Human scale components	Reduces labor intensity
	Use lightweight materials and components	Handled by human labor or smaller equipment
	Safe worker movement, equipment and materials	Saves money and reduces risk
Assembly disassembly process	Allow for parallel disassembly	Decreases time on-site in the disassembly process
	Identify point of disassembly permanently	Reduces the time in planning the disassembly process
	Use prefabricated subassemblies	Can be disassembled for reuse as modular units, or for efficient further separation off-site

Table 2.6 DFD principles and strategies (Source: Author)

2.4.1 DFD FOR THE CIRCULAR ECONOMY

DFD building system can be seen as a approach to tackle the Circular economy goals. However one needs to understand the important role it plays and when. Products must be built in a more intelligent manner, with a longer lifespan and the ability to be repaired, upgraded, and even integrated into other systems. This is possible if products can be dismantled for future reuse. A thorough step by step research is needed to understand the life cycle of a product. This does not fall under the scope of this research, however the process is summarised below to get an understanding.

The first step in determining how and when to intervene is to examine the product's life cycle as well as its environmental and economic effects (Delft University of Technology, 2021). Its production, construction and use phase should be examined carefully to determine its environmental impact. After its end of service phase, the product should be able to disassemble easily where demolition should be avoided at all costs. To avoid demolition, products can already be designed to be easily disassembled and reused. DFD strategies allow this to happen in a more secure manner, making it easier for the product to either be refurbished, remanufactured or recycled.

After the product has fulfilled its service phase where its intrinsic properties are no more valued, the loop is closed by recycling the material. However, attempts should be made to keep the value of the products by upcycling them into new construction materials. Since the process of recycling also has some environmental impacts, it is at present considered to be energy inefficient, lacks infrasturcture and makes it less economically feasible (Delft University of Technology, 2021).

Demountable structures offers a different viewpoint in the present day and age. It is seen as a way to achieve the goal rather than the goal itself. This new viewpoint stems primarily from the fact that landfill and energy costs are skyrocketing, resources are quickly depleting, demand for resources is increasing, and growth, repair, and demolition costs, as well as overall life cycle costs, are all rising (Durmisevic, 2006).

Incorporating DFD design strategy has prospective gains such as (Durmisevic, 2006):

Environmental
- Enhancement in air and water conditions
- Lowering waste streams
- Conservation and regeneration of natural resources
- Improvement and preservation of biodiversity and habitats

Economic benefits
- Lowering running costs
- Developing, expanding, and influencing green product and service markets
- Increased occupant productivity
- Improved life-cycle economic performance

Social benefits
- Improving occupant comfort and wellbeing
- Enhancing aesthetic standards
- Reducing pressure on local infrastructure
- Improving overall quality of life

2.4.2 PERFORMANCE CRITERIA FOR DFD

To analyse how effective a building product is designed for disassembly for either reuse or for transformation to extend its life cycle, it must be evaluated through a set of design criteria. Apart from the basic set of principles and strategies that could be followed for DFD as mentioned earlier in the chapter, a performance criteria based on E.Durmisevic's (2006) paper, Transformable building structures is described briefly. A set of eight performance criteria will be used in this paper to assess the DFD potential of building products.

Functional Independence (FI)
For DFD different components serving different functions on all building levels is desired. If a building component is known as an independent part of the construction of the building, it can be removed. The first step is to split the building into various parts with different functions and life cycles. The same logic can be applied to sub-components within a component for example a façade, where its sub-components such as the framing, glazing, gaskets etc. have different functions and life cycles. Integration of two or more functions into a single component can cause transformation to cease. All functions held within a component must be dismantled and redistributed to separate sub-components. As a result, changing or substituting one function has no effect on the integrity of the others. Separation, incorporation, and integration are the three levels that can be used to assess functional independence.

Systematisation (SY)
Systematization can also be referred to modulation that relates to formation of single parts into sub-assemblies from which clusters of parts (modules) are created based on their life cycle performance assessment, as well as the degree of material integration. This gives an organised and better control over building components during operation and maintenance phases and for disassembly. A large number of disassembly steps can be hindrance, therefore a two-stage assembly and disassembly is preferred where higher-level subassemblies like components are substituted for reuse/reconfiguration on the construction site, and lower-level subassemblies, such as subcomponents and elements, are dismantled and replaced for reuse/reconfiguration/recycling in the factory. When there is no clustering of sub-functions, the majority of them are combined into a single composite component which lacks flexibility and is unable to adapt to various uses.
Systemisation of components is related to the function of a cluster, assembly sequence and the maintenance of components based on their technical life cycle. The more components are systemised into individual assemblies according to their function, the easier it is to coordinate their life cycle and the assembly and disassembly sequences.

Relational patterns (RP)
When building components are integrated into a single dependent structure, it can have a significant impact on related parts when one element has to be replaced, as in conventional buildings. This influences the potential of disassembly. Six relational patterns resulting in assembly types have been listed below along with their diagram in figure x:
1. Closed assembly
2. Layered assembly
3. Stuck assembly
4. Table assembly
5. Open assembly
6. Shared assembly

Closed, layered, and stuck assemblies result from static assemblies where the components are not systematized and grouped into individual units. The table assembly represents a partially open system and open assembly represents independent building parts but are dependent to elements within a sub-assembly. In shared assembly, connections are designed as base parts for the entire assembly which gives flexibility when determining the form and size of connected elements. For easy replacement of parts, sub-components should preferably have only relation with the load bearing element (base element) of the system and different functional groups should not have direct relations.

Base element specification (BE)
Each cluster should have its own base element that performs the load bearing function of that cluster. This way an element of a cluster can be independent from the elements of other clusters which would make replacement easier and not dependent on other clusters. The function of the base element is to connect elements within the same assembly and act as a link to other clusters.

Geometry of product edges (GP)
It is the characteristic of a product edge and its connection with its neighbouring product where it is classified either as an open or an interpenetrating geometry. An open geome-

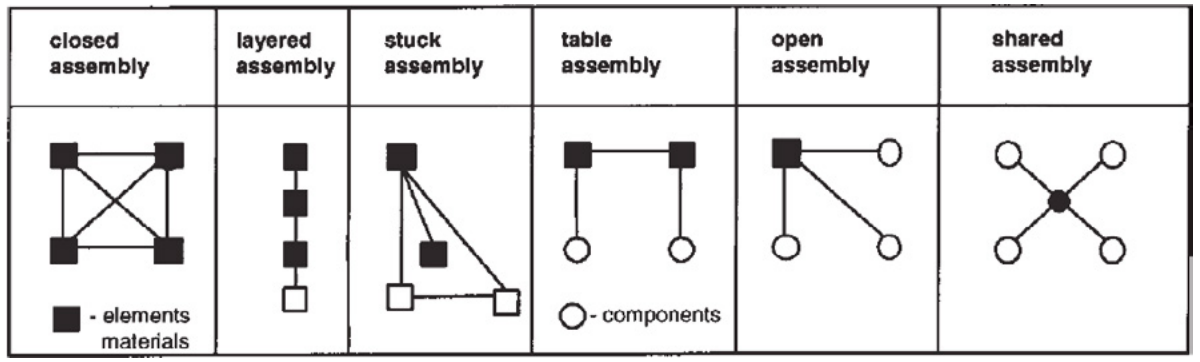


Figure 2.9: Relational Patterns (Source: Durmisevic, 2006)

try is preferred since it can allow parallel disassembly while an interpenetrating is less suitable since elements have to be disassembled sequentially or in a unidirectional manner. Three types of open and interpenetrating situations are shown in figure x.

Assembly sequences (AS)
Assembly sequences can be classified into parallel and sequential assemblies. A parallel assembly is preferred since it can speed up the process, whereas a sequential assembly introduces dependencies within components and makes disassembly more complex. The assembly sequences are affected by the type of material, its life cycle, geometry of the product edge and the type of connection. Within these two types of assemblies, a combination of both can also be achieved, however the number of steps to disassemble a product should also be considered.

Connections (CN)
In DFD, connections between building components determine whether components are demountable and hence play an essential role. Connections are categorized into direct (integral), indirect (accessory) and filled connections.

Direct connections can further be grouped into overlapped and interlocking types where the geometry of the product edges forms the connection. Their edge depends on the material and the assembly is likely to be sequential in most cases which are not preferred for disassembly.

Indirect connections are further categorized into internal and external where an additional component is used to form the connection. As the name suggests, internal connections are components that are enclosed and have identical edge shape of the connecting components while external connections are exposed which makes it more accessible for disassembly.

Filled connections are the types that are filled with chemical material such as adhesive, mortar, welding etc. These are not suitable for DFD since it forms a permanent bond between elements, making it impossible to disassemble or made possible using special technology.

Connections for DFD depend on the following factors:
1. Number of components to be connected
2. Material
3. Form factor of product edge

With these three factors in mind, connections for DFD must be kept independent from other connecting elements and dry connections must be used. Figure x illustrates different types of connections put up in a hierarchical order from fixed to flexible connections.

Life cycle coordination (LC)
All building materials have their life cycles ranging from 5-75 years or even more and these materials should be assembled accordingly for efficient disassembly. The elements with the longest life cycles and the most assembly dependencies should be assembled first and disassembled last such as the base element of a component. Short-life-cycle elements should be assembled last and disassembled first. This way less disassembly dependence is often generated as a result of later assembly. Life cycle coordination for DFD should be considered in the design phase which should result in an optimized disassembly process. If not, there would be unnecessary disassembly steps taken which might affect the cost and time of a disassembly process.

Evaluation of results
Based on these eight parameters a scoring chart is created to evaluate the DFD potential of building components as seen in Table 2.7. The scores are arranged in a manner that aspects that result in demolition are valued between 0.1 and 0.3. Likewise, partial demolition and reconfiguration are valued between 0.3 and 0.6 and aspects that result in good dis-

Parameters	Description	Score
Funtional dependence	Total separation of functions	1
	Planned integration of functions with same material	0.8
	Planned integration of functions with different materials but same life cycle	0.6
	Planned integration of functions with different materials and life cycles but without affecting the integrity of others	0.4
	Unplanned integration of functions affecting the integrity	0.2
	Total dependence of functions	0.1
Systemisation	Clustering according to both function and life cycle	1
	Clustering according to the function	0.8
	Clustering according to the life cycle	0.6
	Clustering for fast assembly and disassembly	0.4
	No clustering	0.2
Relational patterns	Shared and open assembly	1
	Table assembly	0.8
	Stuck assembly	0.6
	Layered assembly	0.4
	Closed assembly	0.2
Base element specification	Base element between systems and components	1
	Base element on two levels	0.6
	Base element with two functions	0.4
	No base element	0.1
Geometry of product edges	Open - Linear geometry	1
	Open - Symmetrical overlapping	0.8
	Open - Overlapping on one side	0.6
	Unsymmetrical overlapping	0.4
	Closed - Insert on one side	0.2
	Closed - Insert on both sides	0.1
Assembly sequence	Total parallel assembly	1
	Partial parallel and sequential assembly	0.8
	Sequential assembly	0.6
	Partial sequential assembly and partial demolition disassembly	0.4
	Demolition disassembly	0.2
Connections	Direct accessible connection	1
	Indirect external connection	0.8
	Indirect internal connection	0.6
	Filled connection leading to partial demolition / reuse	0.4
	Filled connection leading to demolition	0.2
Life cycle coordination	Long LC / Long LC or Short LC / Short LC	1
	Long LC / Short LC	0.8
	Long LC / Medium LC / Short LC	0.6
	Medium LC / Long LC / Short LC	0.4
	Short LC / Medium LC	0.2
	Short LC / Long LC	0.1

Table 2.7 DFD scoring chart (Source: Author)

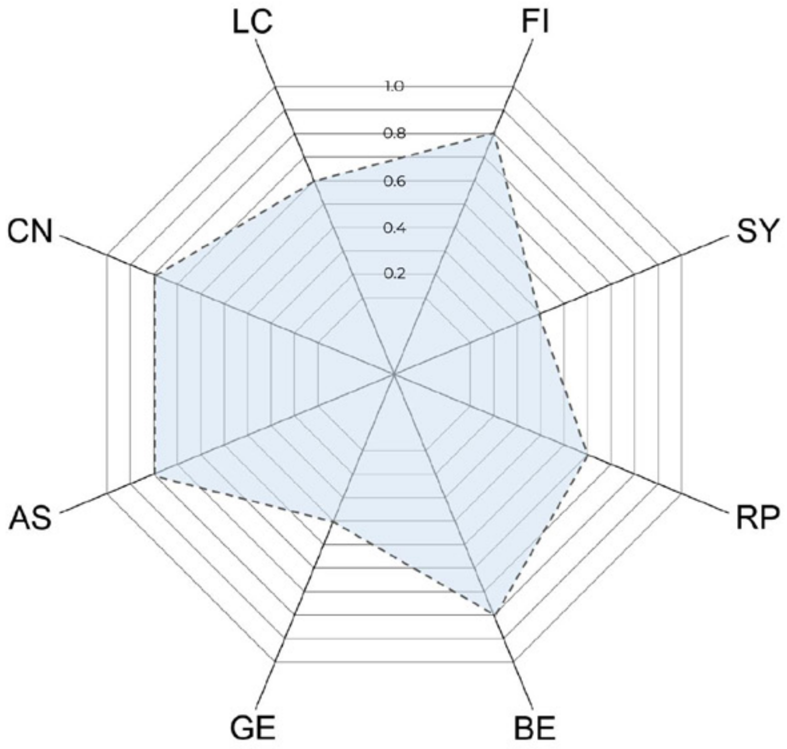


Figure 2.10: Spider diagram (Source: Author)

assembly for possible reuse, reconfiguration and recycling are valued between 0.6 and 1.

The evaluation of each disassembly parameter is plotted in a radial / spider diagram as seen in figure 2.10. All scores are connected by straight lines and a closed diagram is achieved. Scores that lie close to the periphery indicate good disassembly potential while the ones that lie close to the center indicate poor disassembly potential. These scores are further divided into three categories.

- Category 1: Overall DFD score of more than 70% indicate high disassembly potential that result in potential reuse, reconfiguration and easy recycling of products with less waste generated.
- Category 2: Overall DFD score between 70 to 33% indicate medium disassembly potential that result in partial reuse, reconfiguration and recycling of products with medium waste generated.
- Category 3: Overall DFD score of less than 33% that indicates low disassembly potential that result in low reuse, reconfiguration and recycling of products with high waste generated.

2.4.3 Conclusions

In this chapter the DFD building system was introduced with its design principles and its importance in the Circular economy. The performance criteria to assess DFD potential of building products was also discussed.

However, DFD building system also have to be overcome some hurdles to achieve its full potential which might make it difficult to apply in the current building industry due to various factors. The drawbacks of this building system identified by Beurskens et al. (2015) and other sources are listed below.

Creating awareness: Knowledge and marketibility of a new system plays a major role in encouraging designers to design differently and also for the general public to know the benefits of this system. If the advantages have been outlined and illustrated, there is a compelling argument to implement this strategy. It gives people an incentive to implement a new solution if they can measure a contribution to their project.

Additional design cost: Designing a DFD product can be more time consuming since one has to think about how the product can be dismantled and reused. While the selection of building materials for the circular economy can be quite tedious.

Design codes for practice: This building system being relatively new in the industry, it can be said that there is not enough information or building codes set in the industry. The existing codes generally encourage specification of new materials while reused material specification have not been listed. This could change in the near future as the people and the government become aware of Circular building strategies.

Lack of reused materials market: Uptil now most of the building products are either recycled or used as landfill. Reused materials can only be seen in few projects from sustainable extremists and not on a large scale. However, some organisations are taking a big step towards this such as Circlinq and Madaster by providing a platform for building stakeholders for reused materials. These platforms are still in its nascent stages but show a lot of promise for the future CE.

Existing undemountable structures: Most of the buildings in the past were not designed to be demountable which poses a big hurdle for disassembling them. The type of connections used and the inaccessibility of connections still remain a threat that need to be tackled in a efficient manner.

Perception of reduced value, aesthetics, and safety: The DFD sytem does limit the choices of materials and design due to its principles as of now. This is partially due to the fact that this system is still new to the building industry. However, as more new sustainable materials are invented and new DFD designs are explored, a keen interest among individuals can be established. This can be aided by the governing body by providing incentives and subsidies for sustainable construction.

One needs to be aware of these drawbacks in this system which could help in overcoming them in the design of DFD building products. The design principles of DFD will be taken forward to help design a demountable product in this research paper, while the product will be assessed using the performance criteria.

2.5 CIRC-FLEX CRITERIA

This chapter looks into the Circ-Flex criteria derived by Geldermans et al., (2020) in the research paper Circular and flexible infill concepts: Integration of the Residential user perspective. The approach here followed was a mixed-mode methodology, based on literature, case study and expert consultations. In the paper, a partial list of eleven Circ-Flex criteria is extracted from three interrelated categories, each of which contains several sub-criteria. The following are the categories and criteria, as well as shown in Table 2.8.

Flexibility: The ease, with which a partition wall, or a portion of it, can be dismantled, reassembled, repurposed, or discarded. Here, dimensions and connections are given special consideration.

Circularity: The degree to which walls and its components can quickly, securely, and fully meet high-grade renewability cycles including repair, redistribution, remanufacturing, and recycling, as well as bio-cascades for biological materials. The emphasis is on the technological and design aspects of such cycles.

User benefits: Concerning the user's mental and behavioral involvement and reaction prior to or after activities. It was discovered that this user response is often subjective, meaning that factors can emerge that override the solutions chosen by designers and engineers. Multiple factors may act as deciding factors in this regard, contributing to buying conduct that favors or opposes Circ-Flex. In the expert consultations for this project, two requirements were highlighted: willingness to spend time and resources, as well as the ability to choose from a variety of materialization choices, whether DIY or outsourced.

In the research two variants of partition systems were evaluated to check the difference in their performance according to the Circ-Flex criteria. The first variant is a normal timber frame wall with plasterboard panels and glass wool insulation material where the wires, pipes and insulation lies within the cavity between the drywall panels. Metal connections and screws are used to secure it to the floor and ceiling, and conventional materials are typically used for finishing. The second variant is a conceptual partitioning wall constructed with validated constructing techniques and products that are completely engineered for circular material and product flow. It is made up of pre-existing materials, such as a timber frame with metal connections and screws in the structure, and a mounting profile against the ceiling and floor, as listed in Material Passports. Natural fiber insulation and organic board for paneling are used, with lime-based materials used for finishing. The comparison between these two variants is shown in Table 2.9.

CIRC-FLEX CRITERIA	
Unlocking Flexibility Capacity	Ease of Disassembly
	Ease of Re-assembly
	Ease of Repurposing or Disposing
Unlocking User Capacity	User willingness to invest in time and money
	User perceived freedom of choice
Unlocking Circularity Capacity	Ease of Maintenance
	Ease of Redistribution
	Ease of Remanufacturing
	Ease of Recycling
	Ease of facilitating Bio-cascades
	Ease of facilitating Bio-feedstock

Table 2.8 Circ-Flex criteria. (Source: Geldermans et al., 2020)

	Variant I Traditional Partitioning Wall	Variant II *Circ-Flex* Partitioning Wall
Unlocking Flexibility Capacity		
Ease of disassembly (Easy, Moderate, Hard/Strong)	Easy–Moderate. Moderate–Strong impact on direct physical context	Easy. Moderate impact on direct physical context
Ease of re-assembly (Easy, Moderate, Hard/Strong)	Easy-Moderate. Even if dimensions remain the same, constructive adjustments are required	Easy, if dimensions remain the same. Easy–Moderate if material adjustments are required
Ease of repurposing or disposing (Easy, Moderate, Hard/Strong)	Easy, if traditional (linear) routes are sustained. Moderate–Hard if 'regenerative' trajectories are sought.	Easy–Moderate. Depending on status of (reverse) supply chain. Easy from the perspective of material purity
Unlocking User Capacity		
User investment (Time and Expenses)	Time-commitment low with regard to all stages. Initial financial investment relatively low. Expected return on investment low or negative (i.e., discarding costs rather than residual value).	Time-commitment low with regard to (dis-)assembly stages. Initial financial investment low–moderate (purchasing costs often higher). Expected return on investment low–moderate. New financial models may emerge.
Freedom of choice (Availability and Variation)	Abundant and readily available materials and products in a diverse range.	Partly abundant and readily available materials and products, partly limited to a few eligible products. The latter products are, in most cases, not readily available via common channels (such as DIY shops).
Unlocking Circularity Capacity		
Maintenance	Surface layer accessible for maintenance. Other parts dependent on wall-finishing	Surface layer accessible for maintenance. Other parts dependent on wall-finishing
Redistribution	timber, metal, plasterboard, insulation	timber, metal parts, board, mounting profile, insulation
Remanufacturing	metal, possibly timber	metal, mounting profile, possibly timber
Recycling (equal or higher grades)	metal, insulation	timber, board, insulation
Down-cycling (lower grades)	timber, plasterboard, insulation	-
Incineration or Landfill	timber, plasterboard, insulation	-
Bio-cascades	(uncontaminated) timber	timber, insulation, board
Bio-feedstock (e.g., soil improver)	-	Insulation

Table 2.9 Comparison between traditional and Circ-Flex variant (Source: Geldermans et al., 2020)

It is worth noting that in the comparison, the two variants were kept as comparable as possible (Geldermans et al., 2020), which is visible in the comparison sheet. In the flexibility capacity bracket, Variant 2 performs slightly better for ease of disassembly and re-assembly. The user investment (Time and expenses) is understandably more for the variant 2 due to user involvement and of the assumption that it'll be more costly but a return on investment is expected. However, a larger difference emerges in the circular capacity bracket, notably in the down-cycling and incineration parts. This is because of the assumption that the variant 2 is completely designed for circular material and product flow.

It can be concluded that the Circ-flex criteria set in the paper can be useful for direct comparison between products. However, the comparisons of the two variants in the paper are on a conceptual level where assumptions were taken. It could be tested on real-life partition systems which might reveal different outcomes and more accurate results. From the paper with respect to the comparison it was concluded that there are not many products in the market to replace conventional ones while also facilitating renewable energy pathways. However, there are few products such as Ecor board, Everuse insulation etc. that can apply. As an added benefit to the user, partitioning flexibility refers to relational properties (Figure 2.11) such as performance span of the partitioning, dimensional independence, and connections that allow for easy disassembly. Adaptations in partitioning materials, on

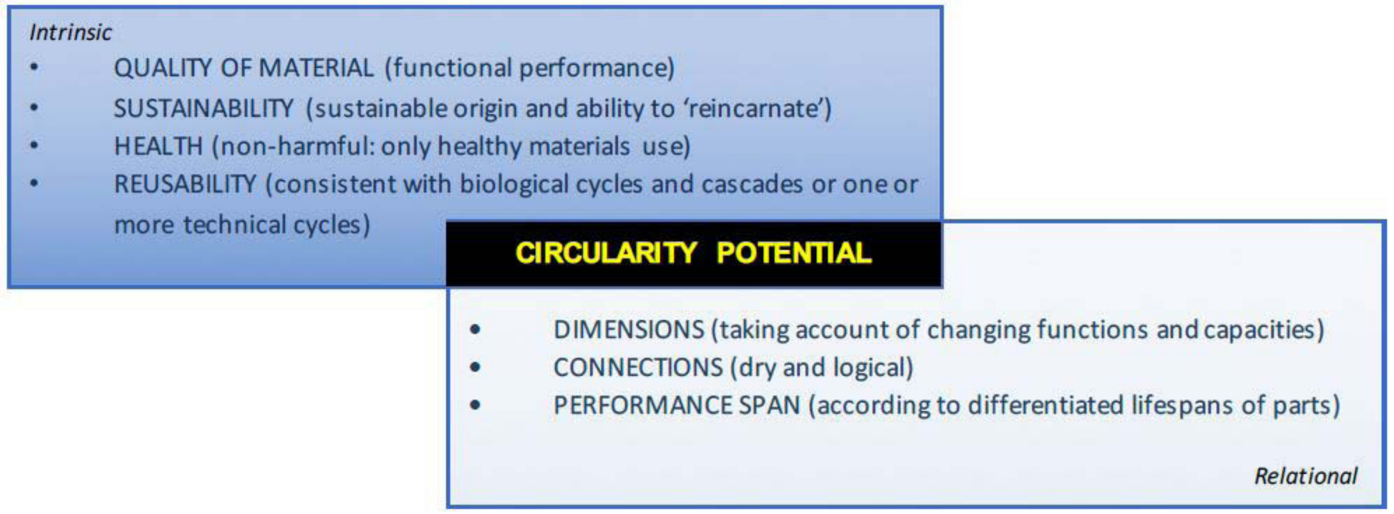


Figure 2.11: Intrinsic and relational properties of materials and products in circular building configurations (Source: Geldermans et al., 2020)

the other hand, should never be made at the cost of the consistency of intrinsic properties (Geldermans et al., 2020). Recommendations were made to design a freestanding flexible partition system geared timely upgrades in the lines of thermal comfort, air purification, VOC reduction and mold control.

3. PREFABRICATION

3.1 Introduction

Prefabrication is a practice that deals with the production and use of pre-manufactured components in the factory and eventually the assembly of the product. Due to the desired working conditions in the factory, higher quality products and better efficiency at a lower cost can be achieved (Knaack et al., 2012). It is associated with standardisation and repetition of components in order to mass produce components at a faster time.

In this day and age, almost all products in the market are prefabricated since they are applied as universal solutions for consumers. In the building sector, universal solutions can also be applied with certain limitations and standardisation to the type of the building and the design requirements. By simplifying the complex planning and construction process great benefits can be yielded. Prefabrication has a positive influence on architecture because it increases the growth of technical information, such as connections, details, and technical standards. In the other hand, it has a negative identity because it instils fear that innovative thought and creativity in architecture will become redundant (Knaack et al., 2012). It is associated with orthogonal shapes and strict grids due to its standardised and modular character and overlooks the vernacular character of a design since it speaks a modern design language. However, generalising this ideology is partly wrong and a prefabricated building system could be created to make designs more flexible and attuned to a particular style.

Prefabrication of building components in a quality-controlled environment has many advantages. The decrease in labor costs and construction time on the building site in prefab construction is profitable due to the high labor costs in on-site construction. Due to the year-round optimum working conditions in the factory, higher precision and better quality of products can be achieved. Another justification for prefabrication in private housing construction is the house building companies' fixed-price scheme, which is advantageous for the client. As a result, prefabrication is a common practice in both residential and non-residential construction.

The approach and scope of construction are informed by how building materials are delivered. The two apparent systems are on-site and prefab construction. To understand the differences between them, both methods have been analysed.

Figure 3.1: Ten fold engineering (Source: Arch2o)

3.2 On-site building

On-site construction refers to the construction of a building and all of its components on the building site. Typically in building construction where concrete is the structural element, shuttering is placed on site with steel reinforcements and concrete is poured in place. Similarly, in timber and steel construction, wooden studs are chopped and joined and steel beams are welded or bolted by hand. As compared to prefab construction ideology, this is considered as an inefficient way of producing buildings (Knaack et al.,2012). However, one can argue in some countries like the Netherlands, due to highly systemised process of on-site construction, it can also be efficient as much as its prefab counterpart. Work can be done with low-cost, unskilled labour by modifying construction methods.
Using a combination of both on-site and prefab construction can also be a way to maximise efficiency. In most cases, the material used and the technology available also dictates the type of construction method to be followed. Prefabricated concrete components have been so technically refined and standardised in the Netherlands that prefab has become the most popular building system (Knaack et al.,2012). Other elements such as finishes are usually performed on-site because they are fairly straightforward and can be managed separately.

3.3 Classification of prefabricated buildings

Prefabricated buildings have been classified by different people in different ways while some classifications are also overlapped. Boafo et al. (2016) classified prefabricated buildings into component, panelized structures, modular structures, hybrid structures, and unitized whole buildings based on their scale, complexity, and configuration. Knaack et al. (2012) divided it into building systems for housing and industrial buildings and further explained them as general prefabrication, flat-pack, modular, container systems etc. Based on the degree of assembly, Gibb and Isack (2003) classified prefabrication into four types: modular, volumetric pre-assembly, non-volumetric pre-assembly, and component sub-assembly. A fundamental understanding of the classification is developed and they have been categorized in the following way.

3.3.1 Component

Components can vary from a small part of a building product such as the hardware for windows or doors to a sizably larger part like the door or window frame. Because of their scale, they allow for the most customization and versatility during the design and implementation phases, but they become more in number on construction sites and arduous to manage (Boafo et al., 2016). Smaller components necessitate more joints and connections, as well as more precise coordination and infiltration inspections. They play a pivotal role, since other prefabricated types are all made up of a number of smaller prefabricated components to form a larger component.

3.3.2 Panelised elements

Panels are 2D planer components used to build structural walls, floors, and roofs (Boafo et al., 2016). They are sized in a way that it is convenient for humans and machines to handle them and for the ease of transportation and logistics that enhance the speed and convenience of delivery. Some of the common examples used in the building industry are sandwich units, structural insulated panels (SIPS), metal frame panels, and curtain walls. They offer a reasonable amount of flexibility depending on their design, however almost all panels are prefabricated according to exact dimensions and very little margin for adjustment or tolerance is allowed on-site.
A Flat-pack can also be categorised in this category since it is considerably compiled of

Figure 3.2: Meridian first light house (Source: Archdaily, 2020)

a number of panels. It is generally seen as a product where the homeowner receives the material directly on site and it is assembled as a do-it-yourself kit of parts. Building components are manufactured in a factory, packed efficiently, then shipped and installed on site. The system in which the components are pre-cut flat panels, efficiently stacked together refers to the name flat-pack (Knaack et al., 2012). Since there are a number of design options for various requirements, the homeowner may skip the planning stage and save money on labour costs by erecting the house themselves. Therefore, it is a prefab solution for the younger generation or those that have good handyman skills.

3.3.3 MODULAR BUILDING

Modular design divides a system into smaller parts called modules, which can be formed, changed, replaced, or exchanged with other modules to form a larger body or a series of modules. Modules may be three-dimensional individual units or partially completed parts in the construction industry. Full volumetric parts, multi-section units, and stack-on units are made. In order to expand spaces, stacking or joining modules side by side creates a repetitive aspect. It is a form of prefabrication where modules are fully assembled in the factory, transported to site and ready for use once building services like power and water facilities are connected (Knaack et al., 2012). Unlike panelized or component types of prefabrication, the majority of interior and exterior finishes are installed in the factory in modular construction. When they leave the plant, they are up to 80–95 percent done (Smith, 2011). They are designed for ease of assembly on the building site.

The size of a module is determined by the position of the module in the building, production and transportation constraints (Boafo et al., 2016). Cranes are normally used to lift and bolt the modules into place. Due to the modularization of a unit as a whole, it faces practical challenges. In transportation, their weight and size are limited by the load capacity and the size of the vehicle they are transported in. In addition, more structural material is generally used since the floor, roof and walls are doubled and are independent of other modules. However, due to tighter connection tolerances, the airtightness and thermal efficiency of modular buildings can be much better than previous prefab types (Lawson, 2011).
Designed by Ar.Kisho Kurokawa, the Nagakin capsule tower (Figure 3.3) in Tokyo was built

Figure 3.3 Nakagin Capsule Tower (Source: Archdaily)

in the 1970s and is one of the earliest examples to use this approach at a bigger scale. Due to the high real estate prices and tight living spaces in Tokyo (Knaack et al., 2012), a modular approach was used where each module or capsule measures 2.5 m by 4 m and they can be connected or combined to achieve larger spaces. Another basic example of modular building is the idea of shipping container homes which was conceived by Philip Clark in 1987. Since then these types of modular shipping containers have taken forms of various buildings especially housing and are still trending today due to their certain aesthetic appeal.

3.3.4 HYBRID STRUCTURES

As the name suggests, hybrids involve integrating panel and modular prefabrication processes to construct the complete building. An example is the Meridian First Light House, as seen in Figure 3.2. The house is comprises of six separate prefabricated modules, with wooden decking wrapping around it, connecting the interior to the outside. The building is a net zero energy house that uses a mix of passive and active energy system to exploit energy drawn from the natural climate (Boafo et al., 2016). The building ranked third in the 2011 US Department of Energy's Solar Decathlon (US Department of Energy Solar Decathlon, 2011).

3.3.5 UNITISED WHOLE BUILDINGS

In comparison to components, panels, modules, and hybrids, whole buildings are prefabricated building types with the best levels of finish (Boafo et al., 2016). Most of the work is done under controlled factory conditions, giving manufacturers the ability to achieve high quality of fit and finish in a predictable time frame. However, due to their large size and weight, it can be difficult to assemble the building in an enclosed factory setting and moving it from the factory to the construction site. Special trailers and transportation permissions must be obtained to transport these building depending from place to place.

3.4 ADOPTED SYSTEM

For the flexible and circular top-up housing units, not only does the design need to be flexible but so should the process of construction too. One should not limit their design by putting a constraint on the construction process and following a specific way of building. Therefore, for the study there are two possibilities.

The first one is a modular building approach, where the whole unit is built in the factory and placed on site as a whole like a container system. This follows the modular building approach mentioned earlier with limitations in transport and doubling up of building components which might not be economically viable.

The second option is to construct the steel structure on site and then follow the panelized system of prefabrication and assemble these on-site. This system would reduce the cost of building materials than the modular building approach. However, the on-site assembly time would increase drastically but one does not how much the difference in time will be. This can only be determined by testing it out in real-time and can depend from project to project.

Therefore, the choice of choosing between these two options remains open. Due to time constraints in this study, the context of the modular building approach has been taken forward. However, the design of building components in this research can also be applied to the second option since panelised components have been adopted.

4. PERFORMANCE OF PREFABRICATED LSF SYSTEMS

4.1 INTRODUCTION

Prefabrication is known as a sustainable construction technique (Matoski et al. 2016). Prefabrication has been shown to improve construction quality and safety while reducing construction time, total costs, material waste, and environmental effects. Designing with prefab components should not be considered as a barrier to creativity but rather an opportunity for innovation. It lowers total cost from advantages of volume by standardizing prefabricated parts and offering mass customization possibilities. For instance, in Hong Kong, the building industry produces a large amount of waste, accounting for up to 40% of total waste intake at landfill sites. Waste disposal space was running out, so prefabrication in building was used, which resulted in an 84.7% waste reduction. (Tam et al., 2007). Another study found that using prefabrication has major benefits, including increased quality control, a 20% decrease in construction time a 56% reduction in construction waste, and a decrease in dust and noise on-site, as well as the labour needed on-site (9.5%)(Jaillon and Poon, 2009).
This chapter seeks to investigate the performance of prefab LSF systems considering thermal behaviour and acoustics performance of existing cases and, thus provide a dynamic case study-based review. However, unpublished or inadequate data of many existing prefab LSF buildings limits the scope of this work.

4.2 THERMAL PERFORMANCE

The tighter integration process of prefab mitigates thermal bridges and air leaks from the standpoint of building physics. The possibility for energy savings in buildings may be significantly influenced by the thermal efficiency of a structure. It is one of the most significant impacting factors in ensuring good prefabricated building quality especially in terms of energy efficiency and associated emission reductions (Yu et al., 2020). In this chapter, thermal performance specifically regarding Lightweight steel framing construction has been studied from literature.

The LSF wall method, which uses cold-formed steel parts, mineral wool, and plasterboard, has proven to be cost-effective and commonly used in the United States, Japan, Australia, and a number of European countries (Yu et al., 2020). Light weight, high recyclability, dimensional stability, fast realization time, high construction standards, system integration in wall depth and greater prefabrication are all advantages of LSF walls (Roque and Santos, 2017). The high thermal conductivity of steel, on the other hand, can cause a thermal

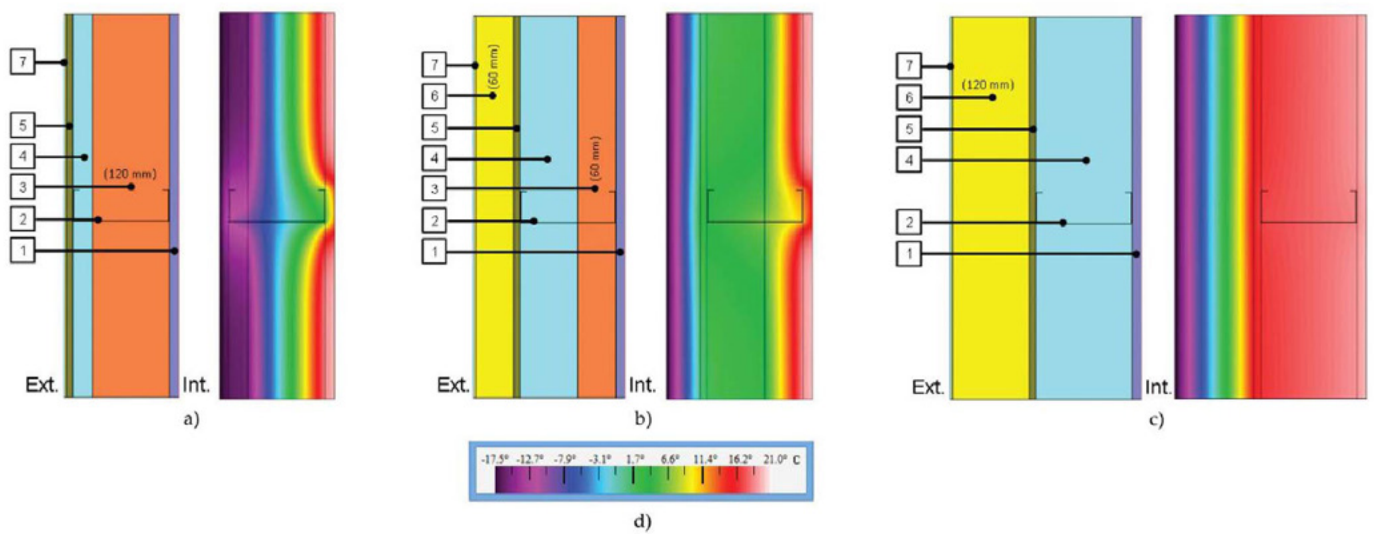


Figure 4.1 Classification of LSF walls (a) Cold, (b) Hybrid, (c) Warm frame, (d) Color legend. 1-Gypsum, 2-LSF, 3-Stone wool, 4-Air gap, 5-OSB, 6-EPS, 7-ETICS (Source: Santos, 2017)

bridge and a reduction in the thermal performance of LSF walls (Yu et al., 2020). Based on the location of thermal insulation, LSF walls can be categorized as cold, hybrid and warm frame construction (Santos et al., 2013). Figure 4.1 illustrates the three types along with their thermal temperature distribution using Therm software by Santos (2017). When the thermal insulation is positioned outside the steel frame (Figure 4.1), the steel frame is warmer, therefore it is called “warm frame construction”. This design is the best choice because it provides continuous thermal insulation and a lower thermal transmission value, which reduces the possibility of interstitial condensation (Santos, 2017).

Since steel has a high thermal conductivity (52 W/mk galvanized steel), the design of building envelope components should adhere to certain guidelines to reduce the effects of thermal bridges. Some of the strategies to mitigate thermal bridges from literature are as follows (S. Yu et al., 2020, Santos et al., 2017):

- Continuous external insulation possibly without and interruption
- If interruption is unavoidable use material with low thermal conductivity
- Incorporating slotted steel studs to increase heat flux path
- Decrease of flange contact area
- Introducing thermal breaks between external and internal components
- Installing thermal break strips over the steel studs

In addition, the dimensions and size of the elements play an important role in reducing thermal bridges and lowering thermal transmittance (Soares et al., 2017). More features were suggested such as:

- Number of steel frames and spacing between them
- Length of the web and flanges
- Thickness of the steel elements
- Cross-section profile

Martins et al., (2016) investigated the impact of several strategies for mitigating thermal bridges on LSF walls and discovered that the best solution included rubber strips (10 mm), slotted steel profiles, bolted connections, and VIPs (Vacuum insulated panels) on both sides (30 mm), which reduced the U-value by 68.2 percent.

Another strategy to increase thermal performance is by increasing the thermal mass. Because of their lighter weight and lower thermal mass, LSF buildings have a lower thermal inertia than typical buildings with reinforced concrete structures and brick walls (Santos et al., 2017). To increase the thermal mass the following strategies have been suggested by Santos et al., (2017).

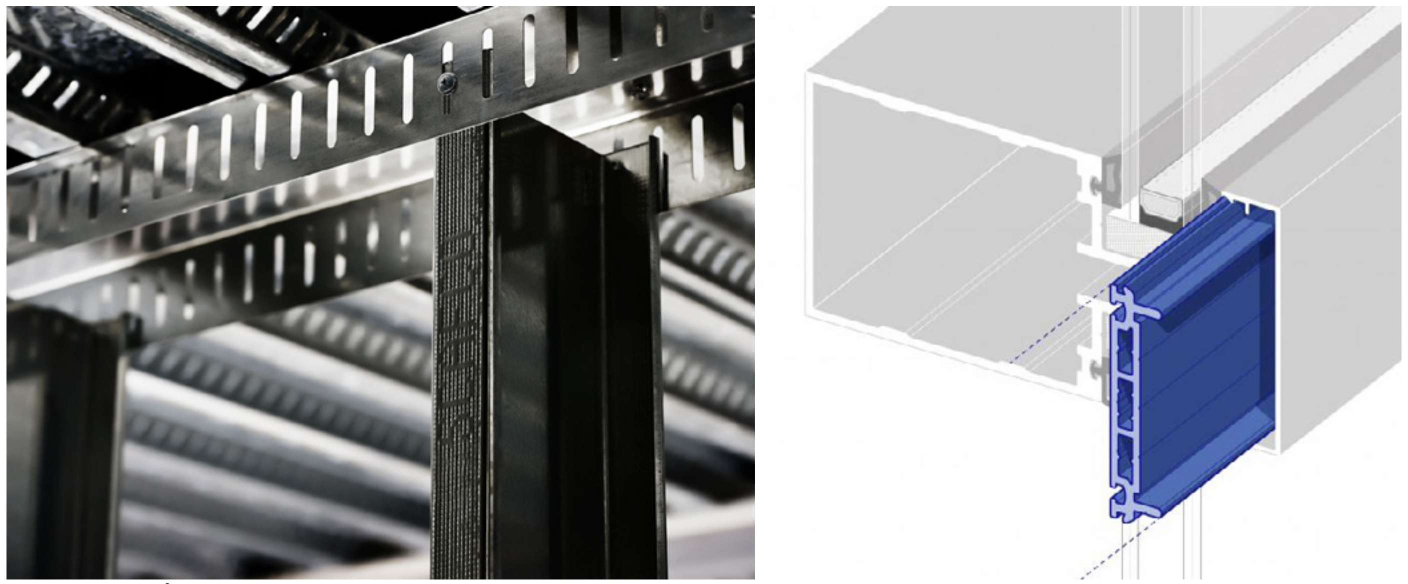


Figure 4.2 (a) Slotted steel studs, (b) Polyamide thermal break (Source: Scafco, Technoform)

- Use of external thermal insulation
- Using huge construction materials. However this is problematic since the idea is to make the building lightweight.
- Use of ground thermal mass
- Using phase change materials

In this chapter the thermal behavior of LSF elements was presented. The two main potential drawbacks were addressed by including several design strategies to enhance thermal performance. These in turn have consequences on the energy efficiency of buildings. These strategies along with acoustic strategies in the next chapter will be concluded as a whole and applied wherever possible in the design of this study.

4.3 ACOUSTIC PERFORMANCE

Building acoustics play an important role for satisfying human comfort levels in dwellings. In lightweight construction this becomes more challenging to tackle due to its mass. To understand the factors that influence the sound insulation in lightweight buildings, Dutch firm Nieman conducted a test in which sandwich panels composing of plasterboard, structural insulated panel (SIP) and cavity filled with and without insulation (Temmink, n.d.). The plan of the assembly and photographs are shown in figure 4.3 (a) and 4.3 (b) respectively. The properties of the tested sandwich panel (SIP – 172 mm Kingspan TEK) are given in Table 4.1.

Important target values for airborne noise and contact noise were set according to their own experiences as shown in table 4.2. Five different cases were tested with minor differences in the cavity thickness and with addition of materials. The composition of the test cases and their results are listed in table 4.3. Type 1 is the starting test sample where Standard level difference (DnT,A,k) of 50 dB is achieved. In Type 2 the composition remains the same but with rock wool insulation in the cavity (Highlighted in the table), where a clear difference of 5 dB was achieved. In Type 3, two plasterboards are used instead of three where only a difference of 1 dB is noticed. In Type 4, the cavity insulation width is increased by 30 mm which achieves a result of 58 dB. In Type 5 links between the panels are removed where the result is reduced by 3 dB.

From the test the following was concluded which will be helpful for making design decisions in the research:

1. Target values should be more than the values set by the building decree.
2. Adding insulation in the cavity increases the sound insulation through absorption.
3. Larger the cavity width with insulation gives better the sound insulation.
4. Adding more mass increases the sound insulation.
5. Links have a limited effect on sound insulation, especially at higher frequencies.

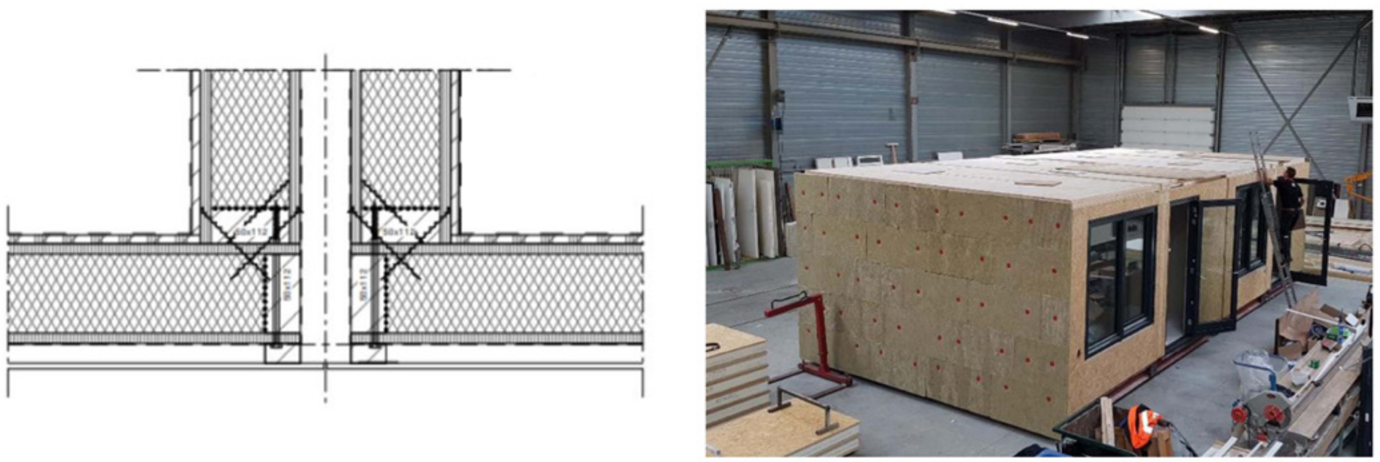


Figure 4.3 (a) Plan of the assembly, (b) Photograph of the assembly (Source: Nieman)

Properties of sandwich panel (SIP - 172 mm Kingspan TEK)	
Type	Load bearing
Composition	15 mm OSB - rigid foam insulation (PU)- 15 mm OSB
Weight	Lightweight, ±25 kg/m2
Thermal insulation	High, No cold bridges
Sound insulation	±30 dB
Coincidence	400 - 500 Hz

Table 4.1 Properties of sandwich panel (Source: Nieman)

Level of protection	Airborne noise	Contact noise
Building decree (Bouwbesluit)	$D_{nT,A,k} \geq 52$ dB	$L_{n,T,A} \leq 54$ dB
Minimal desirable	$D_{nT,A,k} \geq 52$ dB	$L_{n,T,A} \leq 48$ dB
	$R_w + C_{50-5000} \geq 52\text{-}55$ dB	$L_{n,w} + C_{I,50-2500} \leq 50$ dB
Comfortable	$D_{nT,A,k} \geq 57$ dB	$L_{n,T,A} \leq 43$ dB
	$R_w + C_{50-5000} \geq 52\text{-}55$ dB	$L_{n,w} + C_{I,50-2500} \leq 46$ dB
Desirable		Not Desirable

Table 4.2 Target values (Source: Nieman)

	Type 1		Type 2		Type 3		Type 4		Type 5 (Without links)	
	Composition	Width (mm)	Composition	Width (mm)	Composition	Width (mm)	Composition	Width (mm)	Composition	Width (mm)
	Plasterboard	3 x 12.5	Plasterboard	3 x 12.5	Plasterboard	2 x 12.5	Plasterboard	2 x 12.5	Plasterboard	2 x 12.5
	Kingspan Tek	172	Kingspan Tek	172	Kingspan Tek	172	Kingspan Tek	172	Kingspan Tek	172
	Air cavity	70	Rock wool	70	Rock wool	70	Rock wool	100	Rock wool	100
	Kingspan Tek	172	Kingspan Tek	172	Kingspan Tek	172	Kingspan Tek	172	Kingspan Tek	172
	Plasterboard	3 x 12.5	Plasterboard	3 x 12.5	Plasterboard	2 x 12.5	Plasterboard	2 x 12.5	Plasterboard	2 x 12.5
D_{nTAK} (dB)	50		55		54		58		55	
R_w (dB)	48		50		49		52		52	

DnTAK = Standardized level difference, Rw = Weighted sound reduction

Table 4.3 Test cases and results (Source: Nieman)

Another important aspect to consider in building acoustics is the flanking sound insulation. The sound insulation of individual components such as floor, ceiling and walls are relatively simple and can be found in literature. Determination of noise reduction in architectural nodes due to flanking sound transmission is significantly more complicated (Bron van der Jagt et. al, 2011). This becomes more important in light construction than in heavy construction since the sound insulation in architectural nodes is significantly less in light construction. Therefore, the architectural nodes where components are connected via connections have to be designed with noise reduction techniques.

To understand noise reduction in architectural nodes a test was conducted by Bron van der Jagt et al., (2011), where 10 architectural nodes were setup in a laboratory. The schematic representations of the nodes are shown in figure 4.4.

Node 1.1
This knot consists of double UNP (C-section) beams that support both the steel frame floors and the metal stud walls. Both UNP beams are only linked to each other via the main columns. The floors consist of E-beams with a profiled steel plate with anhydrite (mixture of screeding sand and binder) on top. The floors rest on the UNP beams via corner profiles and felt intermediate layers.

Node 2.1
This knot consists of double UNP beams that support the steel frame floors. Both UNP beams are only linked to each other via the main columns. The floors consist of 185 mm high (cold-formed) metal C-profiles with a 20 mm thick layer of chipboard on top. The floors are cold or resilient (via Sylomer intermediate layers) imposed on the UNP beams.

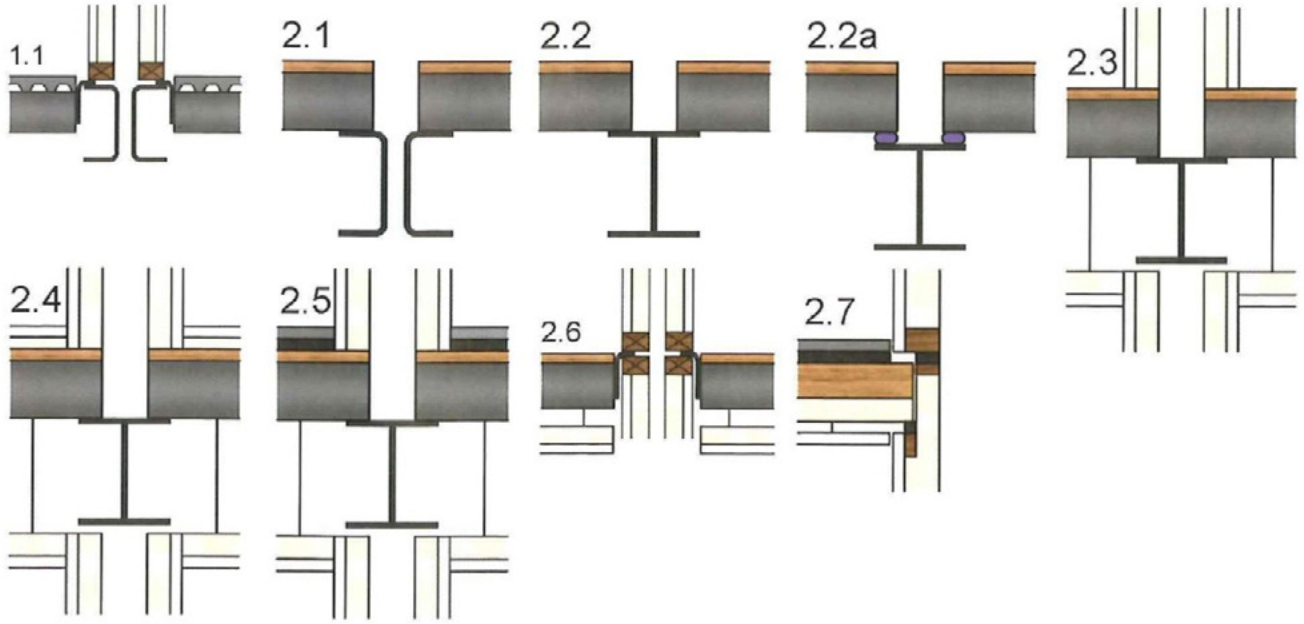


Figure 4.4 Schematic section of architectural nodes (Source: Jagt et al., 2011)

Node 2.2
This node consists of a single HEA240 beam (I-section) that supports the steel frame floors. The HEA beam is clamped between two main columns with welded connections. The floors consist of 185 mm high (cold-formed) metal C-profiles with a 20 mm thick layer of chipboard on top. The floors are cold or resilient (via Sylomer interlayers) imposed on the HEA beam.

Node 2.2a
Similar to the node 2.2 with sprung floor supports as the only difference.

Nodes 2.3, 2.4 and 2.5
These nodes are extensions of construction node 2.2. Metal stud walls and a suspended ceiling have been added to this construction node in construction node 2.3. Furthermore, a light spring-loaded screed has been added in construction node 2.4. The light screed consisted of 20 mm gypsum fiber board on 10 mm mineral wool (product Rigidur E30MF from Saint Gobain). A heavy spring loaded screed is applied in construction node 2.5. The heavy screed consisted of anhydrite on a dovetail plate that is placed on rubber granulate strips (product of Reppel).

Node 2.6
This construction node is a characteristic node that is used in steel frame construction. Here, the steel frame floors are supported by the metal stud walls according to the principle of the balloon method. The floors are suspended between the load-bearing walls using corner profiles.

Node 2.7
This building node is characteristic of the Maskerade system (timber frame construction) and is different from the other building nodes, not a house-separating node, but a node that represents the connection between the house-separating floor and the facade. To prevent vertical sound transmission between facade elements and between the floor and the underlying facade element as much as possible, resilient supports (rubber granulates) have been used.

The nodes 1.1 to 2.5 represent the steel frame construction, in which there is variation between single and double beams and between different variants of screeds. Node 2.6 represents steel frame construction according to the balloon method. Node 2.7 is a variant in timber frame construction.

In the experiment the main objective was to compare the results of the lab measurements with the CAD model results which is not the aim of this research. However, some meaningful conclusions regarding flanking sound transmission can be observed.

The vibration transfer attenuation (Ks) between floors for nodes 2.1 and 2.2 with rigid floor supports and node 2.2a with sprung floor supports were evaluated. From the test it was found that node 2.2a with sprung floor supports performed better to dampen the vibrations. Next, the vibration transfer attenuation (Ks) between floors for nodes 2.3, 2.4, 2.5 and 2.6 with metal stud walls and suspended ceiling were evaluated. From the test it was found that node 2.5 with heavy spring loaded screed performed better to dampen the vibrations followed by node 2.4 with light spring loaded screed. Finally the vibration transfer attenuation (Ks) between the vertical wall parts for the nodes 2.3, 2.4, 2.5 and 2.6 with metal stud walls and suspended ceiling were evaluated. From the test it was found that nodes 2.3, 2.4 and 2.5 had similar results however, node 2.6 showed less vibration attenuation in lower frequencies because the wall is a load bearing structure.

From the experiment, the following conclusions regarding vibration transfer attenuation (Ks) were formed:

- Flanking sound transmission plays an important role in lightweight construction since sound insulation in the connections or architectural nodes is significantly less than in heavy construction.
- This can be countered by providing damping elements such as sprung floor in the connections and by creating more joints or connections to dissipate the vibrations.
- Flanking sound transmission also depends on the mass ratio of adjacent elements like walls, ceiling and floors. The higher the mass, lower the flanking sound transmission.
- Using heavy screed with rubber strips on floors could be a viable solution for better vibration transfer attenuation.
- Load bearing walls should be avoided for vertical vibration transfer attenuation.

Another case has been studied to understand the acoustic performance of steel framing profiles specifically the Jansen steel profiles, an investigation test (Sorichter et. al, 2005) was conducted in 2005 on Jansen VISS TVS profiles to test the edge level difference (DnT), difference in sound level between a pair of rooms and flanking sound transmission.

Different test scenarios were examined (Figure 4.5) with either 1 or 2 transoms in the floor section and 3 mullions running through, different glazing types and thickness, transoms filled with foam and quartz sand, with and without connecting brackets and with plastic T-connector and welded connection. From the test the following findings were obtained:

Vertical flank insulation

1. The foaming of the transom in the floor area did not result in any significant improvement (52 dB with 8 mm laminated glass on the inside).
2. The inner pane of the glazing is decisive for sound transmission. The flank insulation increased by about 5 dB when the inner pane was replaced by an 8 mm laminated safety glass pane with soundproofing film (52 dB) instead of 4 mm float glass (47 dB).
3. The sealing of the transom resulted in an improvement of up to 5 dB, depending on the glazing.
4. If two transoms with lower ceiling connection are installed instead of one transom without ceiling, the flank insulation is increased by 5 dB (52 dB with 8 mm float glass on the inside).

Horizontal flank insulation

1. The transom coupling with a T-connector is about 1/2 dB better than its fusion (welded connection).
2. By changing the inner pane of glazing from 4 mm float to 8 mm laminated safety glass the improvement without the influence of the post is approx. 6 dB.

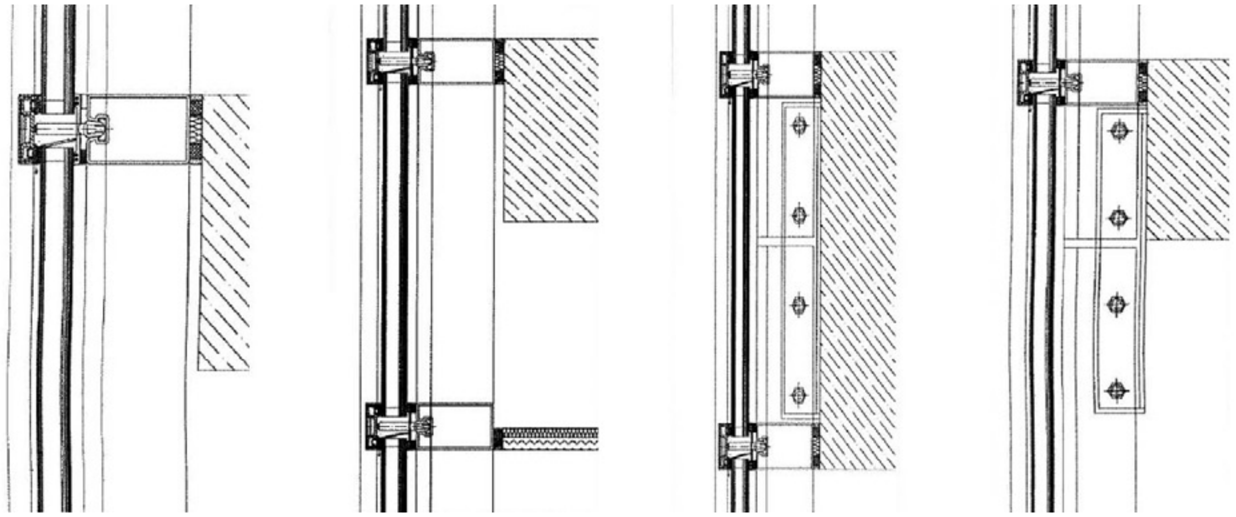


Figure 4.5 Test scenarios of Jansen profiles (Source: Sorichter et al., 2005)

3. By covering the post profile, depending on the glazing, an improvement of up to 9 dB can be achieved.

Transmission measurement of the post profiles
1. The sound insulation was improved by 10 dB by filling the steel profiles with quartz sand (58 dB for 50 x 80 mm profile size).
2. The VISS TV system is about 1 dB better than VISS TVS.

From the results above it is seen that by increasing the mass of the elements such as sand filling and using thicker glass pane, increases the flanking sound performance. It is also evident that when the steel profiles were filled with light foam material, it did not change the results much. Creating partitions between rooms like putting another transom with a ceiling in this case and sealing the connections improved the acoustic performance. Therefore, creating layers and ensuring air tightness is good for acoustic treatment.

4.4 INSULATION MATERIALS

The building skin plays a significant role in controlling the energy consumption of a building. The thermal performance of exterior walls is an important factor in improving the construction sector's energy efficiency and lowering greenhouse gas emissions (Schiavoni et al., 2016). In order to achieve acceptable indoor comfort conditions and energy savings, the thickness and position of the thermal insulation within the building skin should be considered carefully. Along with the thermal properties of the insulating material, other factors such as sound insulation, fire resistance, water vapour permeability and impact on environment etc. need to be accessed as well. This chapter looks into some of the commercial and alternative insulation materials present in the building sector today. However, Polystyrene and other oil based materials have not been looked into since it is flammable and must be treated with a fire retardant called Hexabromocyclododecane (HBCD). The use of HBCD has recently been criticized for the health and environmental threats it poses (Science & AAAS, 2017). From 2015 onwards, the use of HBCD as a flame retardant in insulation materials is restricted as a persistent organic pollutant (POP) (MacLennan & Herzog, 2013).

Stone wool
Stone wool or rock wool is a variant of mineral wool which is made by melting a variety of rocks, such as dolostone (dolomite), basalt and diabase at 1600°C through which a stream of air or steam is blown to produce fibres, which are then held together with binders, typically resins, food-grade starches, and oils (Isover technical insulation, 2021). They are manufactured as panels, felts, pipe sections or rolls for commercial purpose and have thermal conductivity values ranging from 0.033 to 0.040 W/mK. Their density and specific heat ranges in between 40 to 200 kg/m3 and 0.8 to 1.0 kJ/kgK respectively (Schiavoni et al., 2016). They are used for cavity insulation and are considered good for sound absorbtion at a low cost. It is an incombustible material that provides good fire protection with a capacity to resist temperature exceeding 1000°C without spreading flames (Isover technical insulation, 2021). At the end of life, they are either recyled or discarded into landfills (Schiavoni et al., 2016).

Glass wool
Glass wool or fibreglass is made from glass fibers bound together with a binder to give it a wool-like texture. It is manufactured by mixing natural sand and recycled glass at 1300-1450°C which traps small air pockets that helps to keep heat loss to a minimum (Schiavoni et al., 2016). The internal microstructure, which consists of long interwoven fibres, ensures high sound absorption. They are commercially produced as rolls and sheets which make them easy to handle. However, proper safety equipment should be used when handling the product since tiny shards of glass are formed which could cause harm to eyes, lungs and even skin (Thermaxx jackets, 2021). Their thermal conductivity ranges from 0.031 to 0.037 W/mK which is similar to stone wool and density from 15 to 75 kg/m3.

Cellulose
While cellulose may refer to any plant-based insulation, the word has come to refer to newspaper insulation in the building industry. For insulation purposes it is made in a mill from recycled papers, wood fibers, and chemical composites with the aim of enhancing vermin, fire, and rotting resistance (Schiavoni et al., 2016). Even though it can be made into panels and mats, it is more commonly sold as a loose material that is blown into wall cavities. If panels are used, their elasticity permits them to be used as durable materials in raised floors, whereas their porosity and flow resistivity values are sufficient for sound absorption and cavity insulation. The thermal conductivity of cellulose is between 0.037 and 0.042 W/mK, with a density of 30 to 80 kg/m3 and a specific heat of 1.3 to 1.6 kJ/kgK (Schiavoni et. al., 2016). In order to avoid undesirable decrease in insulation properties, it should not be compressed after blowing.These materials can be recycled, but due to the presence of boron salts, they are not suitable for composting.

Vacuum insulated panels
As the name suggests, Vacuum insulated panels (VIP) has vacuum inside the core of the panel that only allows heat transfer through radiation. This provides space saving oppurtunity to create thin insulation panels while achieving low U-values. A core substance with getters, desiccants, and opacifiers is installed in vacuum insulation sheets, which are then protected by a multilayer envelope (Schiavoni et al., 2016). Getters are used to adsorb gases and dessicant for water, while opacifiers prevent infrared radiation from spreading. The most common material VIP core material is fumed silica, although some open cell foams (polyurethane and expanded polystyrene), powders (silica aerogels, expanded perlite and their blends), and glass fiber fit for high temperature uses can be utilised. Since good mechanical strength is required in order to protect the vacuum within the core while limiting the thermal bridge, the envelope design is one of the key VIP aspect. Furthermore, the VIP panel's service life and overall insulation efficiency are heavily influenced by the envelope. Metal foils, metallized films, and polymer films are the most popular materials used for envelopes. However, the latter solution is seldom used due to its limited lifespan. VIP can achieve thermal conductivity values as low as 0.004W/mK with a thickness of 5 mm and a service life of 60 to 160 years (Beatens et al., 2010). However, the panels are particularly vulnerable to piercing, because something sharp, like a nail inserted into a wall, will lower its thermal conductivity significantly (Schiavoni et al., 2016). VIPs cannot be cut on-site during construction. In addition, VIPs are virtually waterproof, which can lead to

Figure 4.6 Mycelium and Hemp insulation panels (Source: Biohm, Hempbuild)

condensation issues.

Aerogels
Aerogel is a solid foam material with pores varying in size from 2 to 50 nanometers in diameter and a high open porosity. The liquid is extracted from a gel and dried under specific conditions by removing the fluid, avoiding shrinking and cracks during the atmospheric evaporation. Aerogels have the lowest thermal conductivity of any solid, due to their high porosity, while remaining transparent to light and solar radiation. They can be made of nearly every material, although silica aerogel is most common and comes in granules or solid tiles. The porosity of silica aerogel ranges between 85 and 99.8%. For a monolithic material, its thermal conductivity ranges from 0.0131 to 0.0136W/mK (Baetens et al., 2011). Density as low as 3 kg/m3 can be achieved due to the high porosity, but most aerogels has density of 70–150 kg/m3 for building applications. Although the results seem overestimated, a sound attenuation of 60 dB was measured for a 7 cm thick multi-layer silica aerogel sample confirming the acoustic capability of the material (Ricciardi et al., 2002).

Mycelium
Mycelium are long thread-like roots, that are formed by mushrooms. These are extremely fine white fibers which spread in every direction, forming a complex, rapidly growing mesh (Souza, 2020). When grown in favourable conditions with respect to temperature, humidity and light, mycelium acts like a adhesive binding the substrate such as sawdust, straw or similar materials and transforming it into solild blocks. The final product can be shaped to manufacture insulating panels or other products such as furniture, packaging materials, and even bricks, depending on the mycelium variant and substrate used (Souza, 2020). It is shown to have good thermal and acoustic properties, as well as strong resistance to fire. In a test conducted by Xing et. al (2018), three species of basidiomycete fungi with straw waste substrate was used to calculate thermal conductivity and specific heat capacity of mycelium blocks. Thermal conductivity values between 0.078 to 0.081 W/mK and specific heat capacity of 0.369 to 0.501 MJ/m3K from the experiment were obtained while density between 51.098 to 61.967 kg/m3 was achieved (Xing et. al, 2018).

Biohm, a bio-manufacturing research company based in London, have manufactured mycelium insulation panels with a density of 128 kg/m3 that can achieve thermal conductivity as low as 0.024 W/mK which outperforms most conventional insulational materials. The company is on-course to produce the world's first accredited mycelium insulation product with testing against thermal and acoustic industry standards, with completion scheduled for Q3 2021(Biohm, n.d.). It is manufactured as rigid insulation panels that can achieve custom dimensions as per the needs of the project, while roll insulation sheets are also under development.

The bio-based material, has a higher level of biodegradability and physical and mechanical properties that are alike existing alternatives such as extended polystyrene (Souza, 2020).With growing trends in the research of mycelium which are showing promising results, it could prove to be a sustainble material that could replace conventional insulation in the market where sustainable and circular building material demands are rising.

Mycelium insulation panels have promised to yield excellent acoustic absoption properties due to their porous and fibrous composition (Jones et al., 2020). A study was conducted to examine mycelium based acoustic absorbers grown on agricultural by-products subtrates such as switch-grass, rice straw, sorghum stalks, flax shive, kenaf and hemp (Pelletier et al., 2013). The results of the study show that mycelium boards can offer a unique alternative to conventional foam insulation boards. The results of the study state that mycelium composites yeilded 70-75% acoustic absorption at the peak frequency of 1000 Hz, which is equivalent to street noise (700-1300 Hz) percieved by humans. All test subjects achieved good results therefore the most economical solution with a preference for panel strength and other applicable physical properties was preferred (Pelletier et al., 2013).

Hemp
Hemp is a strain of the Cannabis sativa plant that is cultivated for industrial purposes that can be used to make a variety of products including building insulation blankets or boards. Hemp wool is made from the hard and woody fibres of this plant while additives like cornmeal or polyester are often applied during the manufacturing process to reinforce it (Insulation-Info.Co.Uk, 2018). They come in different thicknesses ranging from 30 to 190 mm. This material is a natural alternative to synthetic and mineral insulation products that is recyclable and biodegradable with good insulating properties (Hempbuild, n.d.). The commercialized materials have a thermal conductivity of 0.038 to 0.060 W/ m K, a density of 20 to 90 kg/m3, and a specific heat of 1.6 to 1.7 kJ/kgK (Schiavoni et. al, 2016). However, Hemp-based materials, like all natural materials, absorb a lot of water from the air, which increases their thermal conductivity. Moisture, rats and insects must all be avoided while working with these materials.

	Density (kg/m*3)	Thermal conductivity (W/mK)	Specific heat (kJ/kg K)	Fire classification
Glass wool (Fiberglass)	15-75	0.031-0.037	0.9-1.0	A1-A2
Stone wool	40-200	0.033-0.040	0.8-1.0	A1-A2
Cellulose	30-80	0.037-0.042	1.3-1.6	B-C-E
Sheep wool	10-25	0.038-0.054	1.3-1.7	B1-B2
Kenaf	30-180	0.034-0.043	1.6-1.7	B2
Hemp	20-90	0.038-0.060	1.6-1.7	Euroclass D-s1, d0 (B2)
Vacuum insulated panel (VIP)	160-230	0.0035-0.008	0.8	A1
Aerogel	70-150	0.013-0.015	1	C
Mycelium	51-128	0.024-0.078	0.369-0.501 MJ/m3K?	

Table 4.4 Insulation materials data (Source: author)

5. ANALYSIS OF ODS NL

5.1 INTRODUCTION

As mentioned before in chapter 1, Kloeckner metals ODS is a distributor of Jansen façade system in the Netherlands. Here, their basic façade variant, VISS TV system has been analysed including the assembly sequence. The conceptual VISS Quattro profile has also been introduced which will be used further in the research.

5.2. JANSEN VISS

The Jansen VISS system is a façade system for curtain walls by ODS NL. It is a stick façade system and has been on the market for around 50 years or more, comprising of an internal steel load bearing part with a patented VISS groove located in the centre of the width face. The groove enables the connection to the system of fastening anchors and glazing supports that fix the IGU (Insulated glass unit) or insulation panels. A variety of materials are integrated into the Jansen VISS curtain wall framework, but steel, glass, aluminium and EPDM rubber are the four main materials used. The design primarily consists of the following parts (Figure 5.1):

1. The mullion and transom steel frame that plays the structural role and also takes up the wind pressure on the façade. The steel frame has a face width of either 50 or 60 mm and depth ranging from 18 to 280 mm depending on the structural requirements and aesthetic value.
2. The fixation part that binds several layers to prevent water and air from entering the façade. Synthetic insulating studs are used locally in order to prevent a thermal bridge. These studs are available in a variety of lengths and are assembled with special screws that allow for the inclusion of glass units ranging from 6 to 70 mm thick or other infill panels.
3. The outer cover profile which has only an aesthetic function is made of aluminium or stainless steel and is available in different sizes. It is possible to design the outer cover

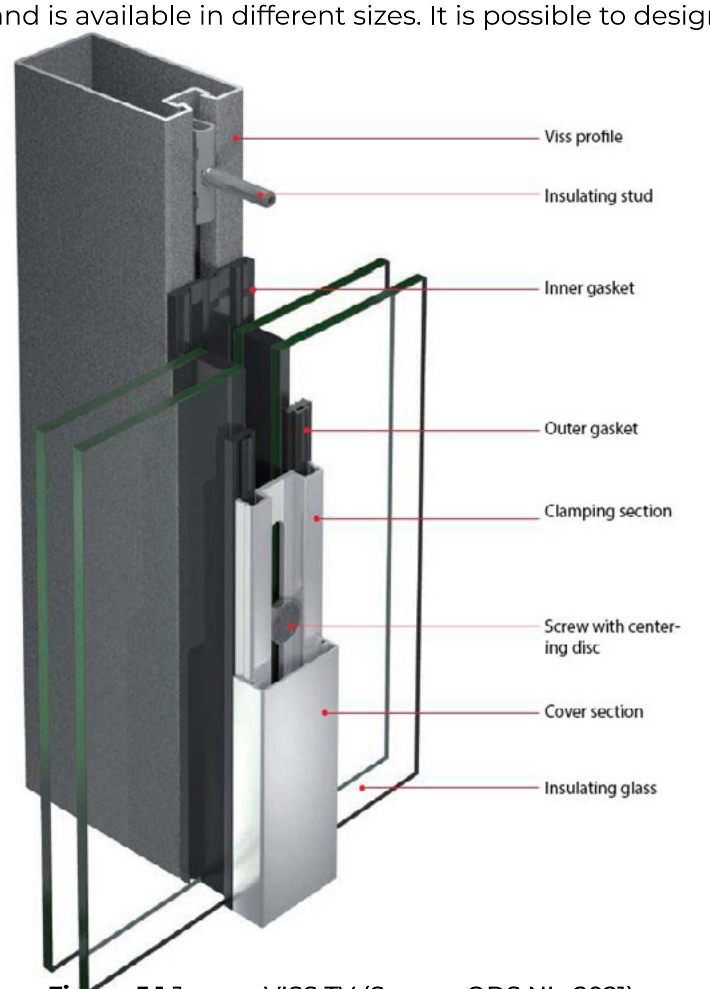


Figure 5.1 Jansen VISS TV (Source: ODS NL, 2021)

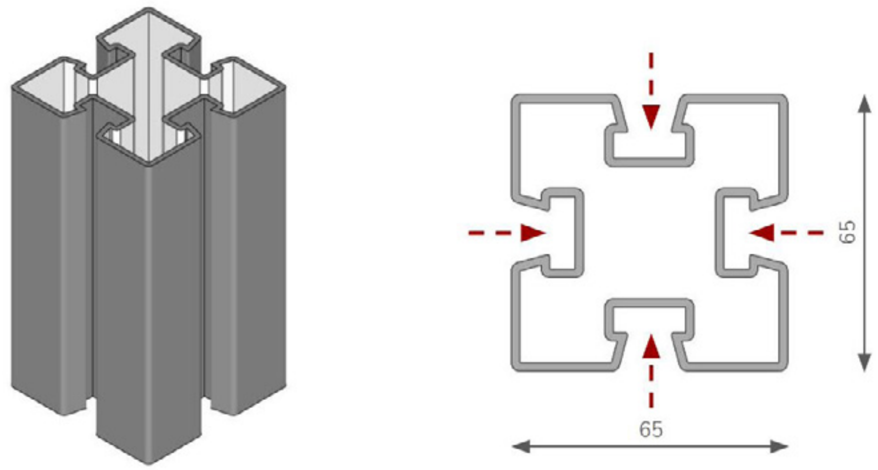


Figure 5.2 Jansen VISS Quattro (Source: ODS NL, 2021)

for the desired appearance. There is also a variant in which a narrow strip is placed between the glass panels.

For the Jansen VISS facade, there is a wide range of accessories, attachments and infill units to satisfy unique structural or functional aspects. A variety of facade constructions can be designed with only few components. Additional thermal insulation, sound reduction and fire safety can be accomplished without altering the facade's exterior appearance. This has led to other variants such as fire resistant facades, highly insulating facades, burglar resistant, bullet resistant, high structural efficiency mullions, or T-shaped or delta steel framing forms.

5.3. JANSEN QUATTRO

The patented VISS groove is a proven geometry that has been in the Jansen profile system since its early years. It is an intelligent T-slot groove system which supports dry connections while avoids the need for drilling or welding. Similar geometry has been seen in the market in other building products such as work tables, shelving systems, staircases etc. mostly made out of aluminium. The idea of adding more grooves on the VISS profile was initiated by a workshop held by Jansen in 1992. Architects such as Norman Foster, Kristian Gullischen and Matteo Thun came up with proposals to create a second groove on the back side of the profile to add other functions.

The Jansen Quattro profile is a system recently developed by ODS which is still in a conceptual stage and has not been in the façade market. In this framing system (Figure 5.2) there are four VISS grooves on each face of the steel profile. This concept opens up a lot of possibilities to mount or anchor various façade or other functions to it. The possibilities

Figure 5.3 Insulating stud and supporting bolts (Source: ODS NL, 2021)

to connect different façade functions such as windows, partitions, balcony attachment etc. was explored by Aashish Vipat (2017) with the guidance of ODS. These ideas will be taken into account in this research and be applied if needed for modular LSF top-up houses. Slight differences could vary depending on the author's input and recommendations. The main research in this paper looks into flexibility of modular LSF top-up houses which mainly lies in the interior domain and partially on the façade elements. The Jansen Quattro profile is used as the base framing element due to its polyvalent interface.

The profile is square shaped which allows it to be used in both vertical and horizontal orientation. However, it might not be the most optimal solution for different structural spans. The Jansen facade system makes use of a common set of interfaces (Figure 5.3) that are responsible for connecting cover caps, gaskets, and glazing to the VISS profile. Depending on the type of connection needed, these are usually slid into place, rotated in, or pushed into the groove. These interfaces are often dry, and drilling holes along the groove is not needed. For facades, these connection components are retained in the design.

The initial square shaped profile size proposed by Vipat (2017) was 50 x 50 mm, however after discussions with ODS representatives, the size was that was recommended was 65 x 65 mm. This was due to practical implications in manufacturing stage where the inside edges of the grooves touching each other were not preferred. However, this could pose a slight problem where a size difference of 5 mm lies between this size and the existing 60 mm profiles. Here one might have to adjust the existing gaskets and the aluminium cover profiles to suit this size, since the set for 60 mm already exists.

5.4 ASSEMBLY OF THE FACADE

This section looks into in detail how the existing Jansen curtain wall frames are mounted or fixed to the structure of the building. This is looked into because the conventional method might differ from the system that is proposed due to the change in the structural system. Before moving forward, it is to be noted that the Jansen framing system assembly is for a stick system curtain wall façade, where several floors are connected together with long mullions. This system might not be suitable for modular façade construction, where the façade of each modular housing unit is built in the factory and then fitted as a whole in the site. Therefore it is important to understand the assembly sequence of the existing system and see where the changes will apply.

First, the brackets are fixed to the structural slab or beam. Thereafter, the mullions are attached to the brackets according to the design. This connection of the bracket and the frame has not been looked into by Jansen, since it could vary from project basis. The next step is the connection of the horizontal transom frame where four types of connecting methods are noticed. These are (Figure 5.4 a,b,c,d):

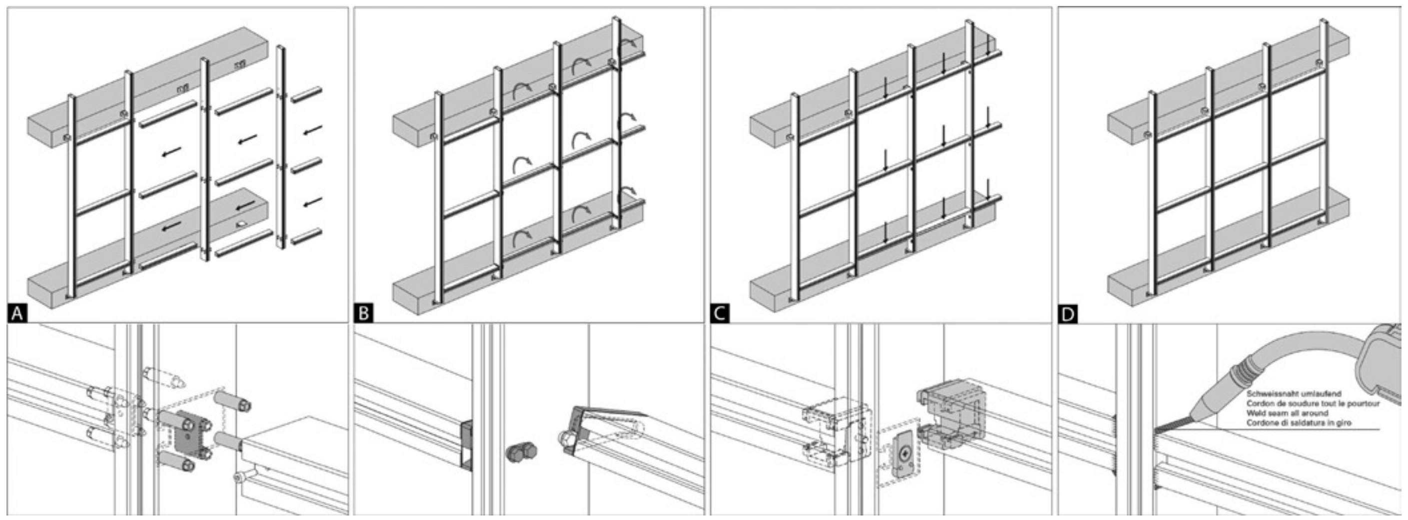


Figure 5.4 Mullion and transom connection types (Source: ODS NL, 2021)

A. Universal connecting spigot: Elements are connected horizontally.
B. Heavy duty connecting spigot: Transoms are rotated in place.
C. Clip-in connecting spigot: Transoms are connected vertically.
D. Welding: Transoms are welded to the mullions.

Some drawbacks in these connections are noticed. In Type A, the assembly type is sequential which will increase assembly and disassembly time. In Type D, a traditional approach of chemical welding connection is used which can be difficult to disassemble in the future but might be cost effective due to the least number connecting elements used.

From here on the rest of the other façade elements are connected such as the insulating studs, glazing support, inner gasket, glazing, outer gasket, cover profiles etc. These connecting elements are retained in this research. The assembly sequence of the Jansen VISS system has been studied in this research and will be accessed according to the performance criteria for DFD laid in chapter 2. Further a new type of connection system to the building structure will be proposed which can make use of the VISS grooves from the VISS Quattro profile.

The glazed panel is secured in the transom with a stainless steel supporting bolt and a pre-assembled key and tenon block that supports the weight of the panels. An insulating stud made up of a pre-assembled plastic turning knob with a friction spring and a special stainless steel screw with a built-in plastic centric disc is used in the mullions. (Jansen, 2018). The air and water tightness is ensured by the inner and outer gasket made from EPDM (Ethylene propylene diene monomer) rubber. Over the gaskets the inner cover profile made from aluminum is inserted and with the help of the plastic turning knob over it, the panels are clamped and tightened to the steel frame. Finally the outer cover profile is inserted over the inner cover profile where the geometry of the profiles allows for a snap-fit connection. The outer cover profile comes in different designs with an aluminum or stainless steel finish which are selected depending on the aesthetic choice. Figure 5.5 presents a typical section through the glazed and non-glazed panel along the building floor.

As mentioned earlier in this chapter, this connection system allows for single, double and

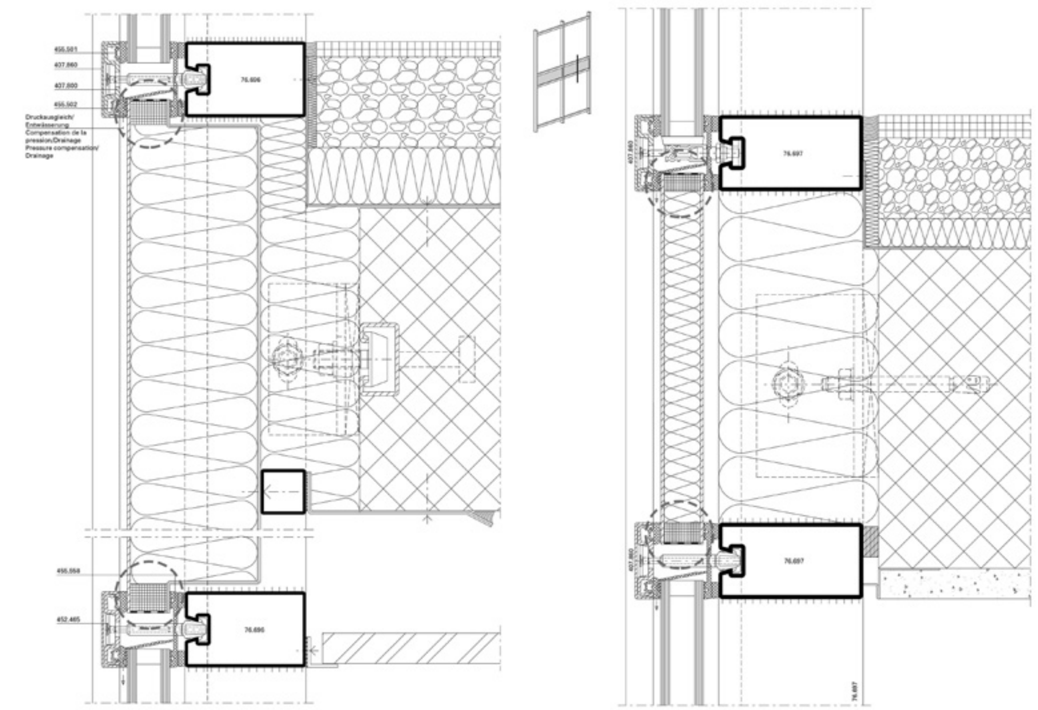


Figure 5.5 Jansen VISS façade section (Source: ODS NL, 2021)

triple glazed panels ranging from 6 to 70 mm thickness. This already gives flexibility in the connection by having an adjustable screwing system. For the glazing part the thickness provided by the connection seems sufficient. However, for the insulating non-glazed panel the thickness has to match the glazing thickness or the panel has to be designed with penetrating geometry at the edges to comply with this system (Figure 5.5). Here, two drawbacks can be noticed:

Interpenetrating geometry: The geometry of the non-glazed panel is an interpenetrating type which is not suitable for DFD. Moreover, the connection of the non-glazed panel to the framing system is overlapping. This gives rise to a rebated geometry which might make it difficult for reuse, refurbish and recycle of the panel. This also limits the thickness of the panel where the connection system might not be able to accommodate a thicker insulating panel.

Assembly disassembly sequence: Due to the interpenetrating geometry the assembly disassembly sequence becomes dependent on adjacent panels which are not preferred. When replacing a panel for maintenance, the adjacent panels are also affected at the same time. This might lead to a sequential disassembly which is not preferred again.

These two drawbacks mentioned will be taken forward and addressed in the design proposal using the Quattro profile.

5.5 DFD EVALUATION

To evaluate the DFD potential of the Jansen façade system the VISS TV (Thermally insulated vertical façade) 60 mm variant has been chosen. The assembly sequence is similar to the assembly described earlier. Figure 5.6 shows the typical plan and section of the VISS TV respectively. As specified in chapter 2, the product will be evaluated according to the 8 criteria. The details of the glazing panel have not been considered such as the desiccant, sealant and the glass itself.

Functional Independence (FI)
The degree of separation between different functions in the system is fairly high. Re-sizing and relocating components such as the mullion, transom, or IGU would not affect the integrity of any of the components such as seals, gaskets, and interfaces in terms of functional autonomy. However, the inner cover aluminium profile is used to clamp the panel and provide the edge geometry for the outer cover profile to snap on it. Also the clamping system is connecting both panels on either side. There are two functions integrated in both cases however it is planned. Score 0.8

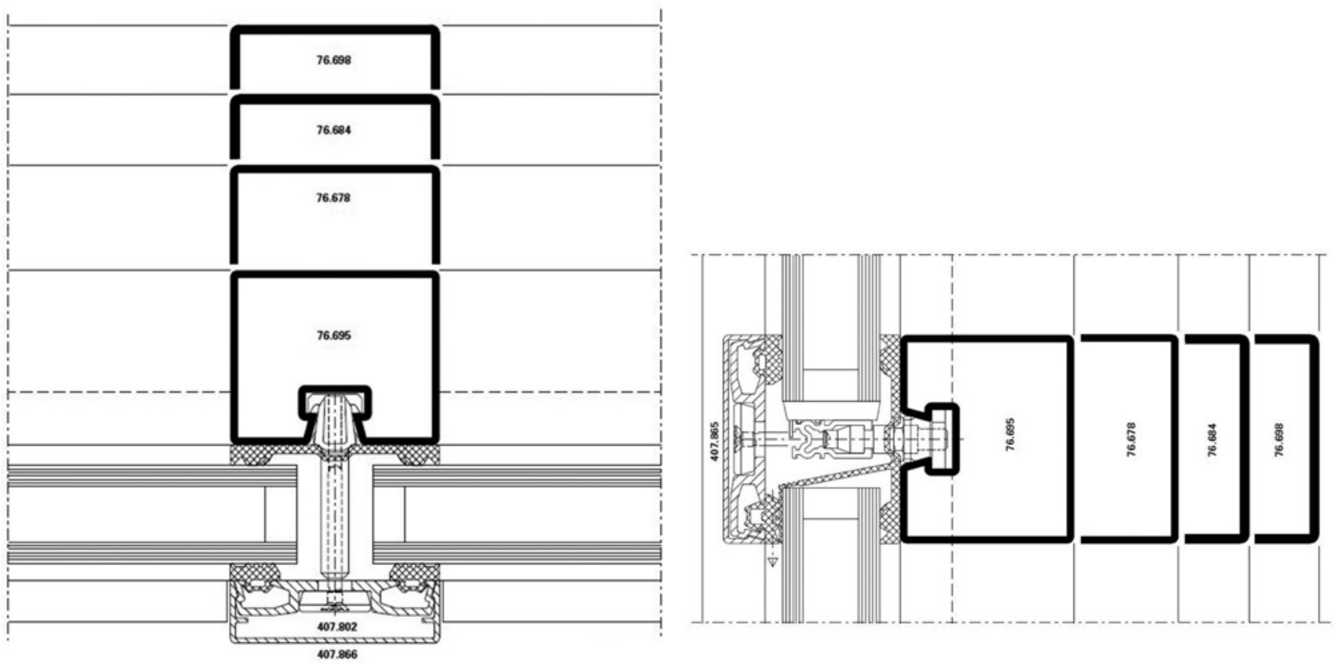


Figure 5.6 VISS TV detail plan and section (Source: ODS NL, 2021)

Systematisation (SY)
Within the stick facade scheme, the division of single parts into sub-assemblies is restricted. The construction itself is such that each part must be connected in a systematic and orderly manner one by one on site. Furthermore, disassembly necessitates dismantling all of the constituents, which is a time-consuming operation if the facade is completely stripped down. The panels are the only thing that forms a cluster. Score 0.3

Relational patterns (RP)
The system has a layered relational pattern in which changing one element affects other elements. This is also due to the lack of clustering and systematization in the system. The interfaces are in charge of several connections, such as the anchors for fastening. The mullion and transom relation, on the other hand, offers some degree of openness. Score 0.4

Base element specification (BE)
Each sub-assembly of the stick system has a moderate amount of base element. There are two base elements that can be seen which are easy to disassemble. The connection that connects the mullion and the transom and the supporting bolt that connects the rest of the façade. Score 0.6

Geometry of product edges (GP)
The facade is made up of many interpenetrating interfaces that overlap in a closed symmetrical pattern. When it comes to disassembly, this should make it less appropriate. However, the path of these inter-penetrating interfaces is very linear, which would allow for easier disassembly, but it would also necessitate the removal of all components relevant to this interface. To access the inner glass gasket, for example, the interface that holds the glass, the outer gasket, and the cover cap must all be removed. Score 0.4

Assembly sequences (AS)
The order in which the facade is put together is related on how it facilitates disassembly. There is a sequential assembly for the IGU, gaskets, and cover caps, which can be defined

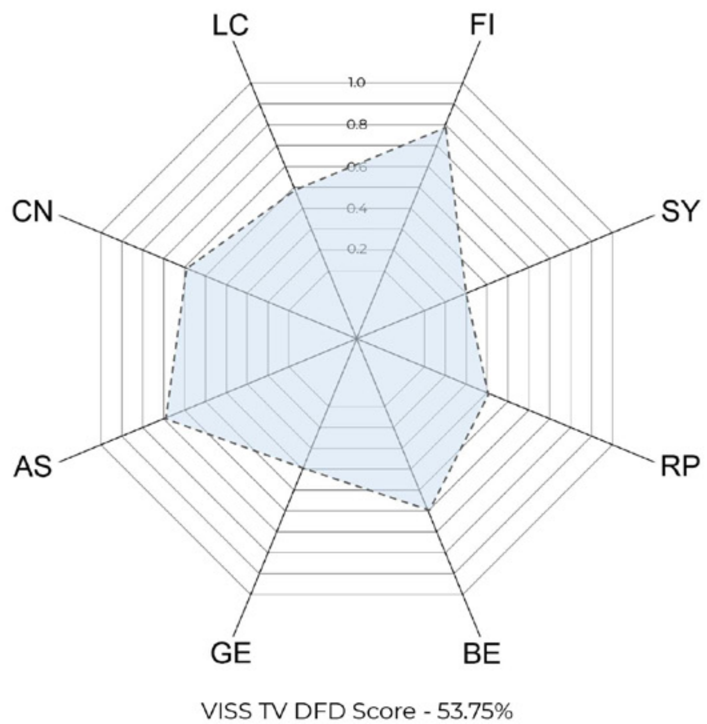


Figure 5.7 VISS TV Spider diagram (Source: Author)

as a step-by-step installation of the components. The overlapping connections generate the interlock. Moreover, if a panel needs to be removed it affects the panel above it in which case some extra safety measures need to be taken to facilitate parallel assembly. The assembly sequence, however, does not result in any demolition. Score 0.7

Connections (CN)
All the connections in this façade system are dry barring the sealant in the glazing unit. In this analysis the IGU is considered as a single unit. However, the connections are internal indirect connections which mean they are not fully accessible unless the outermost element is removed. Score 0.6

Life cycle coordination (LC)
This element of the DfD assessment for a stick facade is well thought out. The outer gasket with the shortest life cycle (five to ten years) is mounted on the second outermost surface. The glass panel, which has a life expectancy of around 40 years, comes next. The steel frame, which has a life cycle of around 50-60 years, is the foundation of the construction. The inner gasket and cover profiles, on the other hand, do not follow this logic. This is particularly problematic when replacing the inner gasket. Score 0.5

Figure 5.7 shows the spider diagram and also the overall score for DFD of the Jansen VISS TV façade. The system secured an overall score of 53.75% according to the DFD criteria set in this paper which makes it lie in the medium disassembly potential category.

5.6 CIRC-FLEX EVALUATION

The Circ-Flex criteria from chapter 2.5 have been adopted to assess the Jansen VISS TV façade system. Due to the unavailability of information and time constraints, all 11 criteria have not been looked into in detail but rather a generalised way of qualitative evaluation has been adopted. The product has been rated as Low, Medium or High for the following categories as per the author’s understanding of the product.

Flexibility capacity - Low: The Jansen VISS predominantly follows a sequential disassembly and assembly process which increases the time and resources spent for the operation which is deemed unnecessary. Even though its components are effective, they are suited only for a specific purpose therefore they cannot be repurposed for other uses.

User capacity - High: Users have a good number of options to choose from. This includes glazing panels, steel frames and even the cover profiles for the appearance.

Circularity capacity - Medium: In terms of maintenance, it can be quite a tedious process due to sequential disassembly process which leads to use of more resources. However, since the system adopts a dry fixing method excepting for the EPDM gaskets where adhesive is used, all elements can be disassembled into smaller individual parts that make recycling easier. Incorporation of bio-materials has not been explored by the company so far, therefore this criterion is not considered.

Figure 4 Nakagin-Capsule-Tower-3.jpg

6. ANALYSIS OF PARTITION SYSTEMS

6.1 INTRODUCTION

For a flexible housing unit, partition systems are important since they can allow different layout configurations and appearance according to user needs. In this chapter two partition systems have been analysed from the current market.

6.2 JUUNOO

The JuuNoo partition system is a smart solution for the circular building industry that is flexible and can be disassembled with ease and reconfigured according to one's needs. They also offer a buyback guarantee which gives their customers a financial advantage. The system consists of 2 types of 0.8 mm thick galvanised steel frame modules that together form a wall. It concerns the start/stop modules (C-modules) and the filler modules (I-modules).All modules can be extended in height, exchanged, or simply rearranged in a different order. 40% of this steel comes from recycling (Juunoo, 2021).

The structure is covered with click panels that are attached to it with special tapes. For heavier panels (>25 kg per board) these need to be screwed to the frame. The click panels can be clicked in one another due to their tooth-groove connection. The generic dimensions with C and I module are given in figure 6.1. The general installation methodology is shown in figure 6.2. The modules each have 4 premade holes (Ø 5 mm) at the top and bottom where it can be screwed to the floor and ceiling. Depending on the application, several screws can be used. There is also an option of fixing using special masking tape without damaging the floor and ceiling surfaces. In some circumstances, the steel frame needs to be cut to fit it within the space since this product is marketed for existing spaces.

To comply with the fire technical and acoustic results, the JuuNoo modules are decoupled from the floor. A PE foam tape of 3x30mm is required for this purpose. For the ceiling, a 2 mm thick EPDM rubber is applied to the modules before they come into contact with the ceiling (Figure 6.3). This connection to the ceiling provides an acoustic seal. Standard acoustic panels can be fit in between the vertical profile of the modules. The JuuNoo modules have square openings 40 x 40 mm for utility lines in the profiles. Through the openings in the horizontal profiles, cables can be pulled into the JuuNoo structure from a Technical floor or false ceiling (Figure 6.4). The system can be finished with any panel

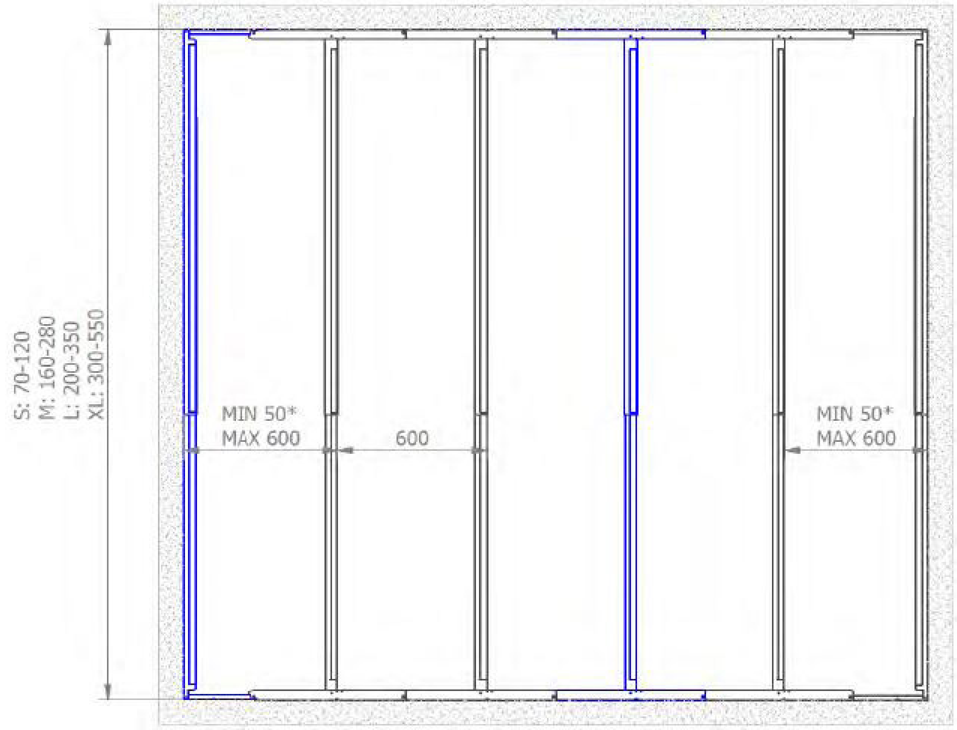


Figure 6.1 JuuNoo C and I modules (Source: JuuNoo)

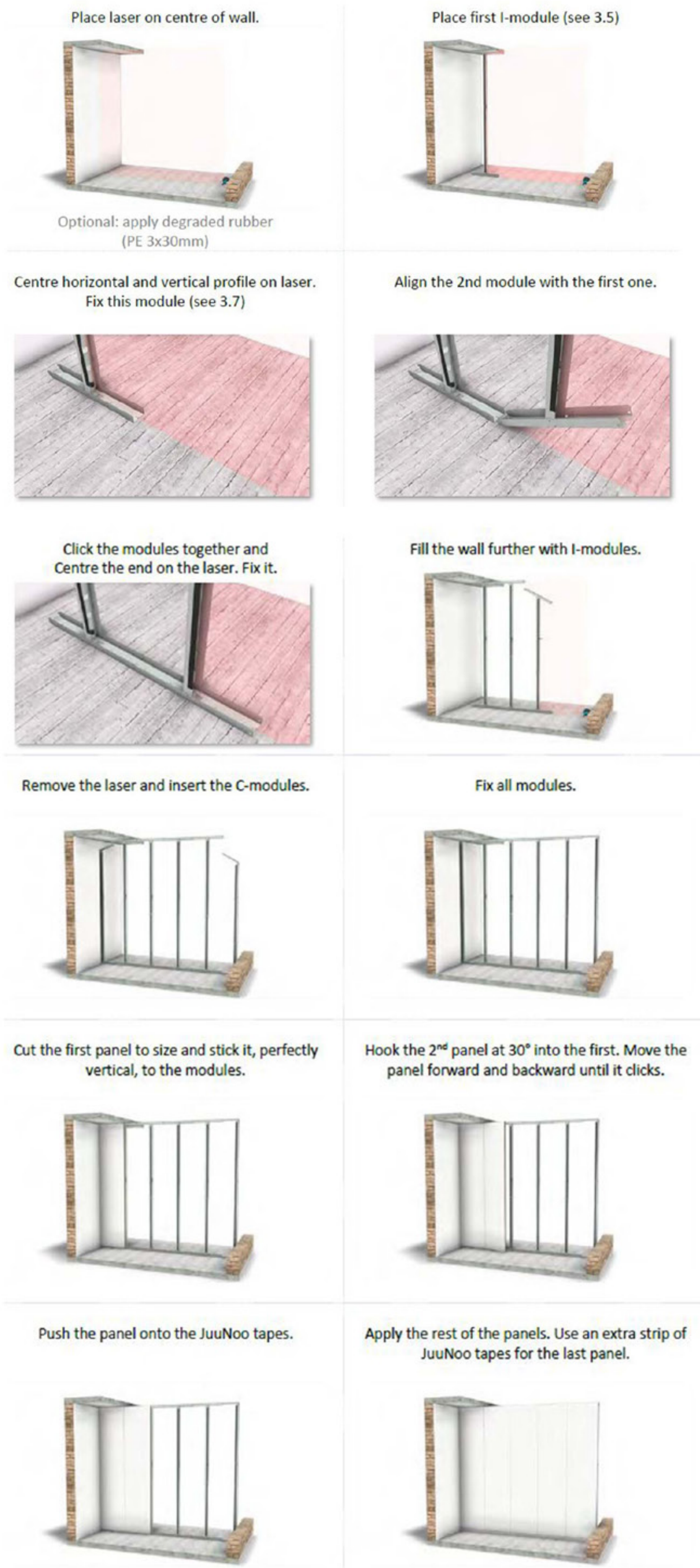


Figure 6.2 JuuNoo assembly sequence (Source: JuuNoo)

Figure 6.3 JuuNoo EPDM acoustic seal (Source: JuuNoo)

Figure 6.4 JuuNoo cable provision (Source: JuuNoo)

finish. These can be applied, depending on the application, with screws, double adhesive tapes or adhesives. The skirting is fixed using silicone glue or double sided tapes.

The system can be disassembled again after assembly, and can then be reassembled without loss of properties. At the end of its service life, the support structure is 100% recyclable. Due to the integration of technical properties in the system, more material is used, resulting in a higher material cost. However, the total cost of ownership is substantially lower than any alternative for 2 reasons: first, the installation speed is 5 to 7 times faster than the current alternatives. In addition, in subsequent applications the material price will drop drastically because the modules will be reused (Juunoo, 2021).

6.3 FAAY VP 54/70

The Faay VP 54/70 partition system (Figure 6.5) consists of a (34 or 50 mm thick) solid flax straw core with plasterboard on either side. The core is made of flax waste, a by-product that is obtained in the production of linen, paper, and linseed oil. (Faay, 2019). Each panel comes in 400 mm or 600 mm width and 54 or 70 mm thick with two built-in vertical cable ducts, allowing electrical wires to be inserted after assembly. Some of the basic connection details are shown in figure 6.5. The edges of the panel have a groove on both sides where a vertical chipboard element is used to connect two panels.

A half chipboard vertical element is used which is mounted against an existing wall and a whitewood horizontal profile of the floor to begin the assembly. These wooden elements secure the wall panels to the floor and ceiling while also providing a strong connection between them. However, the panels are also connected with a special adhesive (FaayFix) in the process. The end panels are cut to size as per the requirement at the top and at the ends. The gap between the wall and the ceiling is sealed with another wooden profile and PUR foam. The 9.5 mm thick plasterboard is fixed to the core using screws after which finishing material is applied such as plaster, paint, tiles, wallpaper etc.

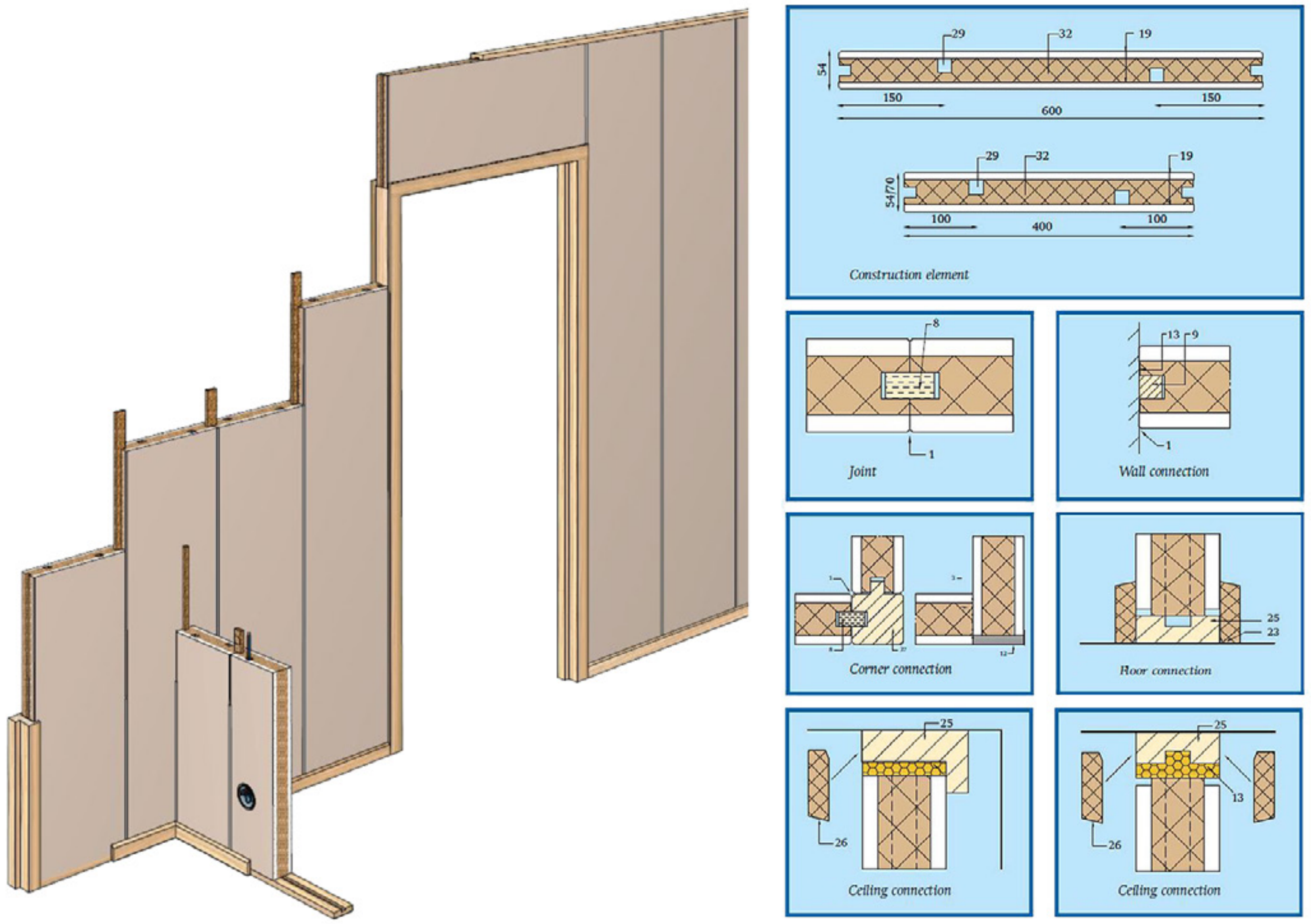


Figure 6.5 Faay VP isometric view and connection details (Source: Faay)

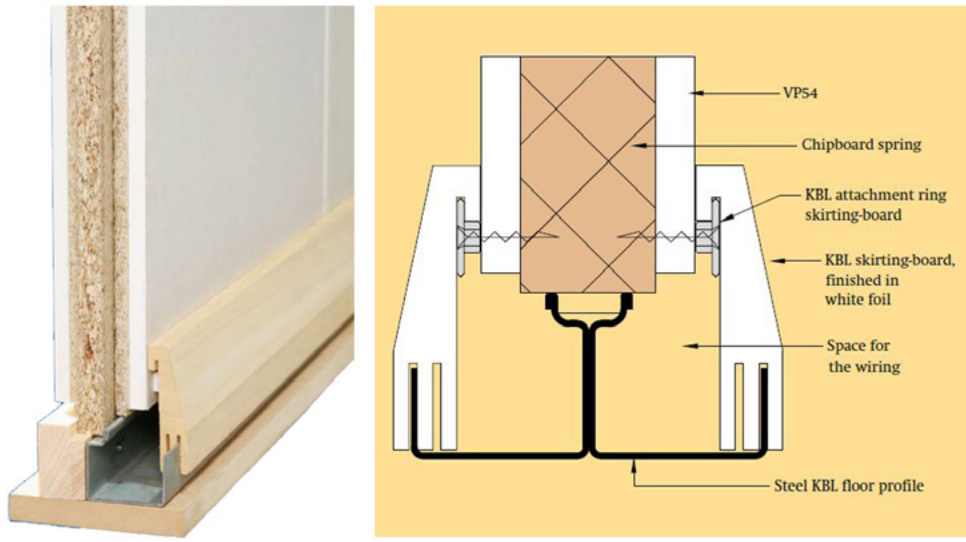


Figure 6.6 Faay KBL isometric view and detailed section (Source: Faay)

The system also includes an optional KBL base profile with a metal section (Figure 6.6), which creates a continuous horizontal space for cables beneath the wall panels. This space is accessible by removing the MDF skirting boards, which are simple to disassemble. The vertical cable ducts always remain accessible from this horizontal space. There are two grooves at the bottom of the skirting board that run along the whole length. The first groove is used when a thin finish is applied such as wallpaper. When the finishing material is thick, the second groove is used.

The following are the basic technical details of the VP 54 variant (Faay, 2019):
Weight: 28.12 kg/m2
U-value: 1.54 W/m2k
Weighted sound reduction (Rw): 30 dB
Fire resistance: 45 min. (NEN 6069)

6.4 DFD Evaluation

For the DFD evaluation, the JuuNoo partition and the Faay VP 54/70 variant with the KBL base profile is used. Both systems are evaluated at the same time.

Functional Independence (FI)
The degree of separation between different functions in the system is high in JuuNoo and medium for Faay system. In the Faay, the solid flax straw core is used both as the structural element as well as the insulating unit. If the acoustic insulation is not enough the whole panel will be replaced by another variant which would mean disassembling almost the entire partition wall. However, the finishing board, skirting profile and connections all have independent functions in both systems. Replacement of these components would not affect the integrity of others. JuuNoo score 1.0, Faay score 0.4

Systematisation (SY)
Within both systems, the division of single parts into sub-assemblies is restricted. The construction itself is such that each part must be connected in a systematic and orderly manner one by one on site. Furthermore, disassembly necessitates dismantling all of the constituents, which is not necessarily a time-consuming operation but can be avoided. Only the horizontal base without the skirting board forms a cluster in the Faay system. JuuNoo score 0.4, Faay score 0.4

Relational patterns (RP)
Both systems have a combination of stuck and layered relational pattern in which changing one element affects other elements. For instance changing wires in the JuuNoo system means insulation has to be removed. This is due to the lack of clustering and systematization in the system. In both cases, there is an amount of adhesives and tapes used more in the JuuNoo system. The skirting element in the Faay system is open while the insulation element in the JuuNoo is open if it needs to change. JuuNoo score 0.5, Faay score 0.6

Base element specification (BE)
In the JuuNoo system the steel frames act as the only base element while the whole flax panel and the steel skirting base in the Faay system. Due to sequential assembly process, replacing the base element of one panel affects the next one. This is because there is no base element between panels. In both cases the base element does two functions. JuuNoo score 0.4, Faay score 0.4

Geometry of product edges (GP)
The JuuNoo follow a symmetrical overlapping for the steel frames and an unsymmetrical overlapping for the panels of the clicking mechanism. In the Faay system, the core uses a closed geometry with wooden insert in between two panels. However, the panels follow an open geometry that is either screwed or glued. An average is taken for both cases. JuuNoo score 0.6, Faay score 0.4

Assembly sequences (AS)
In both cases a sequential disassembly process is clearly noticed. Demolition of EPDM gasket in the JuuNoo might occur since they are glued while the Faay system uses PUR foam. In both cases partial demolition of the acoustic seal can occur. However this is overlooked since the overall sequential assembly outweighs this small part. JuuNoo score 0.6, Faay score 0.6

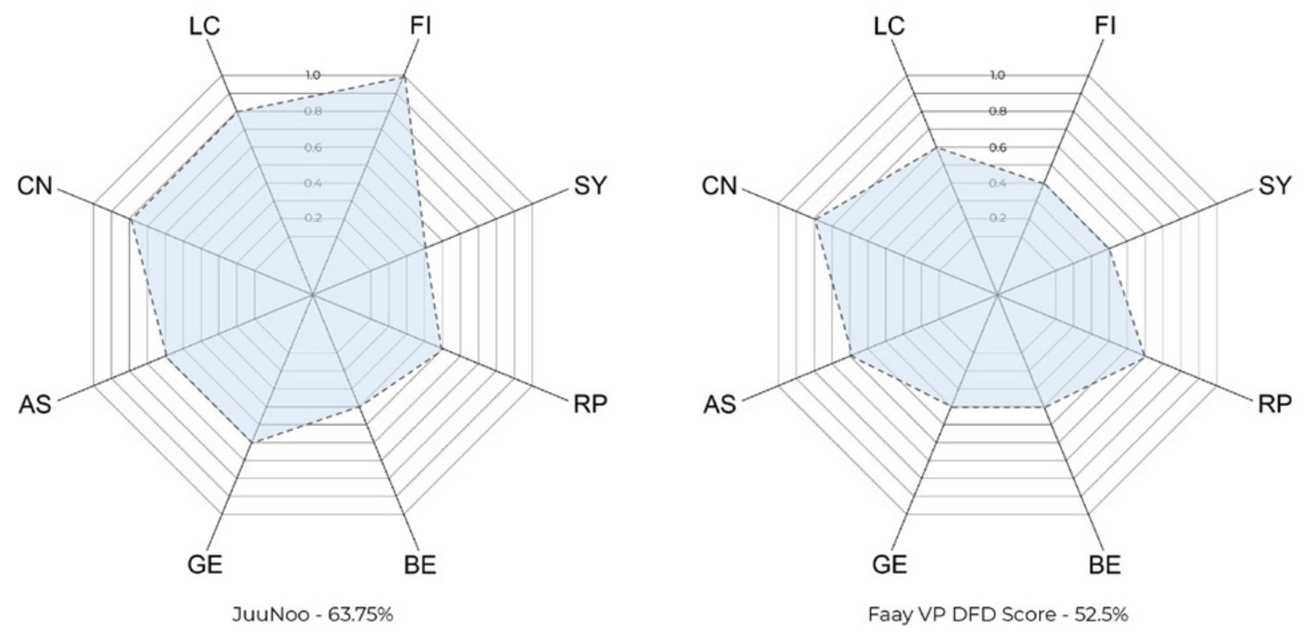


Figure 6.7 JuuNoo and Faay VP spider diagram (Source: Author)

Connections (CN)
In the Faay system, an indirect internal connection via the wooden element between panels is seen, while the JuuNoo system has an indirect external connection through screws drilled on the floor and ceiling. The panels have direct accessible connection in the Faay and JuuNoo has an indirect panel connection. Both systems have glued connections to a small extent which is overlooked again. JuuNoo score 0.8, Faay score 0.8

Life cycle coordination (LC)
In the JuuNoo system, the steel has a long life span but other elements such as the insulation and the finishing board can be chosen from any material in the market. Therefore a Long LC for steel / short LC for other materials has been taken. In the Faay system, the lifespan of flax waste core is not known. However, it is assumed that it would have a longer lifespan than the finishing board which is also can be out of any material in the market. Therefore this criterion is based on assumption. JuuNoo score 0.8, Faay score 0.6

Figure 6.7 shows the spider diagram of both the systems side by side for DFD. The overall score for JuuNoo and Faay partition systems are 63.75% and 52.5% respectively. Therefore both these products lie in the medium disassembly potential category.

6.5 Circ-Flex Evaluation

The Circ-Flex criteria from chapter 2.5 have been adopted to assess the JuuNoo and Faay VP system. Due to the limited availability of information and time constraints, all 11 criteria have not been looked into in detail but rather a generalised way of qualitative evaluation has been adopted. The product has been rated as Low, Medium or High for the following categories as per the author's understanding of the product.

Flexibility capacity: Even though both systems could have a faster installation process than traditional partition walls, they follow a sequential disassembly and assembly process. Therefore, they both score medium in this aspect as validated by DFD evaluation. The ease of repurposing or disposing the elements is medium in case of JuuNoo system since it uses a specialised framing component. While in the case of Faay system, most of its components are bio-based, therefore it is easy to dispose them without harming the environment and also repurpose them with a few modifications. JuuNoo: Medium, Faay: High

Category	Criteria	JuuNOO	Faay VP
Flexibility capacity	Ease of Disassembly	Medium	Medium
	Ease of Re-assembly	Medium	Medium
	Ease of Repurposing or Disposing	Medium	High
User capacity	User willingness to invest time and money	-	-
	User perceived freedom of choice	High	Medium
Circularity capacity	Ease of Maintenance	Medium	Medium
	Ease of Redistribution	High	Medium
	Ease of Remanufacturing	-	-
	Ease of Recycling	High	Medium
	Ease of Facilitating Bio-cascades	Medium	High
	Ease of Facilitating Bio-feedstock	Medium	High

Table 6.1 Circ-flex evaluation of JuuNoo and Faay VP

User capacity: Users have freedom of choice in terms of the finishing board in both cases. Since the structural framing element is separate in the JuuNoo system, users can choose the insulation material as per their needs. This is not possible in the Faay system. JuuNoo: High, Faay: Medium

Circularity capacity: In terms of maintenance, it can be quite a tedious process in both cases due to sequential disassembly process which leads to use of more resources. The JuuNoo system scores high for ease of redistribution and recycling since it uses adopts a dry fixing method excepting for the acoustic seal. While the Faay system scores medium because it uses special adhesives to an extent which can lead to partial demolition while separating components. JuuNoo system scores medium in terms of facilitating bio-based materials since the finishing boards and the insulation material can accommodate them. In the case of Faay, where the majority of the elements are bio-based it scores high. JuuNoo: Medium, Faay: Medium

7. DESIGN PROPOSAL

7.1 Scenarios of Housing Transformation

As mentioned earlier in chapter 1, Netherlands faces housing problems and to overcome this new ones have to be simply built. The solution here is to build these houses in a quick manner using prefabrication manufacturing to overcome the housing demands on time. These solutions are proposed on already existing flat roof buildings where the housing modules can simply be mounted without much complication on site. To achieve these two problems can be noticed on a broad level.

1. The roof top (site) of buildings could come in different sizes and configurations where a rectangular, L-shaped, square or even curved edges etc. might be expected. Technical installations on roof tops might also be encountered such as ventilation shafts, façade maintenance units, mechanical equipment etc. (Not in the scope of this research).
2. User demands are varied from person to person with respect to requirement of number of rooms, layout of spaces, sizes, appearance, and technical aspects etc. These demands could change for investors like private and social housing corporations. In this research the case for social housing has been taken, where basic set of living standards and amenities have been considered according to the author's experience and knowledge.

The demands could also change when the user lifestyle changes such as requirement for a larger room or when a new user takes over or when a new technological product is trending in the market or the building codes for technical aspects change overtime. In both cases it is apparent that a flexible solution is needed to cater to the demands of physical limitations and varying user demands. This means building components need to be designed in an adaptable and demountable manner where the unit could cater to different sites, one could change the size, layout, finishes and replacement of components can take place easily without compromising the intrinsic properties of a material.

In this chapter, different scenarios of basic housing cases and transformations have been looked into using a modular prefabricated strategy where the sizes of components are standardised. This gives an opportunity to add or remove units according to physical constraints and change the layout of units from within using demountable, movable walls.

7.2 Defining the Grid

For a modular housing concept, defining the grid system is significant as these will be applied in most building components such as the structure, façade, walls, floors and roofs. The grid will have to interrelate to each building component so that standardised components are manufactured that will make the prefabrication of components more efficient. Transportation of these components to the building site, either individually or as a whole will have impact on the design.

In this research modular housing units have been proposed that will have to be transported by road in Lorries. The local transportation limits will be taken as a guideline to determine the size of the modular units. In the European Union guidelines, an abnormal road transport may have a major impact on road safety due to its dimensions and/or weight. Furthermore, it can obstruct other traffic. As a result, the majority of Member States

	Type of road	No Escort Necessary	Type A Escort	Type B Escort
Width (W)	Motorways	W ≤ 3,50 m	3,50 m < W ≤4 m	W > 4 m
	Other roads	W ≤ 3,25 m	3,25 m < W ≤ 3,50 m	W > 3,50 m
Length (L)	Motorways	L ≤ 30 m	30 m < L ≤ 50 m	L > 50 m
	Other roads	L ≤ 27,5 m	27,5 m < L ≤ 32,5 m	L >32,5 m
Weight (Not applicable to Denmark[1])	All roads	No specific requirements		

Table 7.1 Escort categories (Source: Directorate general of energy and transport EU)

mandate that unusual road transport be accompanied by an escort (Directorate general for energy and transport, 1996). Table 7.1 shows the escort categories needed for abnormal transport.

Type A Escort: At least one escort vehicle.
Type B Escort: At least:
- Two escort vehicles, or
- One escort vehicle and a police escort or equivalent

The maximum length of Lorries should not exceed 18.75 m, 4 m height and weight should not exceed 50 tonnes (Ministerie van Infrastructuur en Waterstaat, 2018).

For this research a modular housing unit of width of less than 3.5 m will be targeted. This will eliminate the need for Type B escort. This does not mean a larger width cannot be made possible. If a larger width of more than 3.5 m is achieved, it simply means that Type B escort will be applied. However it is worth mentioning that these transport restrictions do apply design constraints for prefabricated modular housing.
The grid system of a building unit is divided into the primary and secondary grid (Figure 7.2). The secondary grid is a combination 300 x 300 mm grid and a tartan grid. The 300 x 300 mm grid is taken because it is assumed in this research that most building products such as flooring, boards, kitchen cabinetry etc. come in multiples of 300 mm. This was also recommended by Open building expert architect Frans van der Werf in chapter 2. The tartan grid is chosen at certain intervals because it takes wall thicknesses into account that makes possible to move wall components around. The intervals of the tartan grid are based on the prediction of future layout changes where the position of walls can be configured to form desirable layout sets.

The primary grid is the structural grid. A column-beam steel structure has been adopted for this research (The detail analysis of the structure is not within the scope of this research). The primary structural grid is left independent of the secondary grid which creates less dependencies amongst them. Nonetheless, it should not lie outside the building skin. This is mainly because of thermal heat transfer reasons. If the structure lies outside the skin, more heat loss can occur which means unnessary costs for insulation.
By creating two separate grids (Structural and non-structural) and keeping them independent of each other, the design principles of Open building, IFD and DFD are being followed as discussed in chapter 2. This gives more flexibility to the related building components thus improving its reuse, refurbish and recycling potential. The overall grid dimensions will be as per the final design proposal.

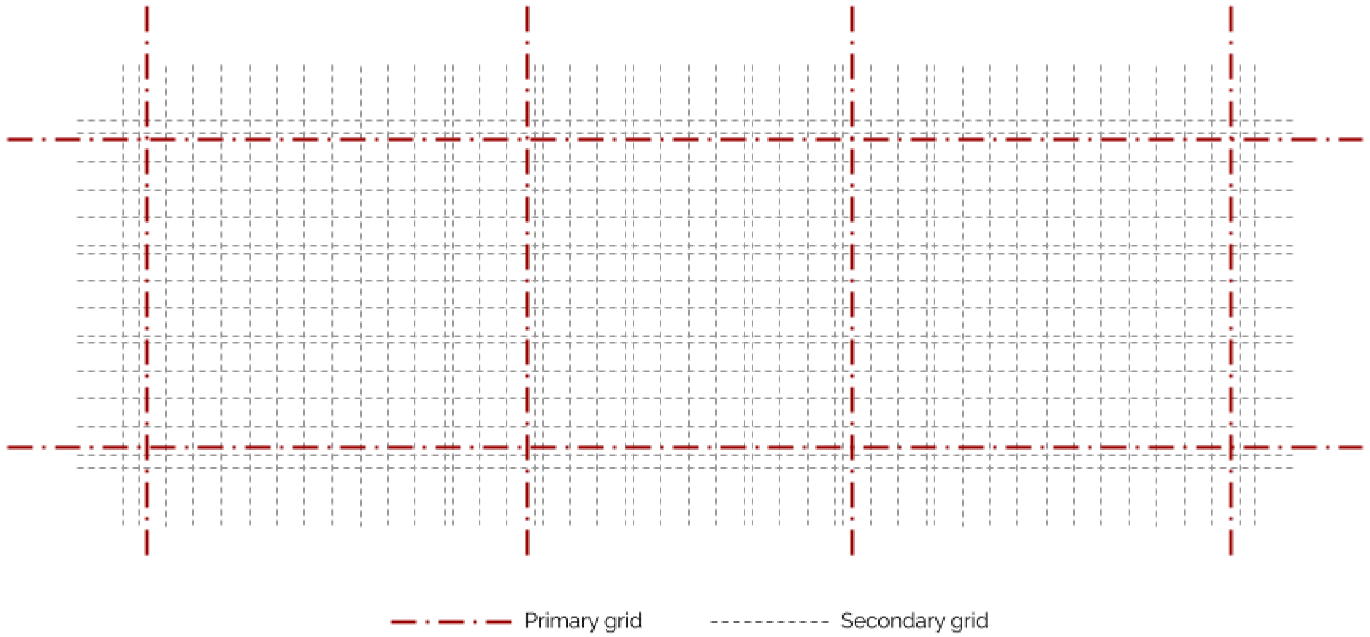


Figure 7.1 Grid system (Source: Author)

7.3 MODULAR LAYOUT CONFIGURATIONS

Keeping the transport limitations in mind, a possible module unit has been designed with overall dimensions of approximately 12 x 3.5 x 3.3 m (Length x breath x height). The length can be shortened or extended depending on the space available and transport capabilities. Figure 7.2 shows the basic layout of a 1 bedroom unit with living and dining room, kitchen and toilet. Here it is assumed that the unit is accessed from one side with a single loaded open corridor and the other side has provision for a possible balcony space. It is also assumed in this research that plumbing lines are accommodated within the raised floor system while electrical lines through the suspended ceiling system. However, these two service lines can also be accommodated within the raised floor system if carefully planned. Plumbing shaft is located next to the toilet and kitchen and electrical shaft next to the entrance.

In the 1 bedroom unit, primarily two transformations are possible, one where the living is next to the entrance and the other where the location of the living is swapped with the bedroom. This can change according to the user or client's personal wishes with respect to privacy, views or other needs. The toilet and the kitchen are kept in the centre of the module for better light and ventilation in the bedroom and the living. However, they can also be shifted more towards either side for to increase or decrease the floor space of the adjacent rooms.

With the addition of a second unit, more possibilities of layouts are achieved. This can be seen in figures 7.3 and 7.4 a, b, c, d, where the house can change from a 2 bedroom unit to a 3, 4 or 5 bedroom unit. 4 and 5 bedroom units can be applicable for student accommodations where compact room sizes that are more economically suitable for them are preferred. These solutions can be presented in student towns like Delft where there is a scarcity of housing options for students. The toilet units can be designed differently into set modules with different options. These toilet units can be placed directly within the whole unit with the necessary plumbing, waterproofing and sanitary fixtures in the factory. It is assumed that the toilet and kitchen elements need not be altered drastically due to plumbing complications. However, they can be changed or easily maintained through the demountable raised floor system if needed. Apart from these layouts more options can be explored where more modules or half modules can be added to suit different configurations.

Figure 7.2 One bedroom unit

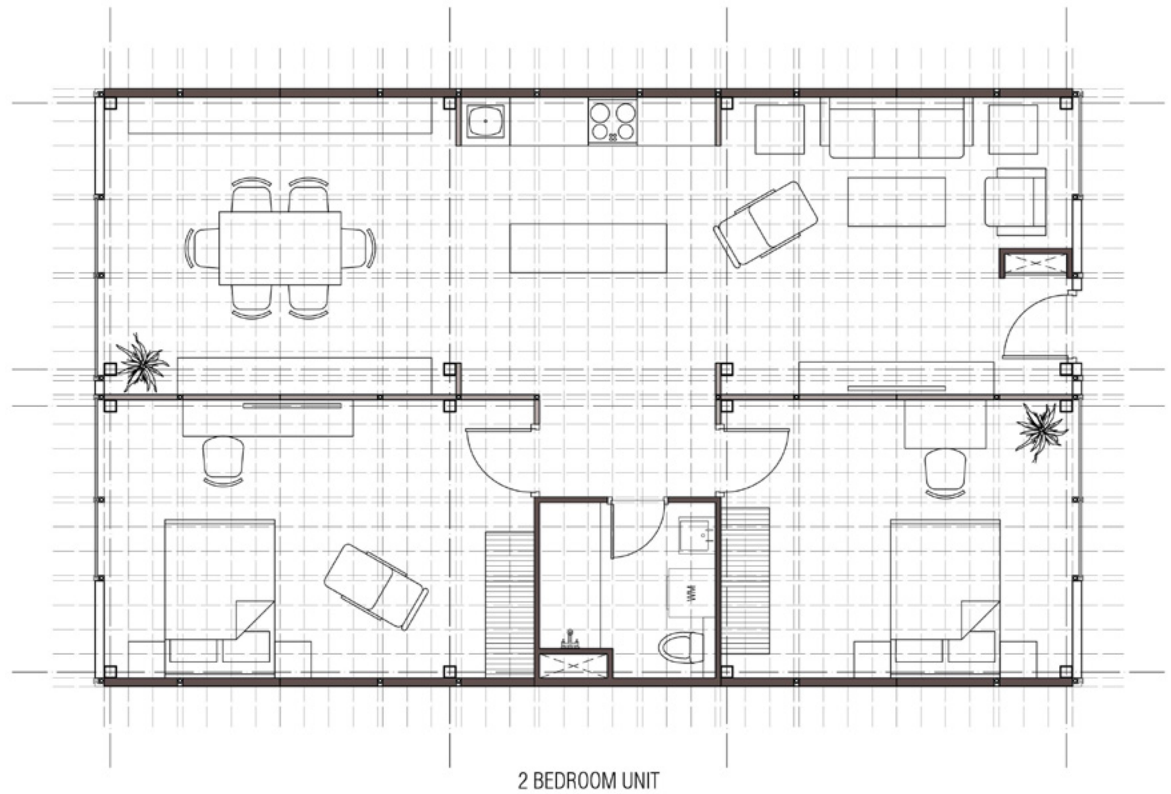


Figure 7.3 Two bedroom unit

Figure 7.4 Unit options (a, b, c, d)

7.4 PARTITION SYSTEM

The partition system has been designed for convenience for the occupants to change and move them easily without much difficulty. Respecting the 300 mm grid size, the panels come in sizes of 900 and 1200 mm width. If needed, 600 mm width can also be incorporated. The framing element is made out of steel C-sections that house the connection details while also providing space for wiring cables. During designing it was important to keep the circular design strategies mentioned in chapter 2 and minimise the number of disassembly steps in case of transformation.

Two options of design have been proposed for the partition system with differences lying mainly in the connecting style. The first option is a simpler solution shown in figure 7.5. Here, an aluminium bracket with rubber gasket at the top is screwed to the ceiling as the first step as indicated in the drawing. After this, the steel frames with 65 mm thick insulation panels are mounted right next to it. This component is free standing. Proper alignment is ensured by the aluminium bracket in the first step. The other aluminium bracket is screwed to the ceiling in the third step from the other side of the wall to hold it and ensure the panel does not tilt or topple in case of accidents. After this the aluminium skirting is mounted in the framing element as seen figure 7.6. The skirting element can be removed anytime to access the wiring cables if needed. The fifth step, which is the last step, connects the finishing board to the aluminium bracket at the top and the framing element at the bottom by simply sliding it upwards and then letting it rest at the bottom. The finishing board can be screwed into its respective brackets at the top and bottom if need be. A thinner board can also be accommodated by simply putting an extra element such as foam tape or wooden block behind it.

Between step 2 and 3 (i.e before the second aluminium bracket is fixed), the framing panel should be connected to its adjacent panels or the VISS Quattro façade frame or the corner VISS Quattro profile with either a T-bolt or a regular nut-bolt connection. These connection details are shown in figure 7.7 a, b, c. For acoustics, the decoupling of the wall to the floor and ceiling elements is provided by the rubber gasket at the top and the rubber shoe at the bottom. The acoustic insulation can be standard industry insulation products studied in chapter 4 such as glass wool and stone wool or more sustainable alternative options like cellulose, hemp or mycelium. In addition, the VISS Quattro profiles in the corners and connections are filled with quartz sand to increase the acoustic flanking insulation. The sand can be filled before in the factory before they are brought to the site.

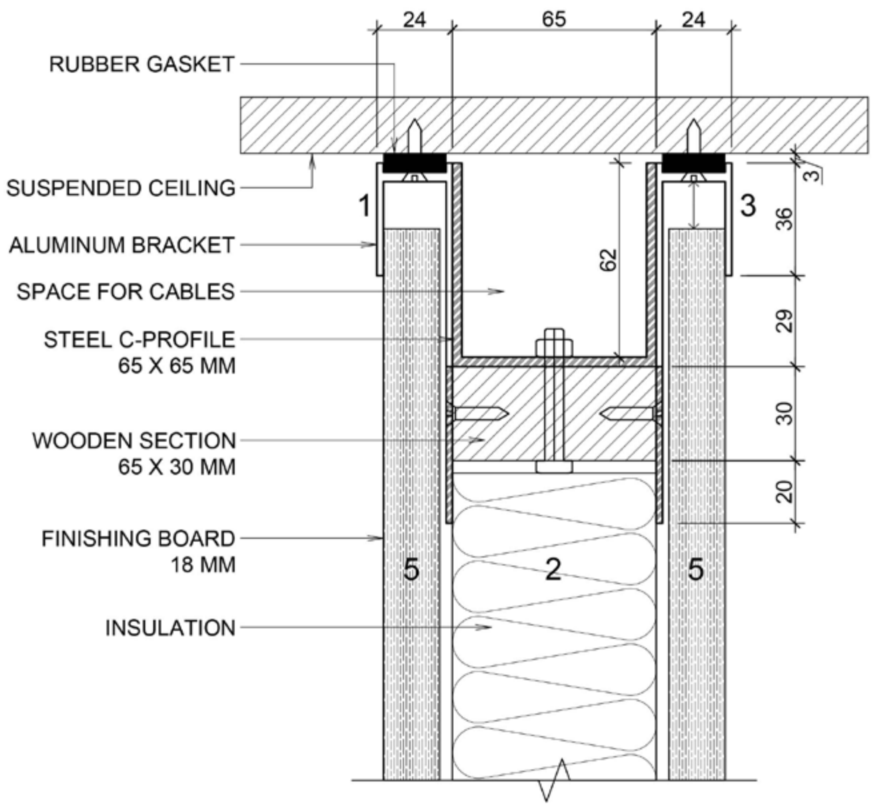


Figure 7.5 Option 1, Top detail (Source: Author)

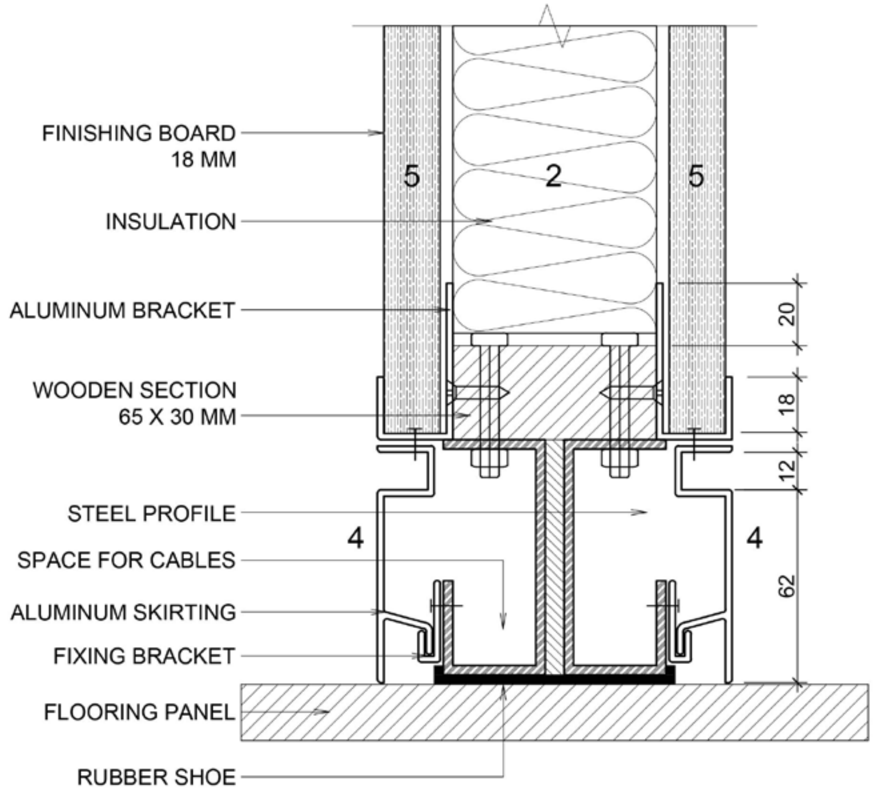


Figure 7.6 Option 1, Bottom detail (Source: Author)

The second option is a more complex system with the difference lying only in the top connection detail (Figure 7.8). Here, the aluminium profile with the rubber gasket moves upwards to ensure the partition wall sticks to the ceiling as seen. This makes it possible not to have any screwed connections to the ceiling, keeping it free from any marks. Here, in the first step the steel framing panel is placed in the desired position and fixed to the adjacent VISS Quattro supporting element. In the second step, the rotating bolt in the top frame located at the centre (Figure 7.9) is rotated in a clockwise direction. This action rotates the steel tube with gears placed at different intervals A, B, C, D which in turn moves the whole aluminium profile upwards. In the corresponding VISS Quattro frame detail (Figure 7.10), the aluminium profile at the top is pushed upwards by the intersecting geometry of the connecting elements. A steel sleeve is inserted in the Quattro profile from the top and connected by screws from the sides as seen in the plan. Finally in step four, the finishing board is mounted from both sides in a similar way as explained above in the first option.

Finally a schematic elevation of the partition panel is shown in figure 7.11. The wooden section is located at the top, bottom, and centre as well. This is done so that the insulation

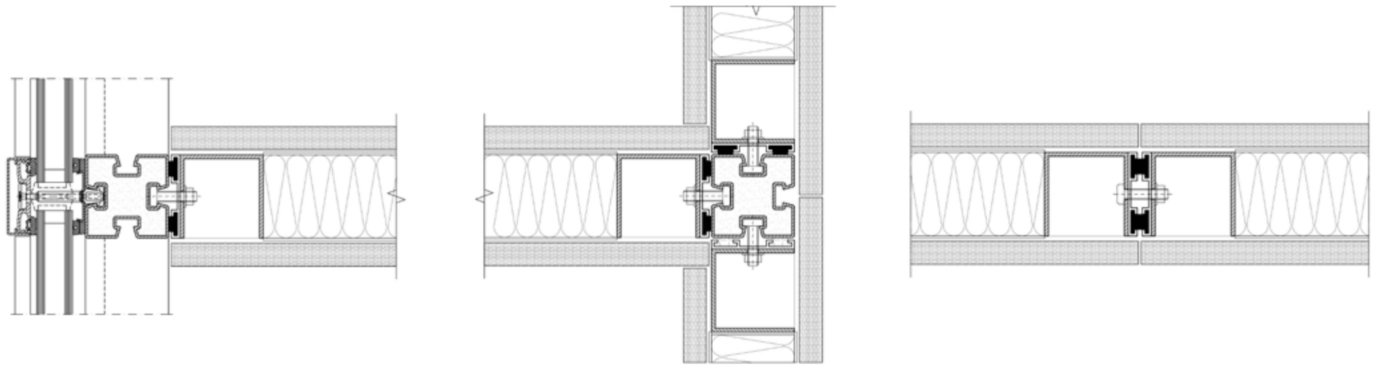


Figure 7.7 (a) Partition-facade connection, (b) Corner connection, (c) Partition-partition connection
Source: Author)

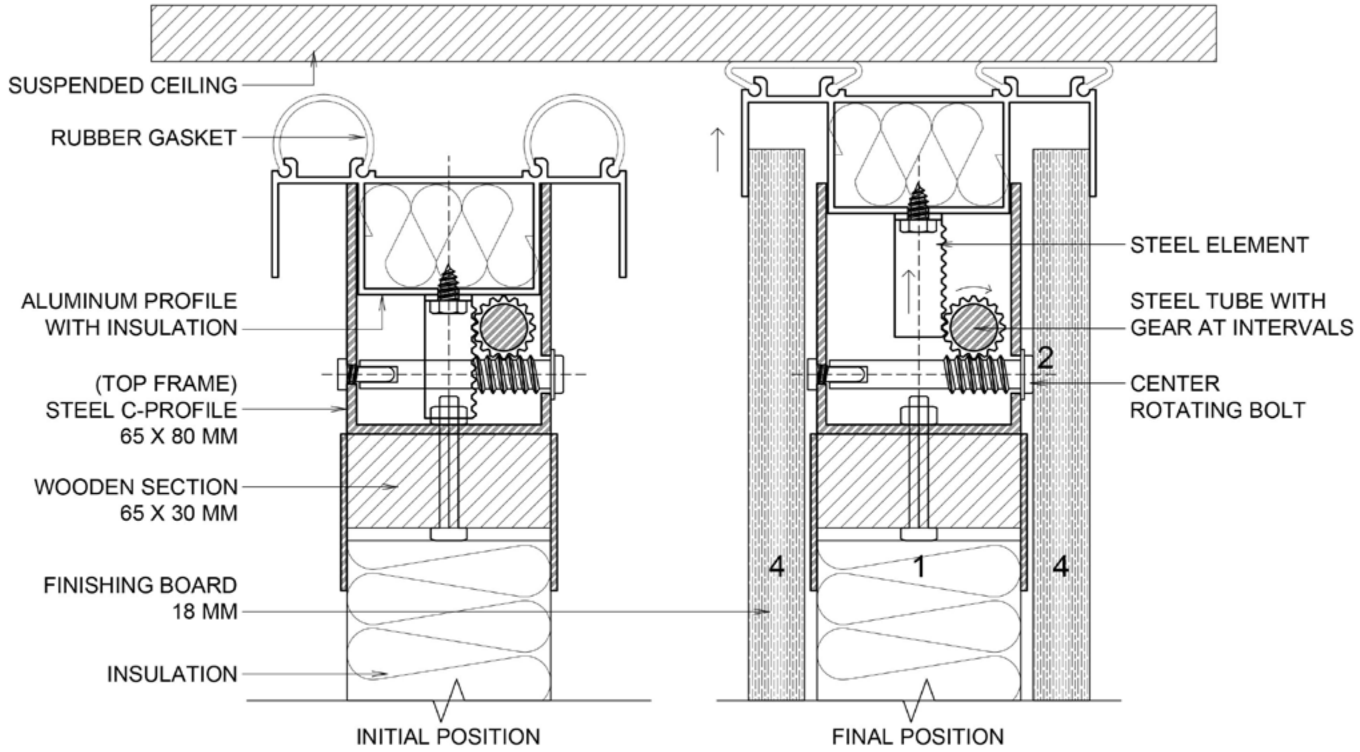


Figure 7.8 Option 2 Top detail (Source: Author)

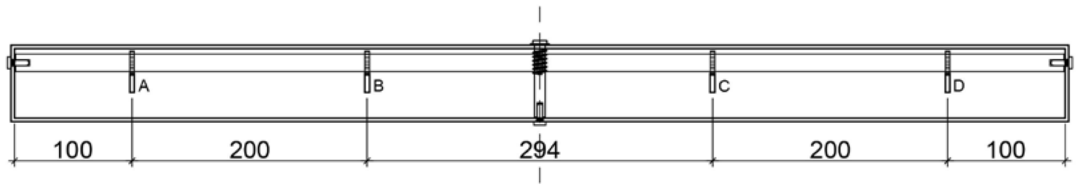


Figure 7.9 Option 2 Top frame plan (Source: Author)

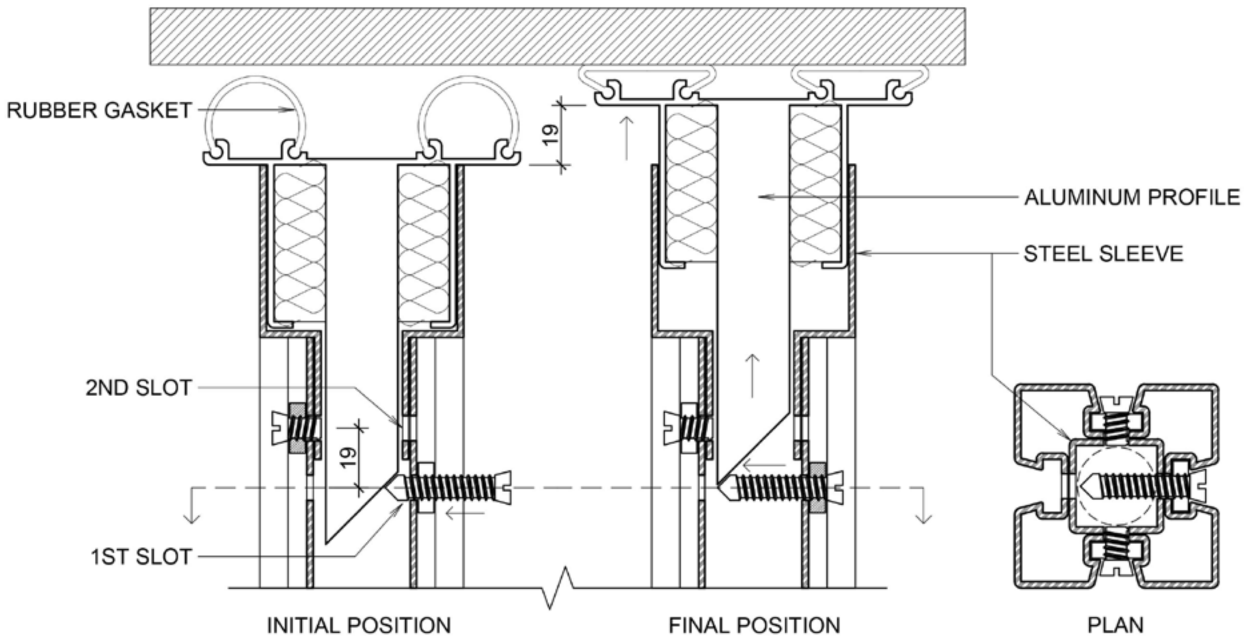


Figure 7.10 Option 2 Quattro fixing top detail (Source: Author)

material sits freely between them on its own weight making it easier to remove if needed. The aluminium plate that is connected to the wooden element ensures that the insulation does not move. 3D views explaining the system is shown in figure 7.12.

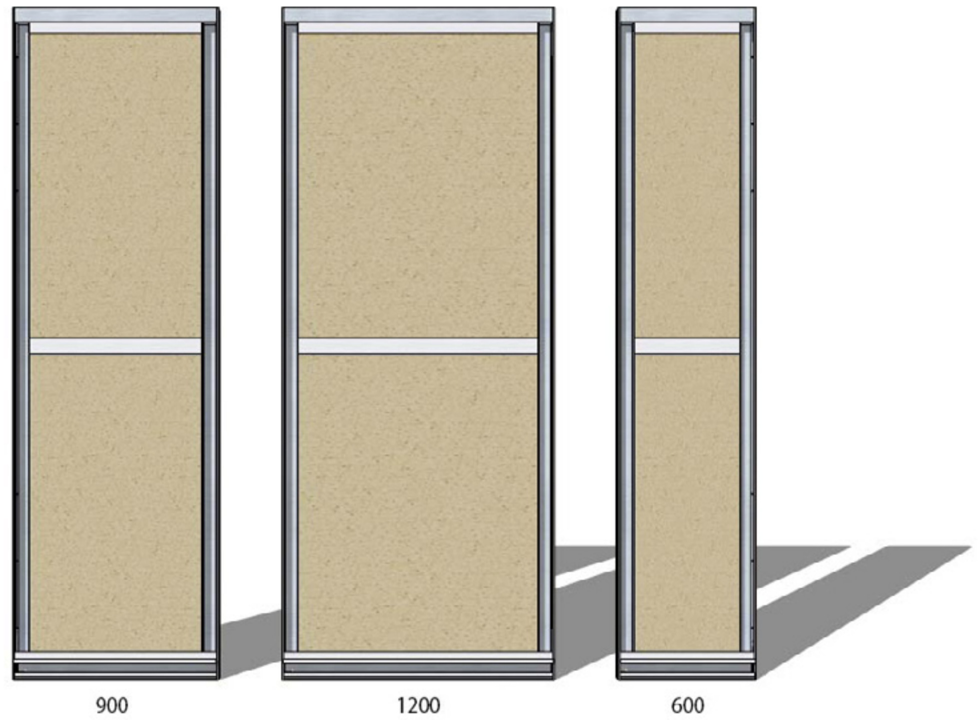


Figure 7.11 Panel elevation (Source: Author)

Figure 7.12 Partition system 3d views (Source: Author)

7.5 FAÇADE FRAMING SYSTEM

For the façade framing the Jansen Quattro 65 x 65 mm profile has been used as the structural element and the construction is assumed to be off-site in a factory. The Jansen curtain wall stick system employs the mullion elements as uninterrupted elements while the transoms are cut according to the distance between the mullions and fitted as mentioned in chapter 5. This fixing system poses a problem because the steel profiles are cut into shorter sizes and joining them for future reuse will result in unnecessary expenses. Moreover, if the size of the façade panel needs to change when a new one is needed after the end of service life of the old panel, new transoms will be needed as seen in figure 7.13. The following points are noted in this stick framing system:

- Mullions can be reused
- If the panel size changes:
1. Transoms have to be replaced
2. On-site construction is needed
- Transoms are cut into shorter sizes
- Panel design variation is possible

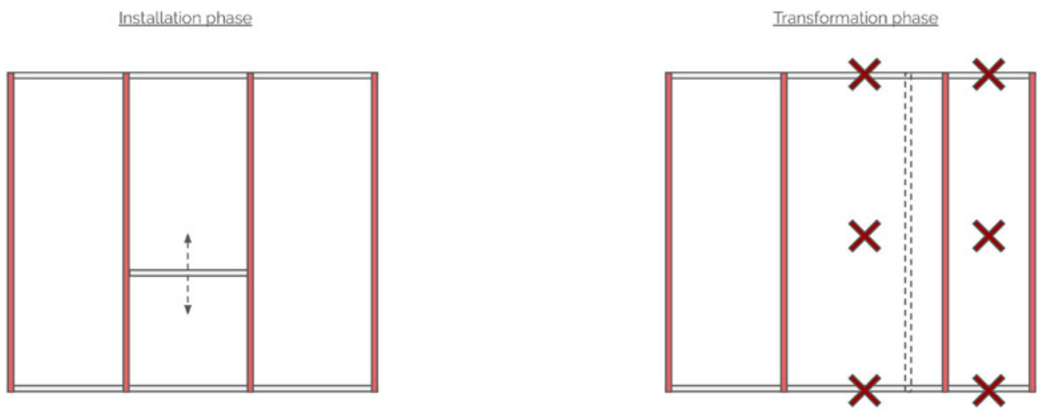


Figure 7.13 Stick system (Source: Author)

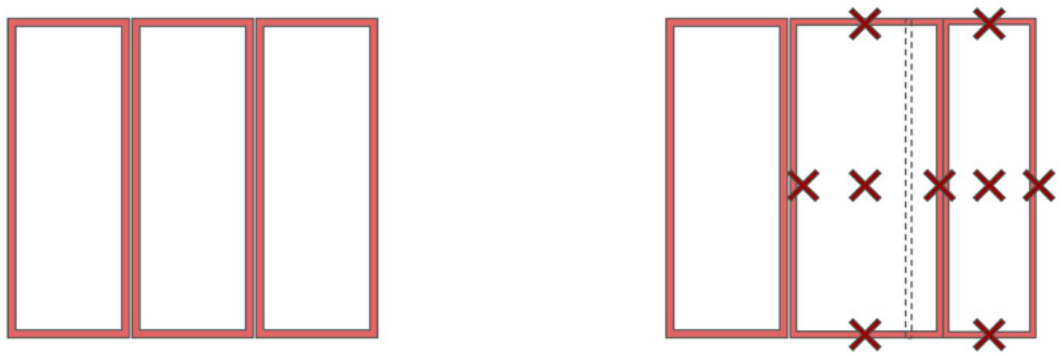


Figure 7.14 Unitised system (Source: Author)

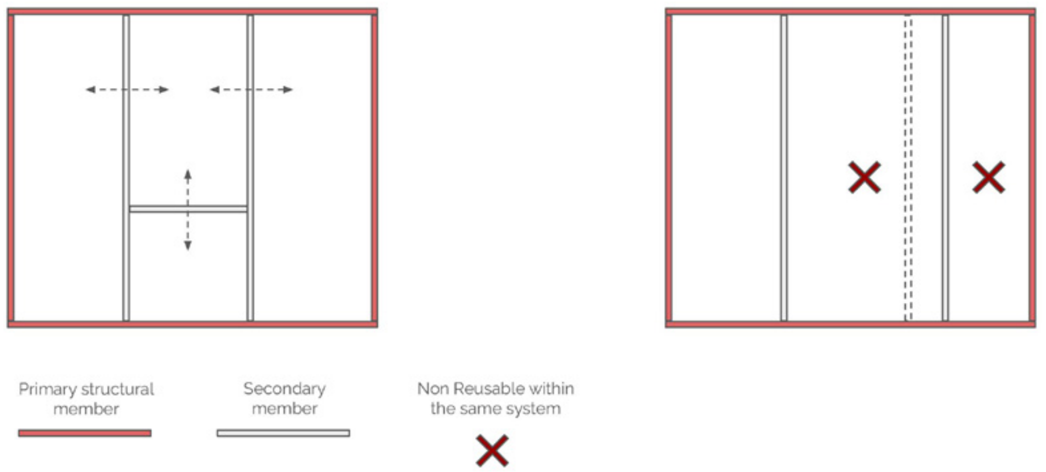


Figure 7.15 Hybrid system (Source: Author)

The unitised framing system was explored (Figure 7.14) and the following were noted:

- Mullions can be reused
- If the panel size changes:
1. Transoms have to be replaced
2. Construction can be fully off-site
- Transoms are cut into shorter sizes
- Panel design variation is possible
- Can be a costly system since each panel uses different mullions

Keeping reuse of framing system in mind when the panel size changes for future adaptability, a hybrid system has been proposed (Figure 7.15). Here, a portal framing system is employed where the edge mullions and transoms are fixed and the in between mullions and transoms can change its position to accommodate any panel size. The framing elements also are not needed to be cut into shorter sizes. The following points are noted for the hybrid system:

- Mullions and transoms both can be reused
- If the panel size changes:
1. Only panels need to change
2. Construction can be fully off-site
- Transoms are not cut into shorter sizes
- Panel design variation is possible

The hybrid portal framing system allows for reuse of framing elements while also ensuring flexibility of panel sizes if the need arises in the future. This framing system has been adopted for this research and details regarding this system will be explored in the coming chapters.

7.6 FAÇADE SYSTEM

The Jansen Quattro 65 x 65 mm steel profile is seen as a versatile element where multiple components can be connected because of the provision of VISS grooves on all four faces of the profile. It is reminiscent of the Polyvalence of spaces concept of Bernard Leupen (2006), where multipurpose spaces can deal with changeability and unpredictability. The same concept can be applied for building components, like in this case the Quattro profile, where its four grooves allow for multipurpose use. The front grove could be used to mount the façade panels, the side grooves for windows and other ancillary functions such as sun shading (if on the inside), shelving units etc. and the back groove to connect the frame to the structure and other interior components.

For the design of façade components it was important to keep the design principles of the literature study in mind and apply whenever necessary. As mentioned in chapter 5, the drawbacks of the Jansen façade system, the interpenetrating geometry that eventually affects the flexibility of panels and the disassembly sequence was looked into. The facade proposal (Figure 7.16) shows the section of the façade through the ceiling and floor section. The structure adopted in this research is a UNP 200 steel beam. Here it is noticed that the glass panel uses the existing connection system, however to make adjacent panels independent of each other, the side grooves have been utilised.

A U-bracket has been proposed that is anchored to the bottom and top of the beam that takes care of the tolerances required for the façade system. Also the underside of the bracket is used to adjust the thickness of the non-glazed façade panel. This gives the possibility to mount façade panels of varying thicknesses. Thickness ranging from 50 to 128 mm or more can be accommodated by simply changing the adjustable steel profile (highlighted in red in the detail view) connected at the underside of the U-bracket (Figure 7.16). The four VISS grooves of the Quattro profile show the polyvalent character of the profile which gives flexibility to the façade system.

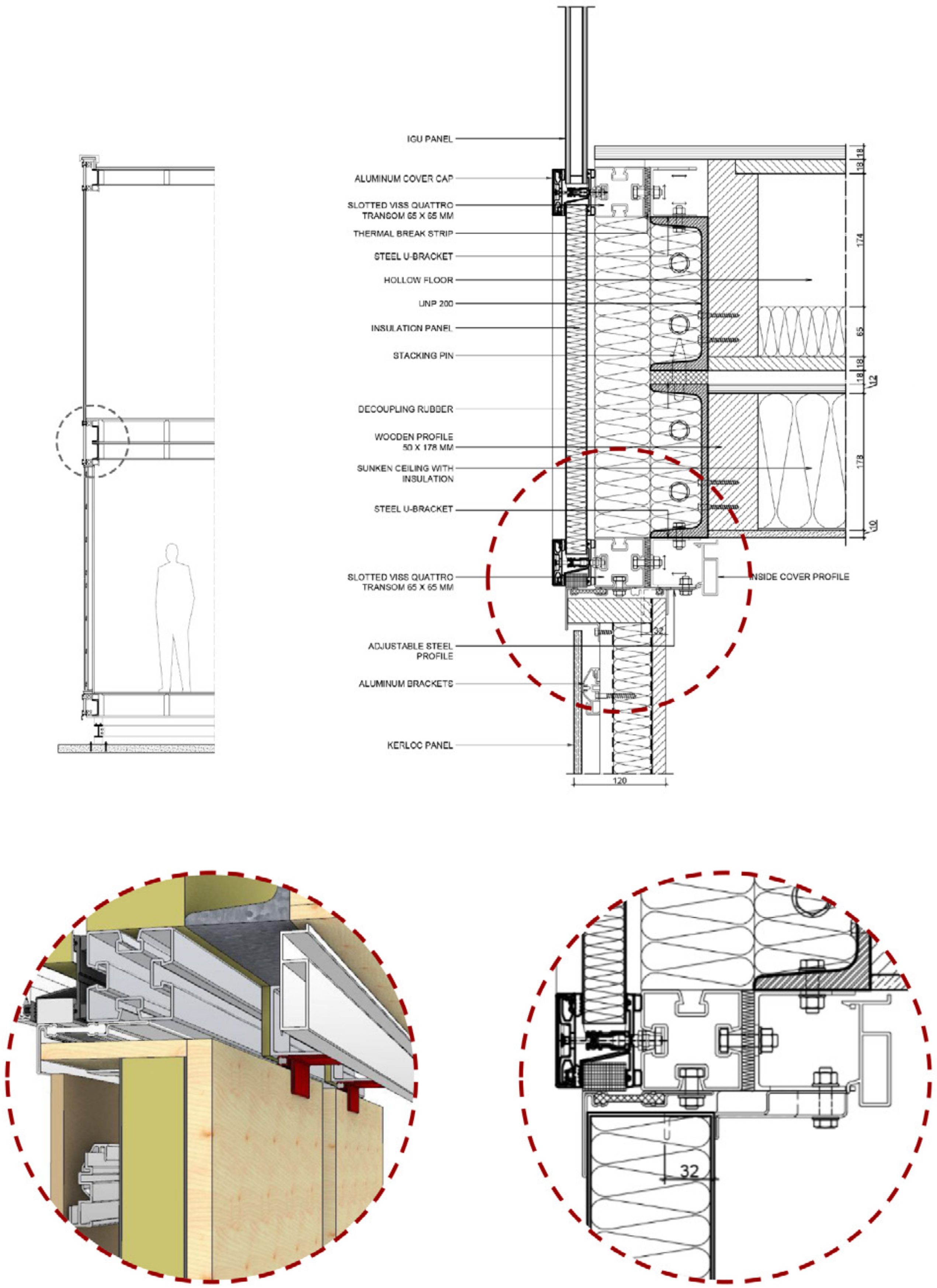


Figure 7.16 Façade section through floor and ceiling (Source: Author)

From here on more options can explored to integrate different kinds of facades into the Jansen Quattro profile while not just limiting to glazed panels. For example in this proposal a ventilated facade type of Kerloc has been employed.

As mentioned earlier this system has also been looked for modular building units that can be stacked on top of each other. For this a stacking pin is used similar to how container homes are stacked as shown in the drawing. Between the two steel beams a rubber element has been proposed to mitigate the vibrations and also providing tolerance to the structure. The thickness of this element could change according to requirements based on the project.

The detail of the unit mounted to the existing floor slab is shown in figure 7.17 and the detail of the parapet / roof junction is seen in figure 7.18. Here in figure 7.17, the steel structure is assumed to be mounted in an existing RCC floor slab. It is expected that the grid lines of an existing building is not aligned with the modular grid proposed in this system. Therefore an intermediate steel structure is installed that aligns these two structural grids together. This makes the design more flexible in terms of placement of housing units on the roof tops.

In terms of improvement in thermal performance, slotted steel profile only in the transom has been proposed for the VISS Quattro. As long as they do not compromise the structural integrity, they could help in increasing the heat path in the profiles. Thermal break strips between the Quattro profile and the U-bracket have also been proposed. An exploded

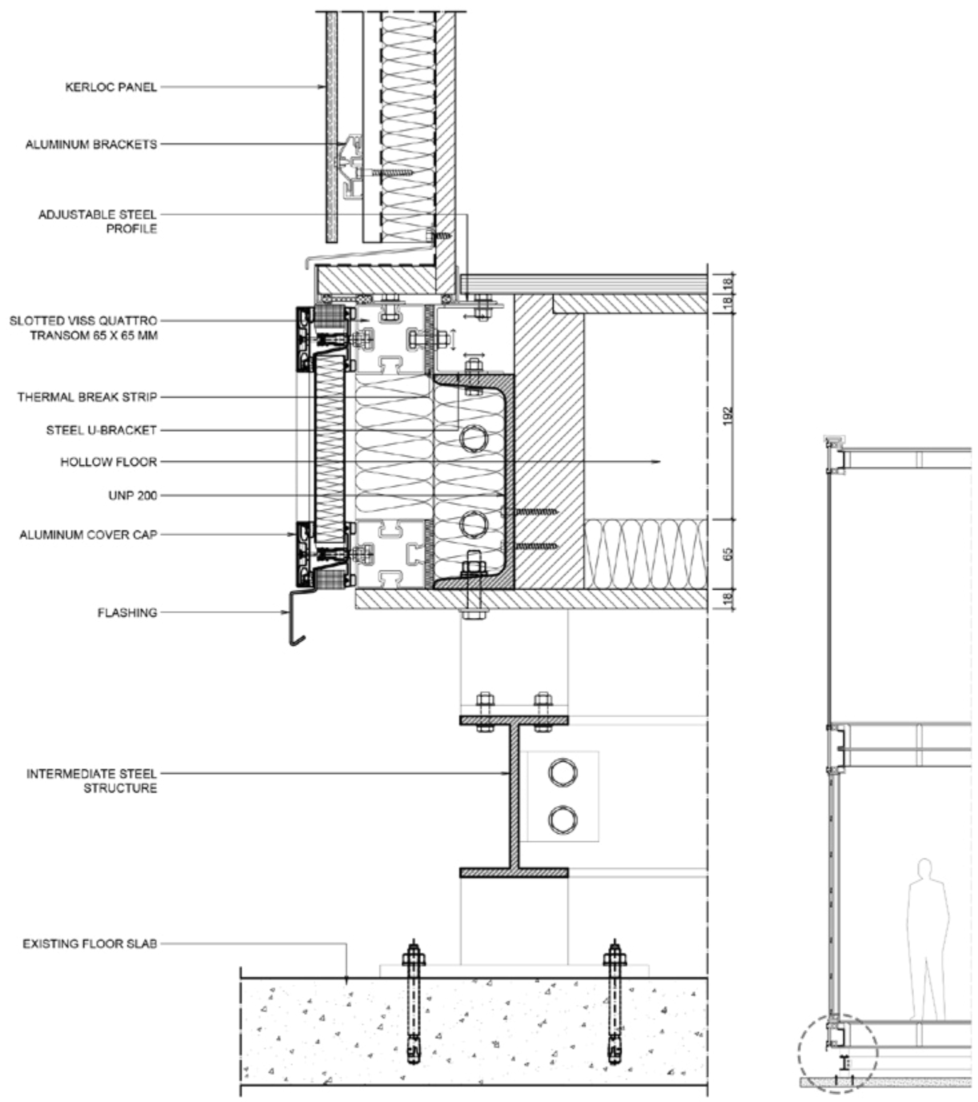


Figure 7.17 Façade section through existing floor(Source: Author)

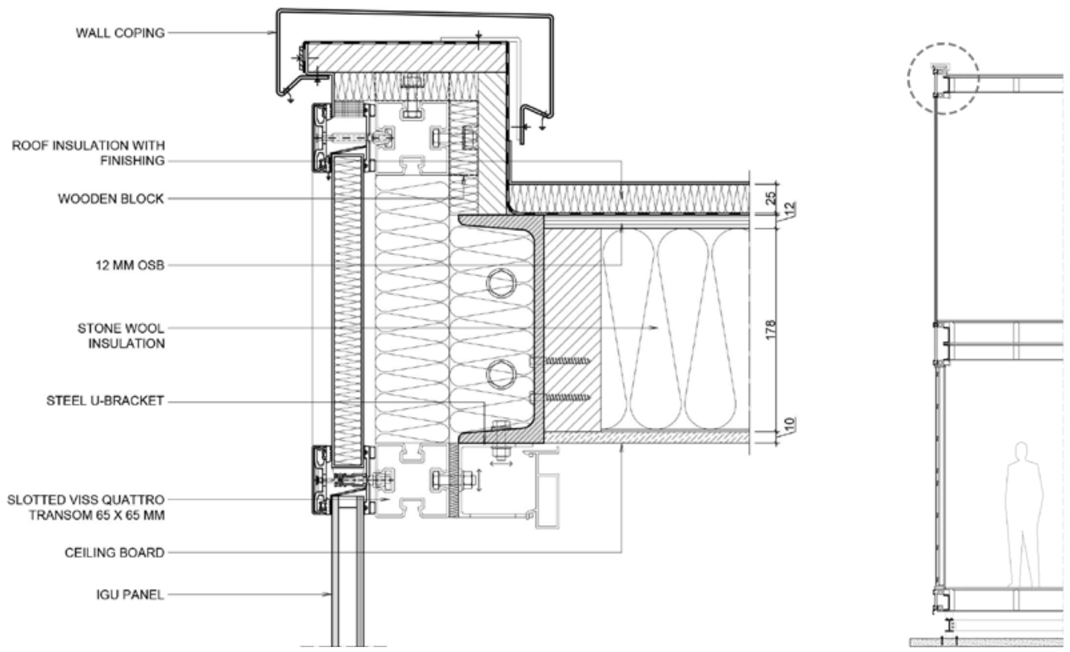


Figure 7.18 Façade section roof (Source: Author)

view of the facade is shown in figure 7.19. Here one can see the different components used in this facade system. Figure 7.20 shows the isometric view of the facade in the assembled state.

Figure 7.21 shows the disassembly of the facade system. Here it is seen that when lower ventilated panels have to be disassembled, the adjacent panels are not disturbed. Likewise the same happens for the top panels as well.

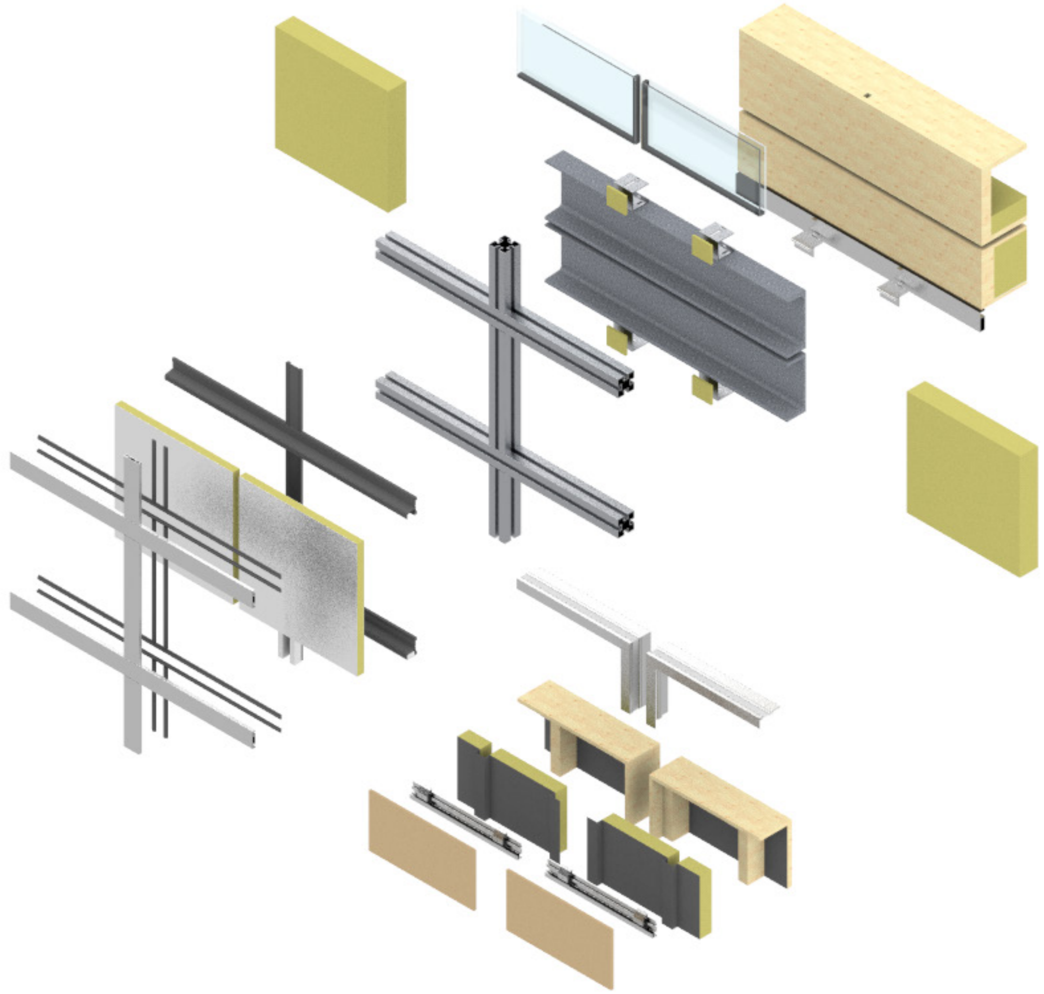


Figure 7.19 Façade exploded view (Source: Author)

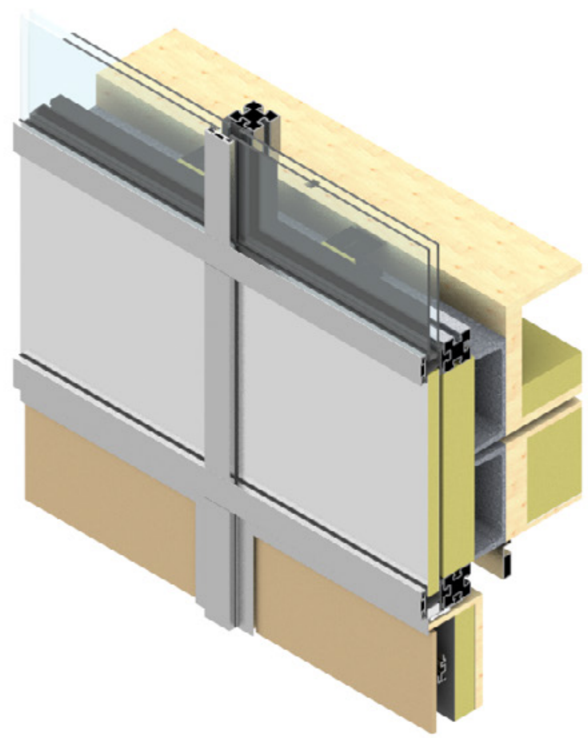


Figure 7.20 Façade isometric view (Source: Author)

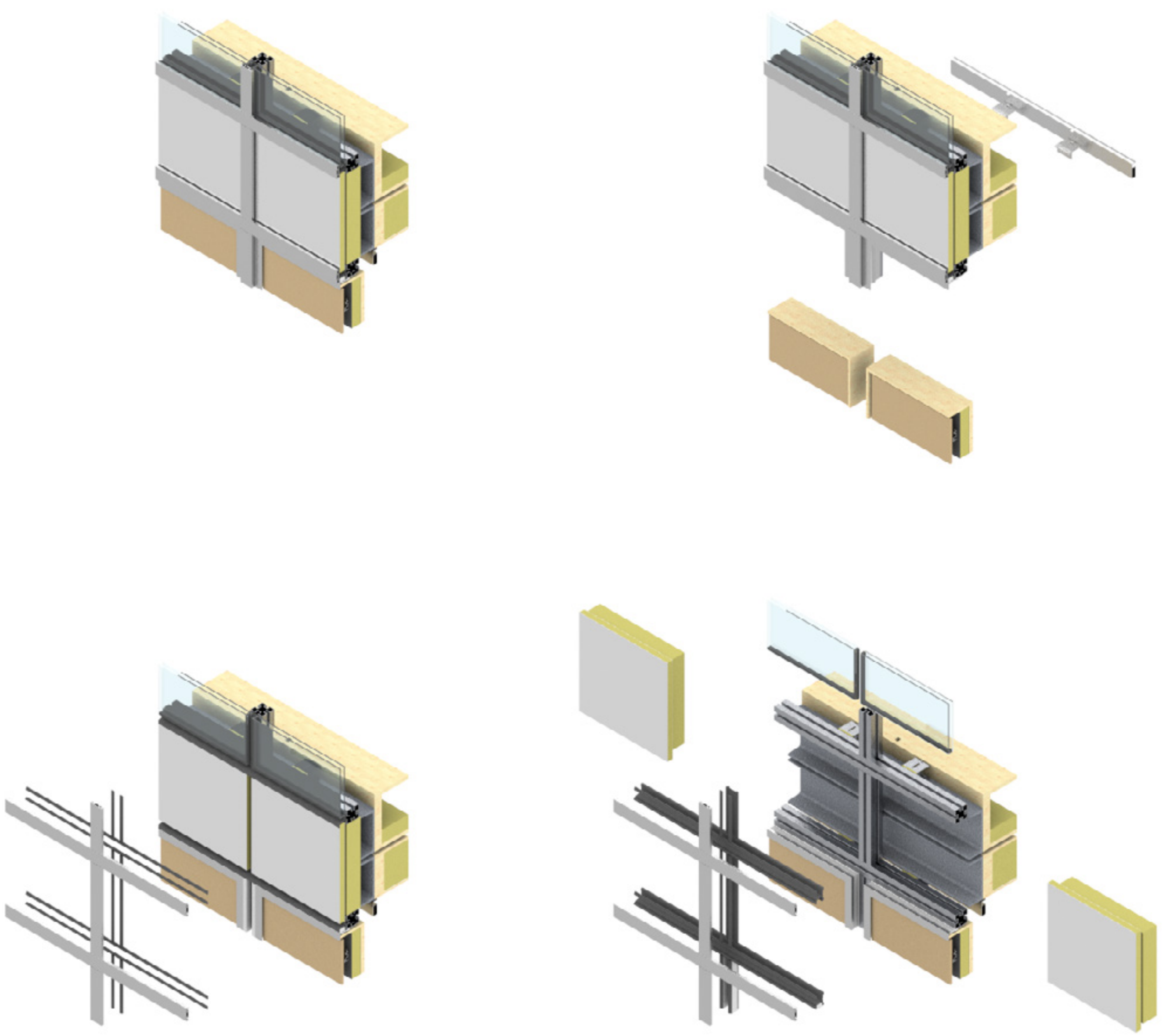


Figure 7.21 Façade disassembly (Source: Author)

7.7 TOP-UP APPLICATION

In this section, the building modules are fitted on an actual site to justify its application as top-up units. The building selected for this case is Menno ter Braaklaan 1-271 in Delft. The building is a gallery housing type that has a fairly rectangular geometric form. Pedestrian and aerial view of the building is shown in figure 7.22 and 7.23 respectively. The floor plan of the building is shown in figure 7.24. Here the approximate dimensions of the structural grid can be seen. The apartments are accessible through the open corridor on the front of the building, while all apartments have private balconies on the back side.

As seen in the section detail (figure 7.17), first an intermediate steel structure is installed on the existing roof. This can also be seen in the conceptual 3D view in figure 7.25 (a, b, c, d) highlighted in red. Here the schematic assembly sequence of the overall structure has been given. First, steel plates are mounted on the existing floor (RCC) according to the structural grid of the existing structure. Then, I-steel sections are fixed to this. Here the steel beams parallel to the width of the building are aligned according to the building structural grid, while the beams parallel to the length of the building are aligned according to the structural grid of the top-up housing units. This way the placement of the top-up units is flexible on the existing roof. The same method can be applied to any other flat

Figure 7.22 Menno ter braaklaan pedestrian view (Source: Author)

Figure 7.23 Menno ter braaklaan aerial view (Source: google earth)

roof structure. However, details regarding the structural aspects have not been looked into since it is beyond the scope of the researach. In step (c) there are two ways to mount the top-up units. The first option is to install the steel structure of the units on-site and then assemble the panelised elements individually. The second option is to assemble the top-up module in the factory and mount them on-site on top of each other as modular units with the help of stacking pins. If the second option is choosen, the connecting facade and wall panels between units will be connected on-site. Finally in step (d), decking elements to cover the raised floor system is proposed.

The process to mount the units on the site is kept flexible and can be organised according to the needs and feasibility of the project with respect to the site. Figure 7.26 & 7.27 shows the proposed top-up units in the context of the neighbourhood.

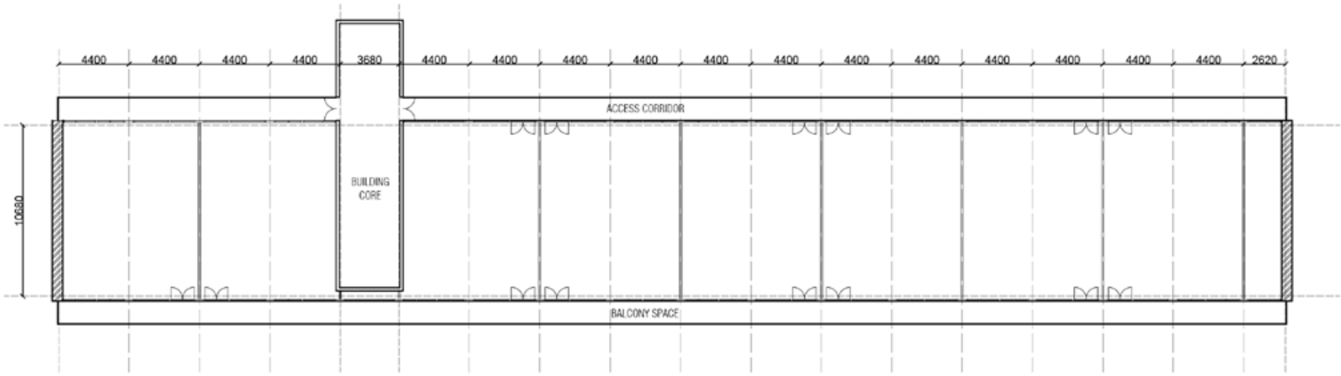
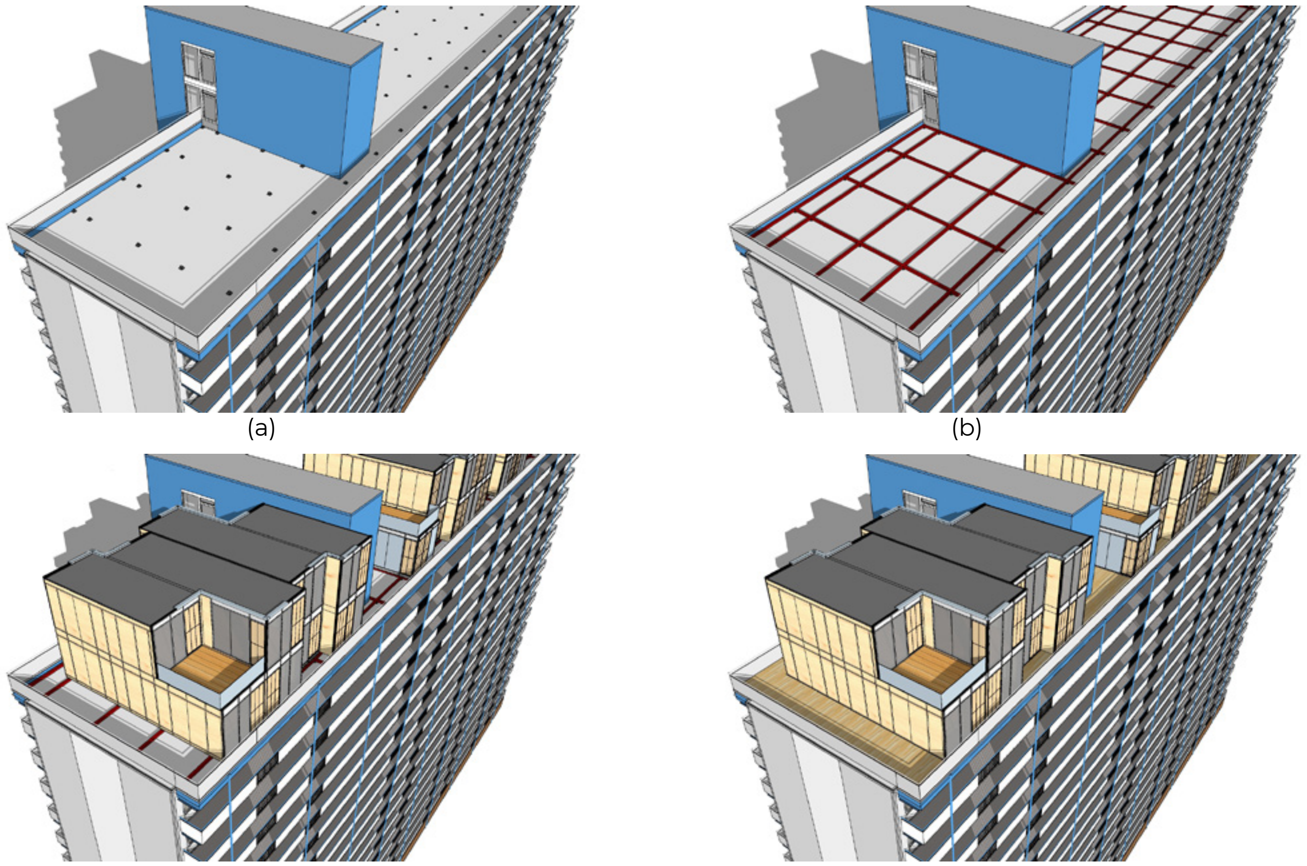


Figure 7.24 Menno ter braaklaan - Floor plan (Source: author)



(a) (b) (c) (d)

Figure 7.25 Menno ter braaklaan - Assembly sequence (Source: author)

Figure 7.26 Top-up units - Context view-A (Source: author)

Figure 7.27 Top-up units - Context view-B (Source: author)

7.8 Overall Assessment

In this chapter the assessment of designed partition products has been looked into. The DFD evaluation and the Circ-flex evaluation described earlier in chapter 2 will be applied for the partition products. Finally overall design limitations and drawbacks will be mentioned.

7.8.1 DFD Evaluation

For the DFD evaluation, the two partition variants with different connecting system at the top are evaluated at the same time.

Functional Independence (FI)
The degree of separation between different functions in the system is high in both variants. Every element is designed to do a specific function in the first option, except the aluminium bracket at the top, where it supports the frame from tilting as well as supporting the finishing board. In option 2, the upward movement of the top aluminium profile provides the acoustic seal as well as the structural stability to the whole panel. This is not ideal but can be validated only by building a mock up to test the fixing mechanism. Replacement of all the components would not affect the integrity of others. Option one: 1.0, Option two: 0.6

Systematisation (SY)
In the first variant three clusters can be noticed, the aluminium bracket with the gasket, the steel framing with the insulation and the connecting VISS Quattro profiles. In the second variant only two exist. In both cases clusters are formed according to the function while finishing elements like the finishing panel and the skirting are installed as final elements. Option one: 0.8, Option two: 0.8

Relational patterns (RP)
Both systems have a combination of open and layered relational pattern in which the finishing layer has to be removed (layered) to access the other components (open). However for the maintenance of the parts in the fixing mechanism of the second variant, it follows a sequential disassembly process which makes it more layered process. Option one: 0.7, Option two: 0.6

Base element specification (BE)
Both variants have two base elements, the VISS Quattro profile and the steel frame. The aluminium bracket at the top for the first variant acts as the third base element. Replacing the base element of one panel does not affect the next one. This is because there are separate base elements (frames) between panels. Option one: 1.0, Option two: 0.6

Geometry of product edges (GP)
In both cases the geometry of product edges are open and linear from panel to panel. However in the first option, there is an unsymmetrical overlapping due to the aluminium bracket at the top holding the panel in place. An average is taken for the first option. Option one: 0.7, Option two: 1.0

Assembly sequences (AS)
In both cases partial parallel and sequential disassembly process is clearly noticed. Parallel for panel to panel, sequential for finishing board for both and sequential again for aluminium bracket at the top for the first option. Option one: 0.7, Option two: 0.8

Connections (CN)
All connections in both variants are dry. Both have indirect external connections which means connections are accessible once the finishing board is removed. However for

Figure 7.28 Partition option 1 and 2 spider diagram (Source: Author)

maintenance again, the second variant connection is indirect internal connection, which means parts have to be removed in a sequential way to disassemble it. Option one: 0.8, Option two: 0.7

Life cycle coordination (LC)
In both options, the steel and aluminum have a long life span (approx. 75 years), insulation material like stone wool of about 50 years and EPDM gaskets of about 10 years. Therefore a Long LC for steel / medium LC for insulation / short LC for gaskets has been taken. Option one: 0.6, Option two: 0.6

Figure 7.28 shows the spider diagram of both the options side by side for DFD. The overall score for Option 1 and Option 2 are 78.75% and 71.25% respectively. Therefore both these products lie in the high disassembly potential category.

7.8.2 CIRC-FLEX EVALUATION

The Circ-Flex criteria from chapter 2.5 have been adopted to assess both the partition options. All 11 criteria have not been looked into in detail but rather a generalised way of qualitative evaluation has been adopted. The product has been rated as Low, Medium or High for the following categories as per the author's understanding of the product.

Flexibility capacity: Both options have a faster installation process than other partition walls analysed in this study. They follow a partial parallel and sequential disassembly and assembly process. Therefore, they both score high in this aspect as validated by DFD evaluation. The ease of repurposing or disposing the elements is high in case of the first option since it uses standard components. While in the case of the second option, it uses a more complex system and components in its top frame than the first one therefore it scores a medium in this regard. Option 1: High, Option 2: Medium

User capacity: Users have freedom of choice in terms of the finishing board and insulation material in both cases. This is possible because the structural framing element is kept separate than the other elements. Option 1: High, Option 2: High

Circularity capacity: In terms of maintenance, both options are relatively easy but again in the second option the top frame mechanism can be a more difficult process. However in

Category	Criteria	Option 1	Option 2
Flexibility capacity	Ease of Disassembly	High	High
	Ease of Re-assembly	High	High
	Ease of Repurposing or Disposing	High	Medium
User capacity	User willingness to invest time and money	-	-
	User perceived freedom of choice	High	High
Circularity capacity	Ease of Maintenance	High	Medium
	Ease of Redistribution	High	High
	Ease of Remanufacturing	-	-
	Ease of Recycling	High	High
	Ease of Facilitating Bio-cascades	Medium	Medium
	Ease of Facilitating Bio-feedstock	Medium	Medium

Figure 7.29 Partition option 1 and 2 Circ-flex evaluation (Source: Author)

both cases due to partial parallel disassembly process time taken for the operation is less. Both options score high for ease of redistribution and recycling since all components can be disassembled. Both options score medium in terms of facilitating bio-based materials since the finishing boards and the insulation material can accommodate them. Option 1: High, Option 2: Medium

7.8.3 DESIGN LIMITATIONS AND DRAWBACKS

Every building material has certain limitations based on its physical properties. Such is the case with steel using it as the main material. It has several structural advantages over bio-based materials like wood. Complex forms as in the case with Quattro profile can be achieved with thin metal sheets. However it has a high thermal conductivity and flanking sound problems as seen from the research. Over on top of that it is a non-renewable material unlike bio-based materials. Therefore reusing it should be a priority while the last option should be to recycle it. Therefore making them flexible gives them more opportunity for reuse.

From a design perspective to make circular products, elements with simple forms should be used. This gives them a better opportunity for repurposing it for other use rather than recycling. This can be seen as a design limitation but also as an opportunity to explore design with simple elements. Optimising the elements used can be beneficial but also might limit its versatility. With the design of circular products aesthetic options also might decrease but it also opens doors for new aesthetic trends which might be interesting to explore.

In terms of assembling modular housing units, transport can play a role in determining the size. For mass housing it would beneficial to stick to the transport limitations in order to avoid unnecessary costs and resources. By taking into account every detail these aspects can be resolved.

The size of the VISS Quattro profile used also limits the height and the span of the framing element. Even though structural analysis was not carried out in this research, through assumption it can be said that open unit to unit spans are not achievable with the steel profile adopted. Therefore the span had to be broken down into smaller sections.

As mentioned in the literature organisational aspects are important for making IFD and prefabrication construction successful. All stakeholders involved should be cooperative in the process for a fruitful outcome.

Flexible components are seen as an added value for the client or the end user. In case of the flexible partition, users tend to adapt to certain situations but do make a change if it is necessary. The change can lead to demolition or renovation. By providing an option for flexible partition systems, these changes might be avoided. In the case of the flexible façade, ODS NL can benefit from such a solution. It can open opportunities for them by serving a wider audience. Architects and other clients can adopt the system into their projects because it gives them an option to mount panels of their choice. How effective this can be? It can only be proven by making a product like this available to the consumers.

Modular design strategies can tend to become monotonous and may not be appealing to some individuals. Further research regarding this can be done to improve this aspect.

8. CONCLUSIONS

8.1 Answering the research questions

How can flexibility of Lightweight steel framed (LSF) construction in prefabricated top-up houses help improve its potential towards circularity with added benefits?

Flexibile building components can have benefits for the construction industry in many ways. From this research on Lightweight steel framed construction for top-up houses it can be seen that flexibility was explored for partition and facade systems using a modular and standardization strategy to achieve it. The research question can be answered in the following way:

1. Flexible steel components makes reuse of steel components possible since it generally has a longer life span than other building materials. By making the steel element flexible, it can accomodate other building components such as insulation and finishing boards. Therefore one does not need to dispose the steel component but rather reuse it within the same system till it finally reaches it end of service life.
2. t uses DFD strategy to make building components demountable which increases its potential for future reuse, reconfigure and easier separation of parts for recyclability.
3. It serves a larger audience with dynamic wishes by:

- Incorporating various facade panels and sizes.
- It allows mountability of other functions wrt. space plan like shelving units, partition walls, furnitures etc.
- A wide variety of modular room layouts can be achieved catering to different user demands hence reducing renovation and demolition scenarios when users change.
- A flexible modular design approach can cater to different housing unit sizes which makes it possible to mount them in varying flat-roof floor sizes.

4. Added benefits of current thermal and acoustic values for housing can be achieved with this system.

Further, the sub-questions have been answered:

What is the relationship between flexible and circular design?
In order for building components to be flexible, it needs to be demountable and adjustable for different uses so that it can be reused. By making reusable components one of the aspects of circular design strategy is already addressed. Moreover, demountable components makes it easier for parts to be separated thereby making them easier to recycle. Therefore a clear relationship can be formed between flexible and circular design.

What are the acoustic and thermal problems for steel prefabricated components and how can we address them?
As discussed in chapter 4, the main thermal problem of steel is high thermal conductivity and the acoustic problem is flanking sound due to low mass ratio. The thermal problem can be tackled by:

- Reducing the contact surface area
- Using slotted steel studs
- Using materials with low thermal conductivity over them

The acoustic problem can be addressed by:

- Providing damping elements in the connections and by creating more joints or connections to dissipate the vibrations.
- The mass ratio can be increased by filling the element with sand or other similar materials.

What are the problems and opportunties of existing houses that affect flexibility?
The problems related to housing flexibility is that user demands change overtime and in some cases there is change in function which lead to new technical demands for a space. The oppurtunities can be seen by using circular building strategies such as Open building, Industrial Flexible & Demountable and Design for disassembly. These strategies allow a flexible design approach that can cater to multiple uses and demountable components that can make reuse and recycling of components.

How can Klöckner Metals ODS steel profiles be used in a flexible and circular manner?
This question has been answered in chapter 7 by designing a flexible and demountable partition system using Jansen steel profiles as connecting elements and in the façade by making them adjustable to different panel sizes. More interior elements that can be mounted on the VISS Quattro profile such as shelving units will be explored after the P4.

8.2 Further research

Due to covid restrictions and time constraints, production of the designed components were not achieved as expected in the research framework. Instead the case study of application on a existing building was looked into.

The research can be further explored by incorporating other building components such as floor and roof systems. Even modular strategies for curved elements can be explored to cater to any roof and site sizes and shapes. The polyvalent character of the VISS Quattro profile can also be further explored for different types of façade systems such as double skin façade, rain screen system etc.

8.3 Reflection

Research and design
This sustainable design graduation research involves the company Klöckner Metals ODS Nederland (ODS NL) and the possibilities of implementing Circular economy concept into their products. Even though the company primarily work with Jansen façade systems in practice, they were open about implementing new ideas beyond the façade domain. After discussions, the core theme of the research led to modular prefab top-up housing with light steel framing (LSF) systems to tackle the housing demand in Netherlands while addressing flexibility and thermal & acoustic aspects with modular LSF housing systems.

Due to the broad possibilities of the subject, the initial part of the literature study was to gain knowledge from all related domains such as Circular design, Design for disassembly, modular prefab construction, building physics, Jansen systems etc. All these aspects have been studied up to a certain extent to formulate the design criteria for the design problem. Getting the knowledge from all these domains was important to understand the complex design task at hand. However due to time constraints, the plan at hand is to implement flexible façade and partition wall systems for modular prefab housing, while not emphasizing much on other building components such as floor, roof, services etc.

As the research has progressed, more insight on various subjects was gained which has led to a deviation in the design assessment criteria. The assessment criteria is based on the knowledge gained from the literature research and serve as a guideline to optimize flexible and circular building facades and partition walls for modular construction.

Theme of graduation lab and the project
For this sustainable graduation studio in Building technology, the program is divided into four tracks namely façade, climate, structural and computational design. This research primarily falls under the façade design track although it also touches on the partition wall domain to implement flexible strategies for circular design. The secondary track that it falls under is climate design where building physics strategies related to LSF components are implemented and issues addressed in the design. The concept of Circular economy is the underlying principle that is used to achieve a sustainable building system and fulfill the primary aim of the sustainable graduation studio. It is achieved by circular design

guidelines for building components that can be disassembled and reused in the future.

Methodological line of approach
The methodology followed by the Building technology graduation studio is primarily divided into literature review, design and evaluation phases. The graduation process is spanned across 5 presentations within three academic quarters. Since the related company to this research was not restricted to façade systems and was open to new ideas, the author was initially more inclined towards flexible and movable partition wall systems to achieve changing user satisfaction to avoid demolition waste. As suggested by the mentors and company representative, a clearer and specific goal for modular top-up solutions for housing was defined.

A straight forward methodology approach was initially expected but the plan deviated during the process. Due to the complex nature and broadness of the subject, the literature is extensive therefore literature research for specific topics is overlapped during the design and evaluation phase as well. Since the parent company has little expertise in modular housing solutions, discussions with other companies, namely Jansnel and Finch buildings related to the modular construction field were held for better understanding of the subject. Even though Jansen products were explored for designing building components, discussions with modular housing companies has helped in the overall design so far.

Design principles and strategies regarding Circular design, flexibility and building physics were compiled from the literature study. These principles were implemented to inform the final design solution for modular top-up housing and the components were evaluated for DFD and Circ-Flex criteria. Some drawbacks and limitations with respect to the design have also been listed. Moving forward, the design will be further updated as per the feedbacks and final improvements will be looked into in the coming weeks.

Societal impact
The underlying aim of this research is to find a solution for the housing demand in Netherlands by proposing modular prefabricated solutions in a circular manner. However, the society also faces challenges and difficulties when their need changes. Therefore in order to reduce waste in renovation to fulfil their needs, flexible and adaptable solutions are needed while also ensuring comfort and convenience. Moreover, reusable and sustainable building components are important for the circular economy. Therefore with the help of this design proposal, a suggestion towards development of flexible building components for modular prefab housing has been made.

Since this research involves Jansen products, particularly the VISS Quattro profile which is still in its conceptual stage, steel has been used as the primary material for the study. The use of basic steel products in the market have been incorporated while trying to eliminate fewer newer products. This way standard steel component in the market can be repurposed for different solutions. Since steel has a finite source, it cannot be easily created and follows the technological cycle as shown in the Butterfly diagram in the figure above. These materials are only used rather than consumed in a circular economy. Materials are recovered at their original value from residual flows after usage. Therefore, it is important to increase the lifespan of these materials by maintaining, reusing, refurbishing and recycling them. Following circular economy strategies has a positive environmental impact than linear economy thus; it has an effect for the future generations.

Circular business models such as leasing entire housing modules, façade and product leasing can also be incorporated in the overall organizational scheme. This not only makes the process circular but also makes building products affordable for the end user in the current inflated market. With the development of flexible and reusable solutions, the need for building renovations will become less and less waste will be generated which can be seen as a way of building for the sustainable environment. Flexible solutions will also gear to respect the dynamic wishes of the user; therefore unique solutions for the built environment can be created.

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