THE POTENTIAL OF CNC MILLING FOR DEMOUNTABLE PARTITION WALLS

Johannes Bohn
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft

ABSTRACT

This study explores the potential of CNC milling technology to improve the ease of assembly and disassembly of demountable partition wall systems. Design for Disassembly is a principle that allows for the reduction of generated waste due to building and component demolition and enables building products and components to be repaired, recycled or reused as a whole or in parts. In the context of this research, the technical advantages of CNC milling compared to conventional means of fabrication are explored and consequently a comparative assessment of demountable partition wall systems, using an adapted evaluation method, is conducted. Part of the assessment are four demountable partition wall systems, of which two rely on CNC milling production while the other two are produced with conventional means. The results reveal certain potentials of CNC milling technology to improve the ease of assembly and disassembly of demountable partition walls.

KEYWORDS: *CNC milling, Design for Disassembly, Ease of Assembly and Disassembly, Assessment*

1. INTRODUCTION

Throughout the process of construction and predominantly at the end-of-life of a building or building component, large amounts of waste are generated. The building and construction sector contributes an estimate of at least one-third of all waste generated in the EU, the figures also align on a state level with that estimate, for instance with rates of 36.7% in Belgium, 41.5% in the UK and 41.6% in the Netherlands, posing a significant impact on the environment (Rajagopalan et al, 2021). Current building practices largely focus on the end goal of constructing a finished building, only rarely taking into account the deconstruction or adaption of a building or building component and the reuse or recycling of its related materials.

Most construction practice, ranging from building scale to component scale, is based on a linear economy model. This economic model consists of the following life cycle stages: resource extraction, processing and manufacturing of products, assembly and use and finally demolition and disposal (Crowther, 2009). In the Netherlands, the greater part of construction and demolition waste finds, in one way or another, a recovery route, often described with the vague expression of *useful application*. This entails predominantly low-grade applications that can be considered down-cycling (Geldermans, 2020). A reason for these low-grade applications is the lack of demountability of building products, resulting in damaged or destroyed components and hard-to-separate materials, which makes potential reuse, recycling or up-cycling particularly difficult (O'Grady et al, 2021).

The Circular Economy model has been introduced as an alternative to the widely practised linear economy by suggesting a system that is based on retaining the value of materials and products, rather than discarding them at the end of their lifespan (Geldermans, 2020). In the construction industry, as well as other industries, design for disassembly is a driving force to move towards a circular economy as it enables partial and full disassembly of buildings and components. As a result, individual components and materials can be reused after the end of a lifespan, rather than demolished and discarded (O'Grady et al, 2021).

Design for adaptability is another design strategy aiming at maximising a building's life time. This can be achieved by applying design for disassembly strategies, which allow for easy dismantling of building components and thus facilitate the possibility for future changes within a building. This is particularly important for indoor partitions as they a more prone to changes than most other layers of a building. As Brand (1994) described in his Shearing Layer model, the *space plan* may be altered within a time frame of three to 30 years, depending on the building's function, while the lifespan of a building's structure far exceeds that of the space plan (Brand, 1994). As a result, easy disassembly of partitioning elements is crucial to facilitate future adaptation of the interior layout and function of a building.

With the advent of the information age, both the architectural design process and the manufacturing and construction processes have been digitised. The construction industry tends to lag behind when it comes to implementing new technologies and methods. Thus, for designers, it is important to apply state-of-the-art technology, such as the application of CNC milling, to design and planning processes and rethink current design and construction methods to address environmental issues and move towards a circular economy in the building industry. The described problems led to the following research question and subquestions covered in this paper:

How could the implementation of CNC Milling improve the ease of assembly and disassembly of demountable partition walls?

This research question resulted in the following sub-questions:

- *What are the technical advantages of CNC Milling in comparison to conventional fabrication methods?*
- *How can ease of assembly and disassembly be evaluated and quantified?*

1.1 Methods

The research in this paper is conducted within the framework of the Architectural Engineering (aE) graduation studio, which is part of the Master of Science (MSc) Architecture, Urbanism and Building Sciences graduation program at TU Delft. As part of an architectural design project, the goal of the research is to provide valuable information for the project and is therefore closely linked to the overall design question. The graduation project deals with the renovation and functional conversion of a 1930s industrial building into working and community facilities and focuses on the design of demountable and adaptable indoor partitions and other infill structures, following the principle of *Design for Disassembly*.

To provide answers to the research question and its sub-questions, first, a literature study about the potential of CNC milling, its characteristics and possible applications for demountable structures is conducted. Further on, literature on the assessment of ease of assembly and disassembly of building components is studied in order to give an understanding of what criteria need to be considered to allow for easy assembly and disassembly of building components. The findings of this literature-based research are used to create an assessment method which specifically aims at demountable partition wall systems. This assessment method will then be applied to four selected demountable partition wall systems. Two of those are utilising CNC milling technology while the other two systems are fabricated with conventional means. These systems will then be studied and reconstructed using 3D modelling software. The 3D models will enable breaking down the constructive principle behind each system and distinct working steps for the assembly and disassembly can be studied. The assessment method uses scoring tables to evaluate all criteria relevant to ease of assembly and disassembly. A detailed description of the assessment method can be found in chapter 3. The goal of the assessment is to point out the strengths and weaknesses of each system regarding ease of assembly and disassembly and evaluate the potential influence of CNC milling on the ease of assembly and disassembly.

1.2 Theoretical Framework

Literature on Design for Disassembly in the context of the built environment is limited and for specific cases like the demountability of CNC fabricated partition wall systems, one will find little to no information on the subject. Assessing ease of assembly and disassembly is more common in the field of product design, putting a stronger focus on the assembly and disassembly sequence and duration of these processes. This research aims to contribute knowledge about the relevance of CNC milling for the fabrication of partition walls and proposes an assessment method that allows the evaluation and comparison of multiple demountable partition wall systems.

2. The Potential of CNC-Milling Fabrication

2.1 Emersion of CNC machinery

The origins of CNC machine technology date back to the 1940-1950s, when John T. Parsons invented the first numerical controlled (NC) machines, the first step towards an automated process of industrial production. Further development and the implementation of a generalised machine language for NC machines promoted a widespread utilisation of such machines in industrial production by the end of the 1950s, offering distinct production advantages. By the 1970s, the first successes in the development of what we nowadays know as computer-aided design (CAD) and computer-aided manufacturing (CAM) were achieved and digital drawings and models of a physical product became the driving data source for the operation of computer numerical controlled (CNC) machines. Since the emersion of NC/CNC machines, which were developed for two-axis and three-axis milling processes, the technology evolved and modern CNC machines constitute a variety of different tools and find application in a wider field (Naboni & Paoletti, 2015). Today's machinery can be utilised for instance for milling, laser cutting and water jet cutting, operated by two or three-axis machines or multi-axis industrial robots.

2.2 Advantages of CNC-Milling

CNC-Milling is an essential part of the production processes in numerous manufacturing industries, not just recently but already for decades. Modern CNC multi-process systems are used today for everything from the mass production of automobile engines to the manufacture of custom components in small quantities (Newman et al, 2008). In the construction industry, CNC milling is mainly used for the fabrication of complex shapes and structures, while the fabrication of simpler components is usually done by conventional means (Naboni & Paoletti, 2015). In this chapter, the advantages of CNC-Milling for the widespread production of conventional building components are discussed, focusing mainly on three-axis milling of wooden, wood-based and wood-like sheet materials.

2.2.1 High Precision and Versatility of CNC-Milling

Nowadays, a large number of manufacturing industries switched from conventional production methods and machines such as lathes, milling machines or drilling machines to CNC machinery due to the technology's advantages in production time and precision. A study of three-axis industrial CNC milling machines has shown that workpieces can be milled with high precision while maintaining quick production times, depending on the processed material and tool bit used. Average deviations of 0.021mm to 0.102mm — the differences in values stem from the different axes — were measured (Subagio et al, 2019). Low deviations in production accuracy allow for low tolerance construction principles and connections of components such as friction-fit or snap-fit connections.

An additional upside of CNC milling is the high versatility in processing methods. A conventional three-axis CNC milling machine is capable of drilling, flattening, engraving, milling and cutting operations, making use of different tool bits which are all operated by the same rotating spindle. Furthermore, the machine allows for the production of a vast range of geometrically complex shapes while being able to operate in micro- to multi-metre dimensions (Newman et al, 2008) (Vischer, 2015). Digital manufacturing implies the creation of one-off objects and components, while variations in serial production tend to come at little to no extra cost. Working with computer-controlled machines eliminates the need for conventional serial production of components, while the easy machinability of wood or wood-like materials opens new possibilities for these kinds of materials, promoting them to the status of high-tech materials (Kaiser, Larsson & Girhammar, 2019).

2.2.2 File to Factory Production

File-to-factory production describes a direct connection and communication between digital drafting software and computer numerical controlled fabrication machines. Computer-aided design (CAD) software allows the designer to draft in a vector-based drawing environment which can then be translated by computer-aided manufacturing (CAM) software into instructions for a CNC machine. These translation processes can be automated and linked to a parametric model, thus creating a direct link between drafting software and physical production machinery. According to Kaiser, Larsson and

Girhammar (2019), ‚File to factory speculates on an almost automated process from design[ ] to construction on site‘. In an optimised file-to-factory process, the initial phase of the design for an object and its digital visual representation is done using the same software that gives instructions to a manufacturing machine to produce the final physical object. The combination of such an optimised workflow with the digitally controlled processing of a wide variety of materials creates a highly flexible procedure that makes it possible to produce individualised components with little economic resources. The consequence of implementing file-to-factory processes is that architects are much closer connected to the fabrication, thus the architect can control the design as well as production and ‚the digitally controlled manufacturing process turns the factory into a computer-aided version of the artisanal workshop‘ (Kaiser, Larsson & Girhammar, 2019). For the field of architecture and construction, this means a new way of production in which design and construction can be joined together, much like it was in times when the architect was considered the „master builder“. It allows the architect to not only design spatial and material properties of a building but also define building components and determine production strategies.

At the latest since the industrialisation, the domains of production of building components and the designing of buildings are divided because the means of production were given into the hands of specialised industrial producers. Means of production for building components such as CNC milling machines become increasingly accessible and affordable, which could ultimately lead to democratised production, making the physical production of components possible for virtually everyone. This already happened in the software and music industry and could also find application in the hardware sector through the use of CNC machines. Industrialised production of building components still remains relevant and ‚it is improbable to imagine that advanced fabrication means could completely replace company's means of production, but they are stimulating the concept of customisation and have the potential to create a wide variety of new building components that, having the possibility to be uniquely produced, can achieve higher levels of performance and degrees of personalization, overcoming the stagnation of repetitive production in construction‘ (Naboni & Paoletti, 2015, citing Gramazio et al, 2014). Digital tools and computer-controlled machines enable the designer's direct participation in the fabrication process, simplifying the collaborations on design and production, which helps overcome, amongst others, locational and logistical limitations (Naboni & Paoletti, 2015).

2.2.3 Locational Independence of Production

Developments in fabrication technology and the democratisation of production will play an essential role in the next industrial revolution. The Third Industrial Revolution can be described as a combination of digital and personal manufacturing. Shifting from centralised and industrialised mass production towards decentralised and personalised manufacturing of products by utilising computer-controlled machines such as CNC milling machines is the key driver for the emersion of collaborative peer-production places, so-called Fab Labs. These production facilities are based on a lateral system of power, where everyone can use the facilities to produce objects straight from file to machine. Fab Labs are community-based places, equipped with affordable digital fabrication machines that are connected to the internet. Fab Lab locations are present in many cities and new ones are continuously emerging, allowing individuals to produce objects regardless of their location.

Furthermore, the fully digitised process allows for a locational independence of designer and producing facility as files for machine instructions can be sent around the globe and executed where ever CNC milling machines are available. A ‚revolution of personal digital manufacturing‘ (Troxler, 2013) cuts out commonplace manufacturing companies and involves the designer directly in the manufacturing process, eliminating issues of production location and long transportation distance, stimulating local or regional production and material sourcing (Troxler, 2013).

2.3 Relevance of CNC-Milling for Demountable Partition Walls

Critical aspects for structures to be easily demountable are the characteristics of connections between two or multiple components. Wood connections without any fasteners or adhesives are not a novel invention, in fact, such connections found application already two millennia ago in Japanese timber construction as well as, later on, in Europe and have been improved to the exact ever since. Such dry timber joints were used for the construction of permanent structures and temporary structures alike, for instance periodically assembled and disassembled Japanese shires. No matter if such connections were used for permanent or temporary construction, an inherent quality of dry wood joints is the capability to be disassembled. The most critical factors of a demountable timber connection are material strength, friction between the interface surfaces of the joint and withdrawal resistance which is linked to the interface friction. Thus, timber joints rely on exceptional woodworking precision. Achieving this degree of precision was a difficult and time-consuming task in the past but technological advancements such as CNC milling allow for high-precision fabrication in a fraction of the time (Erman, 2002).

In a study of friction-fit timber connections, L. Sass (2006) describes the relevance of high-precision machinery for the fabrication of ‚high tolerance-interference connections' and how such machinery enables a new type of friction-fit connection systems. Further advantages of a friction fit construction are a reduction of machinery required on-site, no measuring during the assembly process and high building strength. During the study and to test structural performance, Sass built a plywood box with simple box joints connecting the edges, resulting in a self-supporting, stiff and robust construct without the use of any adhesives or mechanical fasteners (Sass, 2006).

A second example concerns a fully CNC-milled partition wall system. The researchers of this study designed a wall system with a fully friction-fit constructed internal structure, which can be easily assembled and disassembled using only a rubber mallet (Brandão, Paio, Sousa & Rato, 2015). The example shows that the inherent precision of CNC machining can be employed for easily demountable structures, especially for the domain of non-load-bearing structures. Other possible types of component connectors such as snap-fit joints (Robeller, Mayencourt & Weinard, 2014) or T-slot connections (Brandão, Paio & Antunes, 2018) prove the variety of possible CNC-milled solutions that rely on high-precision machining for a demountable system of wooden joints.

3. ASSESSING EASE OF ASSEMBLY AND DISASSEMBLY

To select or develop a design with optimal disassembly characteristics, an evaluation method is required to assess existing systems on ease of assembly and disassembly by evaluating several criteria. To find evaluation methods aiming at the ease of assembly and disassembly, literature on the subject was studied. Most available information on the topic could be found in the context of product design, yet also one evaluation method specifically designed for the construction sector was found. The origin, as well as the content of the used evaluation method for the assessment of demountable partition wall systems, is described in the subsequent chapters.

3.1 The Assessment Method

A study conducted by Vanegas et al. (2018) focussed on the development of a new evaluation method for ease of disassembly specifically designed for the domain of product design. This method, called *eDiM* (ease of Disassembly Metric), was developed to estimate the disassembly time of a given product, focusing on the disassembly sequence, tools that need to be used and the estimated time connected to each working step. The comparable value of this evaluation method is the duration of the disassembly process of an assessed product (Vanegas et al, 2018). The *Disassembly Map*, another evaluation method for ease of disassembly developed by De Fazio et al. (2021), uses a similar principle to the *eDiM* method and evaluates a product on ease of disassembly by estimating the time needed to disassemble a product. Furthermore, the authors describe the main factors that influence the ease of disassembly: disassembly depth/sequence, disassembly time, reusability/reversibility of fasteners and use of common tools (De Fazio et al, 2021). These factors find relevance beyond product design, too, and can also be applied for ease of assembly and disassembly evaluation for building components.

A former student at TU Delft developed a new assessment method to measure the reusability of building components. Design for Reuse (DfR) implies the inclusion of Design for Disassembly, thus the bigger part of evaluation criteria in this method focuses on disassembly, while criteria such as component standardisation and durability assess solely the potential for reuse (Beem, 2020). Because the evaluation method developed by A. Beem specifically focuses on the construction sector and there are no other evaluation methods to assess ease of disassembly in the context of the construction domain, it is chosen as the basis for the assessment method used in this paper. Beem studied various evaluation methods for ease of disassembly from a variety of domains, including the aforementioned methods from the product design sector, and concluded the gained knowledge in a new assessment method to evaluate building components on their potential for reuse.

3.2 Assessment Criteria

As this paper exclusively focuses on the ease of disassembly of demountable partition walls, certain changes/adaptations were made. Changes were mainly done to the individual assessment criteria of the method. As mentioned before, the method by Beem not only focuses on disassembly but reuse of components, which includes disassembly criteria. Thus, the selection of assessment criteria was limited to the ones addressing ease of disassembly. Furthermore, the criteria for ease of disassembly were adapted to specifically find application in the evaluation of demountable partition walls. These adaptations and the reason for the inclusion of each criterion are described in detail in appendix D. The assessment criteria include the aspects of tool complexity, workspace accessibility, labour intensiveness, connector integration and type, number of connectors, number of components, the flexibility of disassembly order, fragility and required operator skills. According to Beem (2020), these criteria give a comprehensive insight into the degree of ease of disassembly and make it possible to compare different buildings components (demountable partition walls in the context of this paper's study).

In the assessment, multiple criteria influencing ease of disassembly are covered, yet not all criteria have the same relevance. In his article *Decision making with the analytic hierarchy process* T. L. Saaty (2008) introduced a method to assign weights to different criteria in a decision-making process. This method engages pairwise comparison, a system to define the importance of one criterion in relation to another and repeating that process for each criterion pair, to assign per cent values to each criterion, thus giving each criterion its weight/importance relative to the other criteria involved. This is done by using a Pairwise Comparison Chart (PCC), in which values from 1 to 9 — from same importance (1) to extreme importance over another criterion (9) — are assigned to each pair comparison. Reciprocal values (e.g. 1/9) consequently describe lower importance relative to another criterion. The PPC for the assessment criteria of the method used within this research can be found in appendix A. The results of the pairwise comparison are shown in Table 1 below.

Table 1. Results of pairwise comparison.

Criteria	Value from PCC	Weight in %
Tool Complexity	11,7	**4,1 %**
Workspace Accessibility	27,2	**9,4 %**
Labour Intensiveness	13,3	**4,6 %**
Connector Integration Structure	23,6	**8,2 %**
Connector Integration Panelling	15,8	**5,5 %**
Connector Type Structure	37,0	**12,8 %**
Connector Type Panelling	37,0	**12,8 %**
Avg. Number of Connectors	45,5	**15,8 %**
Number of Components/Segment	46,0	**16,0 %**
Flexibility of Disassembly of Panelling Elements	11,2	**3,9 %**
Fragility Structure	4,1	**1,4 %**
Fragility Panelling	5,3	**1,8 %**
Required Operator Skills	10,4	**3,6 %**

Several test runs of the assessment method led to a few changes and adaptations of the evaluation criteria and resulted in the final version which can be found in Appendix C. As an example, a criterion for the number of components within a wall system was added, because the compared systems showed a noticeable variation in the number of components between each other, which has a direct influence on the ease of assembly and disassembly and the related time needed to construct and deconstruct. Furthermore, the criterion of *number of connectors* was altered to *average number of connectors,* as not all components are connected with the same number of fasteners and thus sets the criterion in relation to the number of components. The criteria *connector integration, connector* *type* and *fragility* were divided into criteria evaluating the wall structure and the wall panelling separately, as noticeable differences in constructive principles were found.

3.3 Rating of Assessment Criteria

The rating scale of the assessment method uses descriptions for qualitative characteristics of each criterion and attributes a rating value to them, ranging from 1 to 9. Attributing numeric values to qualitative characteristics allows for direct comparison and diminishes room for interpretation or subjective evaluation. The value 9 represents the best obtainable score, while the value 1 represents the lowest, with integral steps in between. Rating all criteria with a score from that range and subsequently multiplying the values with their assigned factor (weight of each criterion derived from the pair comparison) results in a cumulative score (in per cent) that allows for rating and comparison, while 100% is the highest acquirable score.

Tool Complexity	Rating
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Power tools are required	6
Special tools are required	5
Significant time delay	-2
Special care/techniques are needed	-1
A considerable part of the assembly is done using tools of a higher rating category	+1

Figure 1. Descriptive rating scale from the ease of assembly and disassembly criteria.

4. Assessment of Demountable Partition Walls

The weight factors as displayed in table 1 were determined specifically according to the goal of the design project. Thus, the weight factors are not to be understood as a fixed value for all demountable wall systems but are rather meant to deliver the most relevant results for the design project and can be altered according to different requirements. To reach the goal of the design project, the focus lies on the easy assembly and disassembly of partition walls that can be constructed and deconstructed by the users within the context of an existing building. Easy disassembly is required because the spatial needs of users are assumed to change over time, estimated that parts of the spatial layout may be altered yearly.

4.1 Selection of Assessed Cases

Four different demountable wall systems have been selected for assessment on ease of assembly and disassembly and for consequent comparison. This selection is the result of a market analysis and aims to reflect a variety of demountable wall systems using different constructive principles to achieve characteristics of demountability. As the goal of this research is to identify potential improvement of demountability through the use of CNC milling technology, two of the total four selected wall systems are produced partly or fully utilising CNC milling. The two other assessed demountable wall systems are fabricated with conventional means. These are included in the assessment because they engage distinct constructive principles and connector types allowing for demountability. For better understanding, all systems were reconstructed using 3D modeling software and drawings of each system can be found in Appendix E.

The first wall system within this study that utilises CNC milling technology is a prototype named *Cork ReWall* that was developed within the framework of a study about digitally fabricated partition walls for existing buildings, which was conducted by Brandão, Paio, Sousa & Rato (2015). The second system studied is a wall segment by the open-source provider *WikiHouse*. This system was studied as two different options, one solely relying on friction fit connections while the second option uses screws to secure component connections. Of the two systems that don't utilise CNC milling fabrication, the first one was designed by the Canadian company *Partitions* and the second one by the Italian company *VetroIn.* Both systems aim at the market of office partition walls. Although both systems share some similarities, the constructive principles to reach demountability differ and thus offer a valuable basis for comparison.

4.2 Assessment Results

Generally, the comparison of the assessment results shows that all systems score the same or very similar in the categories of tool complexity, workspace accessibility and fragility of panelling components. This is due to the nature of non-load bearing partition walls consisting of relatively lightweight and easy workable materials, requiring only hand tools or simple power tools like electric screwdrivers to assemble and disassemble. All the other assessment criteria led to widely varying scores between the assessed systems mostly due to different constructive principles. In the overall scoring (table 2) the CNC fabricated wall system by *WikiHouse* (friction fit alternative) scored highest, closely followed by the non-CNC fabricated system by *VetroIn.* The *Cork ReWall* system reached an intermediate score relative to the other assessed systems while the *WikiHouse* system (screwed connections alternative) and the system by *Partitions* scored lowest. The full scoring table with ratings of all criteria can be found in Appendix B.

Table 2. Results of assessment of demountable partition wall systems.

	Compared Systems				
	Partitions Executive	VetroIn Solid Wall	Cork ReWall	Wiki House (Screws)	Wiki House (Friction-fit)
Score	71,7 %	79,5 %	76,9 %	72,0 %	81,8 %

The *Partitions* system scored well in most categories but due to a high number of fasteners and components, the system fell behind its competing alternatives. The wall system by *VetroIn* delivers a high overall score, while the only categories in which it reaches a lower score compared to the other systems are labour intensiveness due to large panel sizes and the connector integration within the structure of the wall system. The *Cork ReWall* scores many points due to the simplicity of the system's internal structure, only using friction-fit connections without the need for separate fasteners but falling behind in the categories regarding the system's panelling. While smaller panel sizes improve labour intensiveness, they also negatively impact the number of fasteners needed to fix all panels in place. The *WikiHouse* wall system, when based on friction-fit component connections, scores highest in the overall comparison because very few fasteners are needed to construct the system and due to these connections, mostly common hand tools are needed to connect components. When screws are used to secure component connections, the scores for the criteria connector type and number of connectors decrease considerably, thus negatively affecting the overall score.

Altogether, the assessed CNC fabricated systems score higher in the criteria connector integration of the structure, connector type of the structure and the average number of connectors. These higher scoring results are due to simple internal structure design and friction fit connections. The assessed non-CNC fabricated systems, on the other hand, score higher in the categories of connector integration of the panelling, connector type of the panelling and flexibility of disassembly of panelling elements because the systems utilise quick connection systems such as clips.

5. CONCLUSION

Overall, the assessment and comparison showed that friction-fit component connections, enabled by CNC milling, improve the ease of assembly and disassembly of a wall system on the connection points where it is applied. Although all systems score the same or similar in some criteria, the results widely vary in the bigger part of the assessed criteria due to different constructive principles. The gained knowledge from this study allows to point out specific qualities and downsides of each system and enables to eventually propose an ‚optimised' system based on the assessment results by combining different principles from all assessed systems. For future studies, this proposal of an optimal solution can be further improved by assessing more wall systems and thus creating a larger collection of options.

The advantages of CNC milling compared to conventional fabrication means could be defined, pointing out the intrinsic qualities of CNC milling fabrication. These are high-precision manufacturing, versatile application of the technology, file-to-factory production and locational independence. CNC milling enables high degrees of customisation, yet allows for fast production times similar to mass production. This is an inherent quality of CNC milling and digital fabrication in general and can be summed up under the term *mass customisation.*

An assessment method for ease of assembly and disassembly, based on existing evaluation methods, allows to quantify criteria of ease of assembly and disassembly by engaging a descriptive rating system. The results of the assessment give insight into the individual qualities of each system and allow for easy comparison. The assessment method is limited to aspects that directly influence the ease of assembly and disassembly and does not consider aspects such as the clarity and understandability regarding the constructive principle of a system or the number of assembly steps, which can vary in complexity and are thus hard to measure. These aspects can indirectly affect the ease of assembly and disassembly of a demountable partition wall system, are due to the difficulty of measurement not included in the assessment. Defining these aspects was beyond the scope of this research project and could be subject to further investigation.

The main question, if the implementation of CNC milling can improve the ease of assembly and disassembly of demountable partition walls, is answered by the results of the subquestions. The qualities of CNC milling fabrication and the gained assessment results clearly show that CNC milling has the potential to improve the ease of assembly and disassembly of demountable partition walls when it is employed at the right points. As the assessment results show, CNC milling positively affects the categories connected to the constructive principle of the internal structure of a wall system. When the panelling is concerned, alternative solutions seem to deliver better results but by combining different systems' qualities, a solution can be developed in which CNC milling plays a vital role in the ease of assembly and disassembly.

REFERENCES

1. Brand, S. (1995). *How buildings learn: What happens after they're built.* Penguin, 35-39.
2. Beem, A. (2020). Research Towards and Prototyping of an Evaluation Method for Design for Reuse for Building Products in the Design Phase, 1-8.
3. Brandão, F. J. S., Paio, A., & Antunes, N. (2018). Towards a Digitally Fabricated Disassemble-able Building System: A CNC fabricated T-Slot Joint. *FABRICATION | Virtual & Physical Prototyping* , 2, 11-15.
4. Brandão, F. J. S., Paio, A., Sousa, J. P., & Rato, V. (2015). Cork re-wall: computational methods of automatic generation and digital fabrication of cork partition walls for building renovation, 86-93.
5. Crowther, P. (2009). Designing for disassembly. *Technology, design and process innovation in the built environment*, 250-263.
6. De Fazio, F., Bakker, C., Flipsen, B., & Balkenende, R. (2021). The Disassembly Map: A new method to enhance design for product repairability. *Journal of Cleaner Production*, 320, 1-6.
7. Erman, E. (2002). Demountable timber joints for timber construction systems. *Architectural Science Review*, 45(2), 133-143.
8. Geldermans, B. (2020). Securing healthy circular material flows in the built environment: The case of indoor partitioning. *A+ BE| Architecture and the Built Environment*, (06), 37-84.
9. Gramazio, F., Kohler, M., & Willmann, J. (2014). The robotic touch: how robots change architecture. Park Books. 1-488.
10. Kaiser, A., Larsson, M., & Girhammar, U. A. (2019). From file to factory: Innovative design solutions for multi-storey timber buildings applied to project Zembla in Kalmar, Sweden. *Frontiers of Architectural Research*, 8(1), 2-7.

11. Naboni, R., & Paoletti, I. (2015). *Advanced customization in architectural design and construction.* Cham: Springer International Publishing, 17-35.

12. Newman, S. T., Nassehi, A., Xu, X. W., Rosso Jr, R. S. U., Wang, L., Yusof, Y., Ali, L., Liu, R., Zheng, L. Y., Kumar, S., Vichare, P. & Dhokia, V. (2008). Strategic advantages of interoperability for global manufacturing using CNC technology. *Robotics and Computer-Integrated Manufacturing*, *24*(6), 699-708.

13. O'Grady, T. M., Minunno, R., Chong, H. Y., & Morrison, G. M. (2021). Interconnections: An Analysis of Disassemblable Building Connection Systems towards a Circular Economy. *Buildings*, *11*(535), 1-4

14. Rajagopalan, N., Brancart, S., De Regel, S., Paduart, A., Temmerman, N. D., & Debacker, W. (2021). Multi-criteria decision analysis using life cycle assessment and life cycle costing in circular building design: A case study for wall partitioning systems in the circular retrofit lab. *Sustainability*, *13*(5124), 1-12.

15. Robeller, C., Mayencourt, P., & Weinand, Y. (2014). Snap-fit joints-CNC fabricated, integrated mechanical attachment for structural wood panels. *ACADIA 2014 Design Agency: Proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture*. Riverside Architectural Press, 189-198.

16. Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International journal of services sciences*, *1*(1), 83-98.

17. Sass, L. (2006). A wood frame grammar: A generative system for digital fabrication. *International Journal of Architectural Computing*, *4*(1), 51-67.

18. Subagio, D. G., Subekti, R. A., Saputra, H. M., Rajani, A., & Sanjaya, K. H. (2019). Three axis deviation analysis of CNC milling machine. *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, *10*(2), 94-97.

19. Troxler, P. (2013). Making the 3rd industrial revolution. *Fab Labs: Of Machines, Makers and Inventors*, Transcript Publishers, Bielefeld, 1-6.

20. Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W. & Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. Resources, Conservation and Recycling, 135, 323-334.

21. Vischer, L. (2015). Shaping CNC-cut plywood structures, 4-16.

APPENDIX A

Pairwise Comparison Chart (PCC)

Table A1. Pairwise Comparison Chart.

	Tool Complexity	Workspace Accessibility	Labour Intensiveness	Connector Integration Structure	Connector Integration Panelling	Connector Type Structure	Connector Type Panelling	Avg. Number of Connectors	Number of Components/ Segment	Flexibility of Disassembly of Panelling Elements	Fragility Structure	Fragility Panelling	Required Operator Skills		
Tool Complexity		1/2	1	1/5	1/3	1/3	1/3	1/4	1/4	1/2	4	3	1	**11,7**	***4,1 %***
Workspace Accessibility	2		2	1	1	1/3	1/3	1/5	1/3	5	7	5	3	**27,2**	***9,4 %***
Labour Intensiveness	1	1/2		1/2	1/2	1/4	1/4	1/7	1/6	2	4	2	2	**13,3**	***4,6 %***
Connector Integration Structure	5	1	2		1/2	1/3	1/3	1/5	1/4	4	5	3	2	**23,6**	***8,2 %***
Connector Integration Panelling	3	1	2	2		1/5	1/5	1/6	1/4	2	2	1	2	**15,8**	***5,5 %***
Connector Type Structure	3	3	4	3	5		1	2	1	5	3	3	4	**37,0**	***12,8 %***
Connector Type Panelling	3	3	4	3	5	1		2	1	5	3	3	4	**37,0**	***12,8 %***
Avg. Number of Connectors	4	5	7	5	6	1/2	1/2		1/2	5	5	4	3	**45,5**	***15,8 %***
Number of Components/Segment	4	3	6	4	4	1	1	2		7	5	5	4	**46,0**	***16,0 %***
Flexibility of Disassembly of Panelling Elements	2	1/5	1/2	1/4	1/2	1/5	1/5	1/5	1/7		3	2	2	**11,2**	***3,9 %***
Fragility Structure	1/4	1/7	1/4	1/5	1/2	1/3	1/3	1/5	1/5	1/3		1	1/3	**4,1**	***1,4 %***
Fragility Panelling	1/3	1/5	1/2	1/3	1	1/3	1/3	1/4	1/5	1/2	1		1/3	**5,3**	***1,8 %***
Required Operator Skills	1	1/3	1/2	1/2	1/2	1/4	1/4	1/3	1/4	1/2	3	3		**10,4**	***3,6 %***
														288,1	***100,0 %***

Figure A1. Saaty's rating scale for PCC (Saaty, 2008).

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1–1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities.

Appendix B

Results from Assessment

Table A2. Results from Assessment.

		Partitions Executive (case 1)		VetroIn Solid Wall (case 2)		Cork ReWall (case 3)		Wiki House screws (case 4.1)		Wiki House friction-fit (case 4.2)	
	Factor	Rating	FxR	Rating	FxR	Rating	FxR	Rating	FxR	Rating	FxR
Tool Complexity	11,7	6	70,2	6	70,2	7	81,9	6	70,2	7	81,9
Workspace Accessibility	27,2	7	190,4	7	190,4	7	190,4	7	190,4	7	190,4
Labour Intensiveness	13,3	7	93,1	2	26,6	9	119,7	7	93,1	7	93,1
Connector Integration Structure	23,6	7	165,2	5	118	9	212,4	9	212,4	9	212,4
Connector Integration Panelling	15,8	9	142,2	9	142,2	5	79	7	110,6	7	110,6
Connector Type Structure	37,0	7	259	7	259	9	333	5	185	9	333
Connector Type Panelling	37,0	9	333	9	333	5	185	5	185	5	185
Avg. Number of Connectors	45,5	4	182	7	318,5	7	318,5	7	318,5	9	409,5
Number of Components/Segment	46,0	5	230	9	414	8	368	8	368	8	368
Flexibility of Disassembly of Panelling Elements	11,2	9	100,8	8	89,6	3	33,6	5	56	5	56
Fragility Structure	4,1	9	36,9	9	36,9	5	20,5	5	20,5	5	20,5
Fragility Panelling	5,3	5	26,5	5	26,5	5	26,5	5	26,5	5	26,5
Required Operator Skills	10,4	7	72,8	8	83,2	7	72,8	7	72,8	7	72,8
	288,1		1902,1		2108,1		2041,3		1909		2159,7
Max. Value: 100% = 2653,2 (Sum of all factors x best possible rating [9])			**71,7 %**		**79,5 %**		**76,9 %**		**72,0 %**		**81,4 %**

Figure A2. Results Wall System *Partitions*.

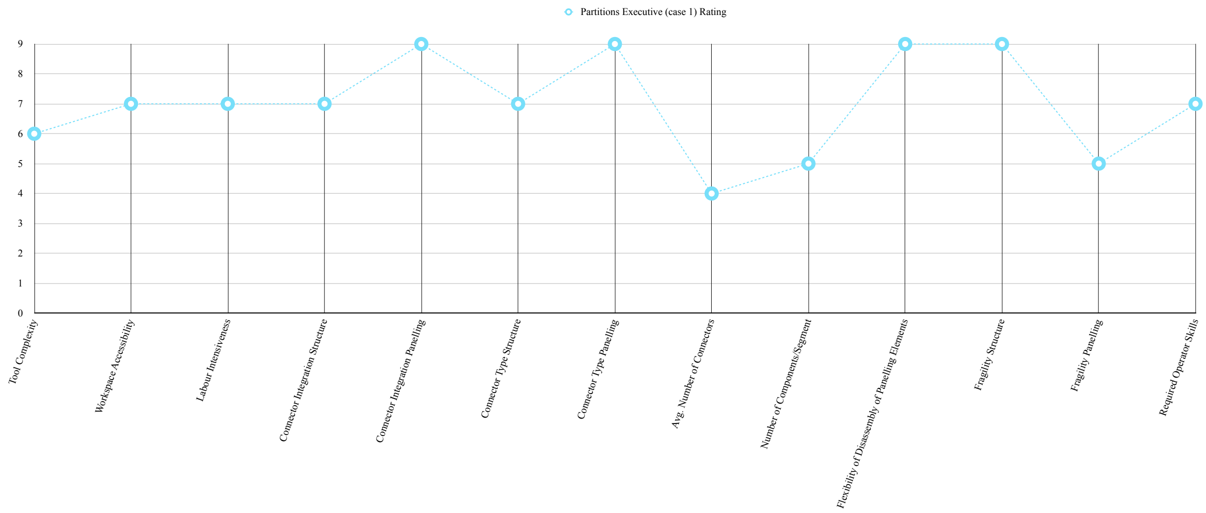


Figure A3. Results Wall System *VetroIn.*

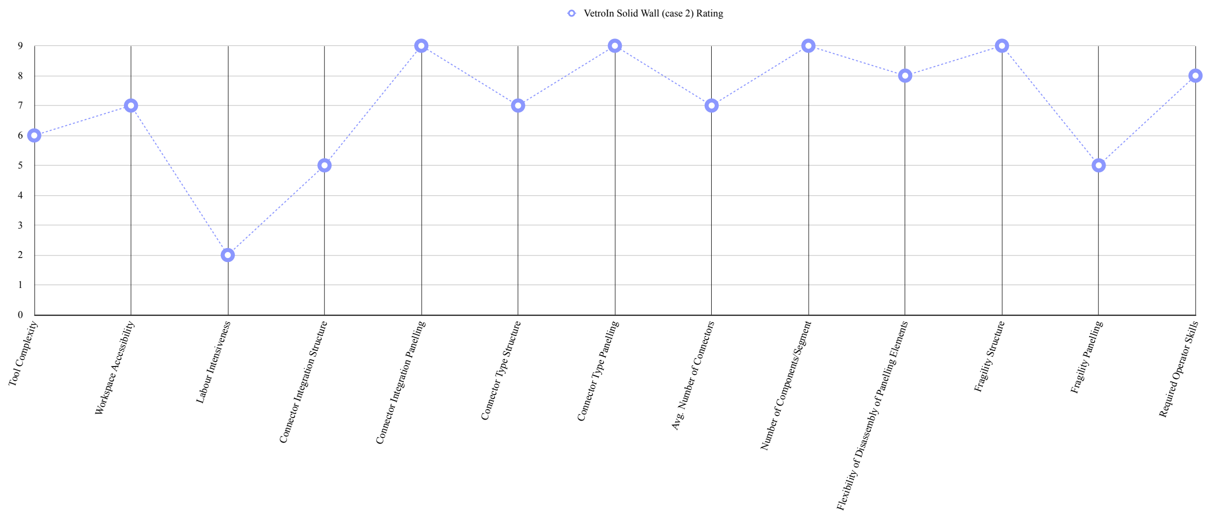


Figure A4. Results Wall System *Brandão et al.*

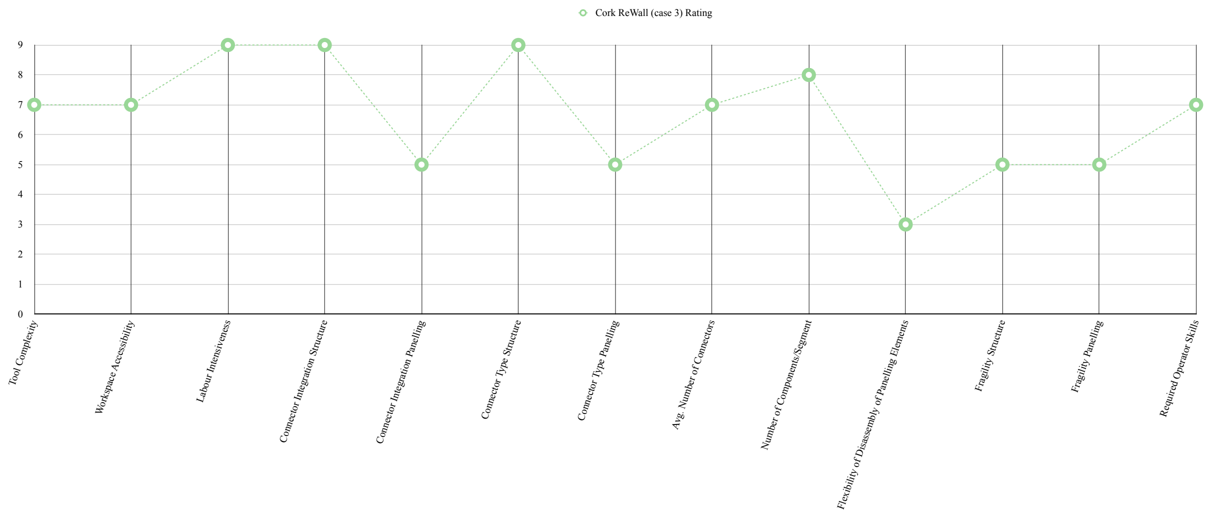


Figure A5. Results Wall System *WikiHouse (screws)*.

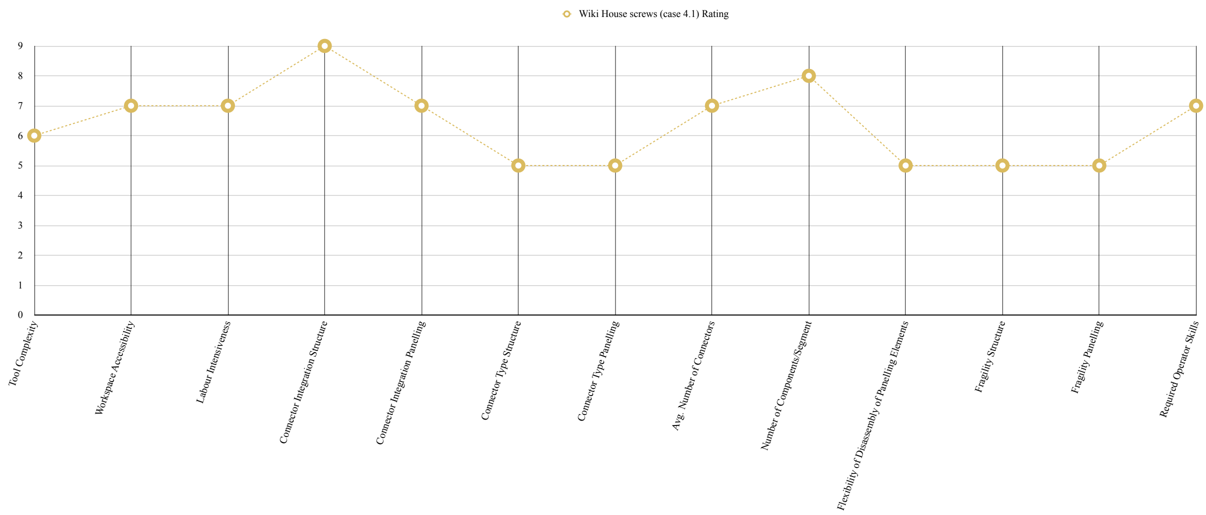
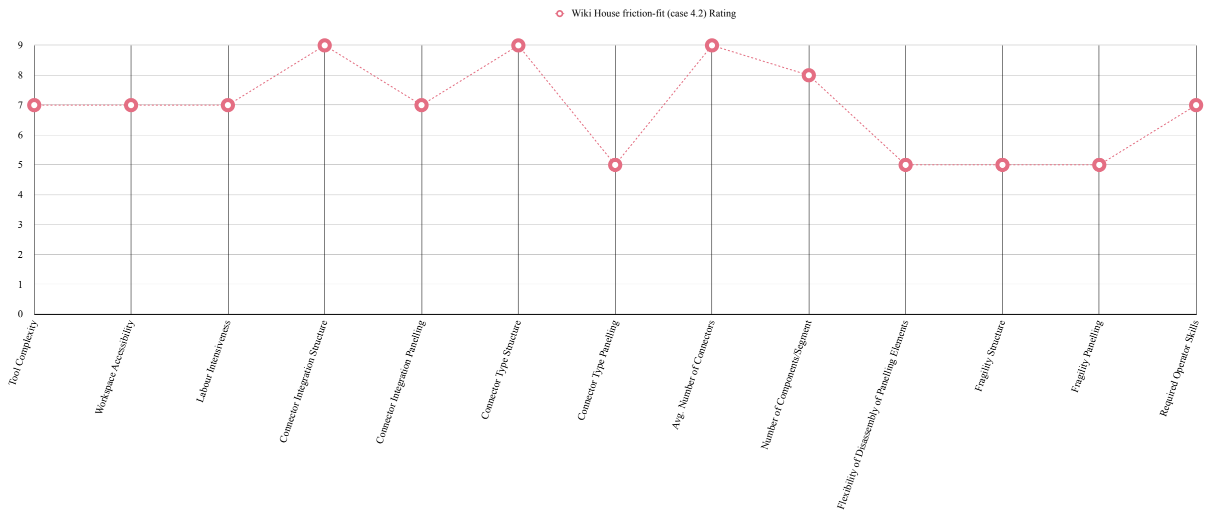


Figure A6. Results Wall System *WikiHouse (friction fit)*.



APPENDIX C

Descriptive Rating Criteria

Tool Complexity Rating

Tool complexity assesses the complexity/types of mechanical tools required to assemble and disassemble a wall system.

Tool Complexity	Rating
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Power tools are required	6
Special tools are required	5
Significant time delay	-2
Special care/techniques are needed	-1
A considerable part of the assembly is done using tools of a higher rating category	+1

Workspace Accessibility Rating

Workspace Accessibility describes the space required to construct and deconstruct a wall system. The metric is derived from the space needed to operate the tools required for assembly and disassembly and thus linked to the tool complexity criterion.

Workspace Accessibility	Rating
Mounting can be done with hardly any space required (< 5 cm)	9
Mounting requires some space for hands or small hand tools (< 20 cm)	7
Mounting requires significant space for hand or powered tools	5
Special care/tools/techniques are needed	-1
Blind assembly/disassembly	-1
Significant time delay	-1
One product has to be removed to access the area	-1
Multiple products have to be removed to access the area	-2

Labour Intensiveness Rating

Labour intensiveness is linked to the dimensions and weight of components, thus assessing the ease of handling components.

Labour Intensiveness	Rating
The elements are manageable with one hand (<7.5kg)	9
The elements are manageable with two hands (7.5-15kg)	7
The elements are liftable in accordance with working conditions (15-25kg)	5
The elements require two people to manage (25-50kg)	3
Integrated handles or lifting facilities	+2
The elements are hard to grasp or manage (tool needed, flexible, slippery, long or similar)	-1
Placement above head, sitting or squatted while lifting	-1

Connector Integration Rating

This category assesses the degree of connector integration into the design of components connections and the type of separate connectors needed. This criterion is divided into a rating for a system's structure and its panelling as distinct differences could be identified.

Connector Integration (Structure)	Rating
Connectors are fully integrated into the product	9
Connectors are partly integrated into the product, but separate connecting products are needed	7
Connectors are not integrated into the product, but design allows for aided affixing of connectors	5
Connectors are not integrated into the product, and design does not allow for aided affixing of connectors	1

Connector Integration (Panelling)	Rating
Connectors are fully integrated into the product	9
Connectors are partly integrated into the product, but separate connecting products are needed	7
Connectors are not integrated into the product, but design allows for aided affixing of connectors	5
Connectors are not integrated into the product, and design does not allow for aided affixing of connectors	1

Connector Type Rating

Connector type describes the types of fasteners used to connect the components of a system. This criterion is divided into a rating for a system's structure and its panelling as distinct differences could be identified.

Connector Type (Structure)	Rating
Products are connected without dedicated fasteners	9
Products are connected with bolts or clips (or similar)	7
Products are connected with screws (or similar)	5
Products are connected with nails (or similar)	3
Products are connected with a fixed connection, but can be detached with some difficulty	2
Products are connected with a fixed connection, and cannot be detached without heavy damage to the product or its host	1

Connector Type (Panelling)	Rating
Products are connected without dedicated fasteners	9
Products are connected with bolts or clips (or similar)	7
Products are connected with screws (or similar)	5
Products are connected with nails (or similar)	3
Products are connected with a fixed connection, but can be detached with some difficulty	2
Products are connected with a fixed connection, and cannot be detached without heavy damage to the product or its host	1

Average Number of Connectors Rating

This category assesses the average number of connectors needed to connect two components within a system. An average rating is being used because a system consists of multiple components with varying number of connectors needed for connection. The average number of connectors between two components stands in direct relation to the number of components within a wall system.

Average Number of Connectors Between two Components	Rating
An average of 0-0,5 fasteners is needed to connect two components	9
An average of 0,5-1,0 fasteners is needed to connect two components	7
An average of 1,1-1,5 fasteners is needed to connect two components	5
An average of 1,6-2,0 fasteners is needed to connect two components	4
An average of more than 2,0 fasteners is needed to connect two components	1

Number of Components Rating

Number of components describes the total number of individual components one segment of a system consists of.

Number of Components per Evaluated Segment	Rating
One segment of the system consists of max. 20 single components	9
One segment of the system consists of 21 - 30 single components	7
One segment of the system consists of 31 - 40 single components	5
One segment of the system consists of more than 40 single components	3
A considerable amount of components (10 or more) of the same type is used	+1

Flexibility of Disassembly Rating

Flexibility of disassembly assesses the amount of adjacent components that need to be removed in order to demount a panelling element. This category focusses only on panelling elements as flexibility of the disassembly order in the structure was found to be of little relevance.

Flexibility of Disassembly of Panelling Elements	Rating
Elements can be replaced without removing an adjacent element	9
Elements can be replaced by removing one adjacent obstructive element	8
Elements can be replaced by removing two adjacent obstructive elements	6
Elements can be replaced by removing several adjacent obstructive elements	3
Elements can’t be replaced	2
Special care/tools/equipment/techniques are needed	-1
Significant time delay	-1

Fragility Rating

Fragility assesses the robustness of a system's components and is predominantly related to the used materials. This criterion is divided into a rating for a system's structure and its panelling as distinct differences could be identified.

Fragility (Structure)	Rating
The elements are extremely robust and can be handled without special care	9
The elements are decently robust and can be handled with little care	5
The elements are somewhat fragile and needs to be handled with care	3
The elements are very fragile and needs to be handled with special care at all times	1

Fragility (Panelling)	Rating
The elements are extremely robust and can be handled without special care	9
The elements are decently robust and can be handled with little care	5
The elements are somewhat fragile and needs to be handled with care	3
The elements are very fragile and needs to be handled with special care at all times	1

Required Operator Skills Rating

This category assesses the required skills required to assemble and disassemble a system.

Required Operator Skills	Rating
Operator is not required to operate any tools	9
Operator is required to operate common hand tools (rubber mallet or similar)	8
Operator is required to operate common electric tools (electric screwdriver or similar)	7
Operator is required to operate special tools	5
Operator needs to have one or multiple certificates to assemble/disassemble the elements	3

APPENDIX D

Assessment Criteria - Description and Argumentation

Tool Complexity

Tool complexity describes the types of tools that are required to assemble and disassemble a system. The highest rating can be achieved when no tools are required, while the lowest rating is given when complex to use/special tools are required. Practical rating steps in between give a variety of options.

The category of tool complexity is included in the assessment method because the type of tool is directly linked to ease of assembly and disassembly and is furthermore linked to the category of required operator skills. The category is used to assess the assembly and the disassembly process alike, as for all of the assessed systems no differences between the two processes were identified.

Workspace Accessibility

Workspace accessibility rates the space that is required to assemble and disassemble a system depending on what kind of tools need to be used.

This category is important for the assessment of ease of assembly and disassembly because space can be a limiting factor and requiring as little workspace as possible positively affects the ease of assembly and disassembly.

Labour Intensiveness

The category of labour intensiveness deals with weight and size of components of a system.

To consider labour intensiveness is crucial for the assessment of ease of assembly and disassembly because size and weight of elements directly influence work efficiency and time as well as the number of operators required to construct and deconstruct a system.

Connector Integration

Connector integration rates the integration of connectors in the design of components. The highest score can be achieved if connectors are fully integrated in a component, while missing integration results in a lower score. Intermediate rating steps give a variety of options. This criterion is divided in two sub-criteria, one for the structure of a system and one for the panelling. This is due to considerable differences between structure and panelling in all assessed systems.

The integration of connectors is vital in the assessment of ease of assembly and disassembly because this category is directly linked to assembly and disassembly time and the number of working steps.

Connector Type

This category rates the type of connector between components of a system, if separate fasteners are required and if so what kind of fastener is used. This criterion is divided in two sub-criteria, one for the structure of a system and one for the panelling. This is due to considerable differences between structure and panelling in all assessed systems.

The types of connectors are essential in the assessment on ease of assembly and disassembly as connectors directly impact the assembly and disassembly time, the required tools, labor intensiveness and the number and sequence of working steps.

Average Number of Connectors between Two Components

This category rates a system on how many connectors are used to connect components within the system. The rating refers to an average value because all systems rely on multiple types of connections with different amounts of connectors. Thus an average value, in connection with the following category ‚number of components per segment‘, allows for a comprehensive rating of a complex system.

This is valuable for the assessment as the number of connectors have a direct impact on assembly and disassembly time, thus influencing the ease of assembly and disassembly.

Number of Components per Segment

Number of components per segment describes the amount of individual components used within a system. For comparative reasons, all systems are rated on one segment of the same or very similar size. A segment is defined as a part of a system that, when replicated arbitrarily and connected, results in a complete system. A segment can also be understood as a module.

This category finds relevance in the assessment because it directly affects the number of working steps, number of connectors and the time required to assemble and disassemble a system.

Flexibility of Disassembly of Panelling Elements

This category rates a system on how flexible panelling elements can be removed, optimally without the necessity to remove any adjacent components.

The flexibility of disassembly of panelling elements is important for assessing ease of assembly and disassembly because, beyond full disassembly, also partial disassembly needs to be considered. This can be the case if components need to be replaced due to damage or different functional requirements. Within this category, only panelling elements are considered because these elements are exposed and therefore prone to damage or need for replacement due to functional change.

Fragility

The category of fragility evaluates a system on the robustness of components and how careful these components need to be handled.

This category is included in the assessment because it influences the assembly and disassembly time due to more or less careful handling of components.

Required Operator Skills

Required operator skills describes the skills or qualifications necessary to construct and deconstruct a system.

A system that can be built by an operator without special knowledge and skills can be considered easier to assemble and disassemble because no specialists need to be employed to fulfill the task.

Appendix E

Images of Assessed Demountable Wall Systems (for more detailed drawings and sequences of working steps for assembly and disassembly of each system, please contact the author)

Figure A7. Cork ReWall by Brandão et al.

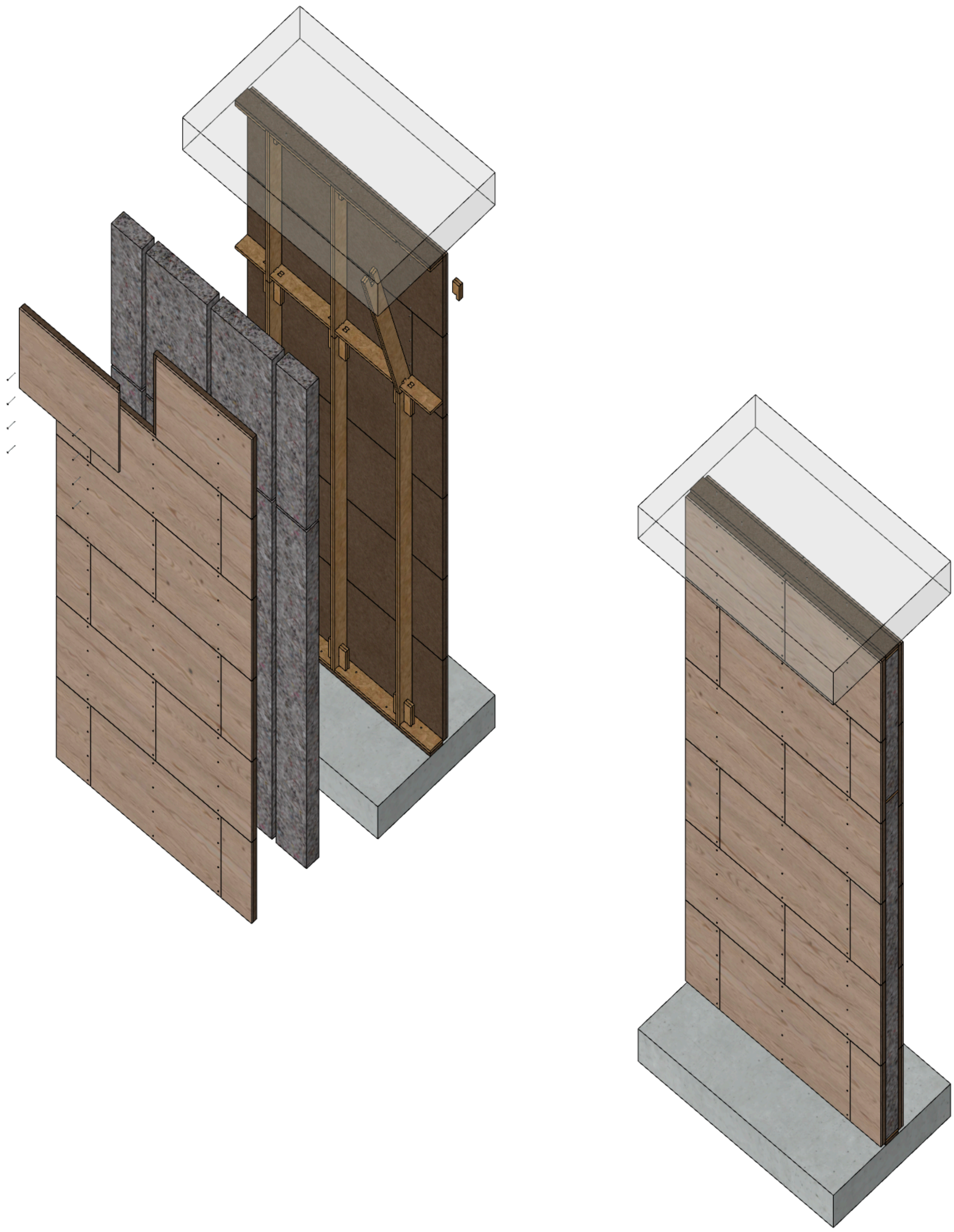


Figure A8. Wall System by WikiHouse.

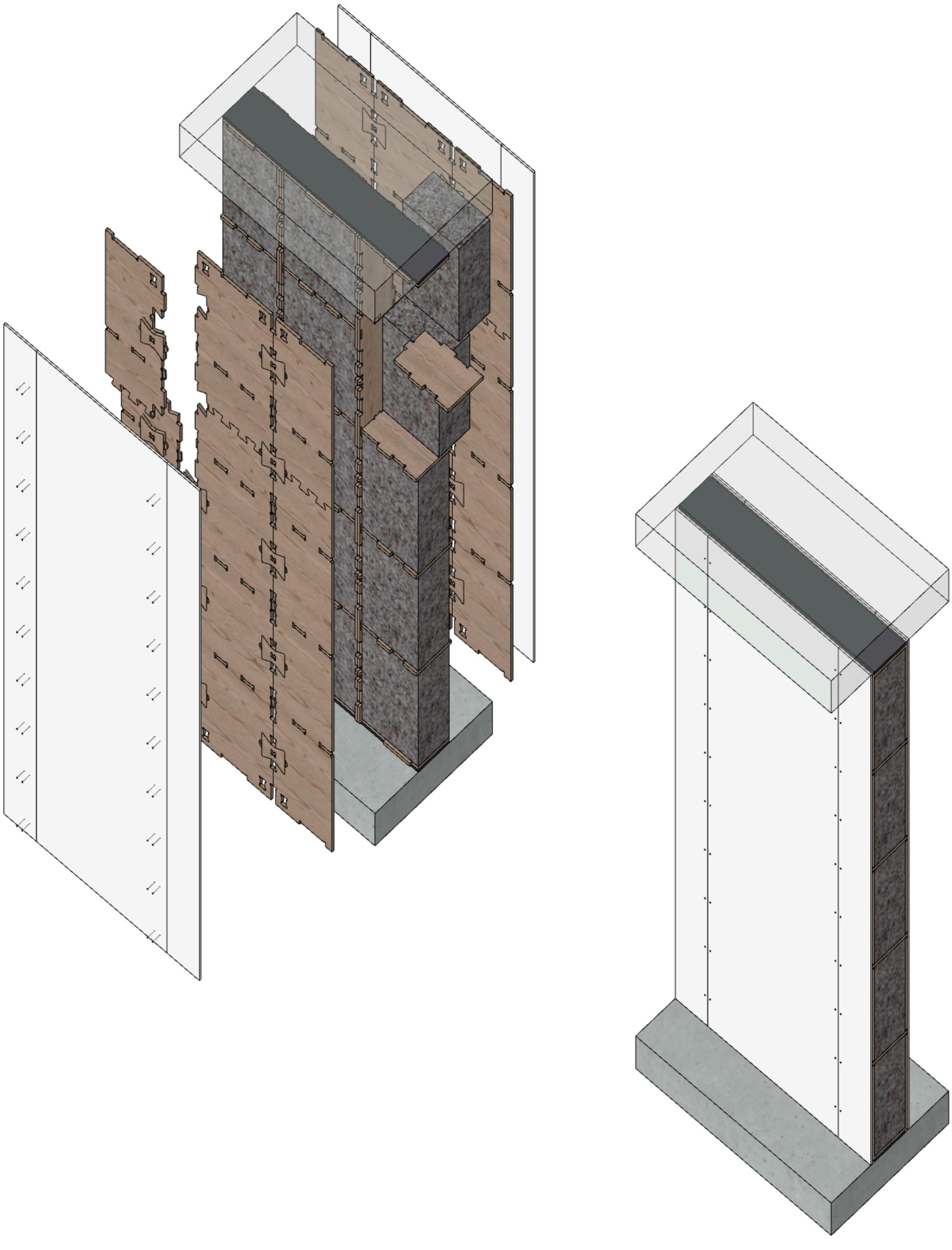


Figure A9. Wall System by VetroIn.

Figure A10. Wall System by Partitions.