MEASURING THE EASE OF ASSEMBLY FOR DEMOUNTABLE PARTITION WALL SYSTEMS

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ABSTRACT

Design for disassembly (DfD) is a design strategy, that aims to reduce material consumption, increase reusability and minimize waste. This study aims to evaluate strengths and weaknesses regarding the ease of assembly and disassembly currently on the market for available partition wall systems. An existing Design for Disassembly (DfD) method was adjusted for the scale of the partition wall systems. A multi-criteria decision-making method is used that relies on a descriptive rating. The application of the evaluation intends to create demountable and changeable interior spaces for a multi-purpose building.

KEYWORDS: *Ease of Assembly, MCDM, Evaluation Method, Partition wall, Space plan*

1. INTRODUCTION

To cope with the climate crisis and adapt to higher sustainability standards, the problem of demolition and construction waste is becoming an essential topic for the construction industry. The waste generated during demolitions also requires an ever-increasing financial investment for disposal, reuse, and recycling. 33% of the European Union landfill waste is generated with solid construction waste. Estimations show that the environmental impact of demolition and construction waste will increase by 20.2 % by 2025 (Tahir, 2021). In recent decades, many different industries have tried to integrate the circular economy model into their product development to close the loop of materials by maintaining their maximum value. The construction industry is trying to embrace this model, which offers great potential for reducing demolition and construction waste (Benachio, Freitas and Tavares, 2020). One of the reasons for that is the poor demountability of buildings and the lack for end of life scenarios for building components (Ghisellini, Ripa and Ulgiati, 2018).
In the "building a circular future" report of the architecture office, 3XN multiple influences of the circular economy are displayed. The often referred approach of Design for Disassembly (DfD) is displayed closer where it is possible to extend the life of a building component and the life of the building itself. This approach could lead to a new view of buildings in the future where "buildings become material banks" (3XN, 2019 p.86) where the building parts can be demounted and easily reused afterward.

1.1 Problem Statement

The awareness that building components have different longevity depending on their layering and material, and therefore need to be perceived as such, was originally described by Frank Duffy as the "The Shearing Layers of Change" and later developed further by Steward Brand (Brand, 1994). With an expected life span of 3-20 years according to Brand the space plan undergoes multiple changes during the existence of a building and is therefore a underestimated waste contributor if not planned demountable. Due to their affordability, acoustic insulation, and fire resistance, the most common non-load-bearing partition wall in Europe is a simple wood or aluminum frame wall with insulation and gypsum cladding on each side. On the other hand, they lack demountability and possibly end up as waste (Valencia-Barba et al., 2021). Although often pictured as not hazardous, used plasterboards need mono-cell storage at a landfill to prevent sinking into groundwater levels (Greenspec, 2022).

While the existing DfD methodologies are focused on the separation of parts in electronics and large building components none of the existing evaluations consider focus on partition walls. Since the partition wall is the part that is the most likely to change in a building according to Brand and the partition wall system that is currently mostly used has little demountability a methodology that can give insight into what factors are relevant for a more demountable space plan on for different space plan design goals. This tailored evaluation can serve future designers as guidelines from a product development aspect. Investigations showed on the other hand there are alternatives to the conventional partition wall system. The digital fabrication process is included in some of them. The digitally manufactured systems are cut from standardized, flat wood panels whose joints and corners can interlock because of their geometric shape, with the concept of friction-fit joints at the core without further fasteners (Brandão, Paio and Antunes, 2018).
With a combination of research about the design for disassembly, the existing methodologies, adjusting the methodologies to the scale of partition wall systems, and adding new criteria and recent developments in digital fabrication the main research question aims towards answering the question:

Can CNC-milling increase the ease of assembly of biobased and demountable partition wall systems?

Subquestions:

- *What advantages can CNC milling bring in comparison to manual work?*
- *What demountable partition wall systems already exist?*
- *What assessment methods can be used to quantify the ease of assembly?*
- *How can the criteria of existing ease of assembly methods be adjusted to be used for partition wall systems?*
- *How useful is the adjusted DfA evaluation for creating guidelines and how can it be improved*

1.2 Methods

This research paper was written during the graduation studio of architectural engineering, which is part of the Master of Architecture (MSc) Urbanism and Building Sciences program. The research paper topic is strongly connected to the overall design question and give insights into the advantages of CNC-milling, demountability in general and will aim for guidelines for demountability across different architectural scales from partition wall system to bigger building parts and possible material passports.
To give answers to the research question and sub-questions, the main research method applied in this paper is the literature research about different DfD methods across diverse industries, products for demountable partition wall systems, and digital fabrication.
First, the literature research about the advantages of digital fabrication and CNC-Milling was gathered to understand the potential and possibilities of this branch of production. Furthermore, the market for partition wall systems got investigated for a possible demountable case study of CNC-milled systems and not CNC-milled products. The selected examples were then simulated in 3D software. After choosing an existing evaluation method the assessment was adjusted to the scale of partition walls and criteria for a closer assessment were added. The assessment is then used for a comparison of four case study examples of existing demountable partition wall systems. Out of the results, a correlation can be assessed between the production of the system with a CNC-Mill and increased ease of assembly. The results also lead to a possible conclusion to validate the methodology to help create guidelines for future designs.

1.3 Theoretical Framework

One building type that is known for its high adaptability is the open building. The open building system was developed by John Habraken in the mid-1980´s and was put into practice multiple times over the last decades (Melvin, 2019). In this framework, demountability plays an essential role to

have interiors that change but should not create waste. In a flexible housing system like the open building system, it is understood, that a building changes over time and it's the role of architects to enable the possible change of the future by separating the structure from the infill and the user program of the building (Habraken, 2000).
In this framework, demountability plays an essential role in having interiors that change but should not create waste. Design for the disassembly and reuse of building parts has increased its importance due to the increasing construction waste over the last decades. This approach is closely related to the open building system, which is a framework for designing and constructing buildings that are modular, adaptable, and easy to modify (Lammersen, 2020). Both DfD and the Open Building System are based on the idea of creating products or buildings that are flexible and adaptable, and that can be easily modified or disassembled for reuse or recycling (Durmisevic, 2006).

2. DIGITAL FABRICATION AND DESIGN FOR DISASSEMBLY

The type of construction has always been connected with the available techniques and tools of the time. This can be observed particularly well in wood construction, which has constantly changed with the available processing possibilities (Schittich, 2013). CNC (Computer-Numerically-Controlled) machines and other digital fabrication tools are attracting increasing interest over the last decade as they reduce costs and the international operation of Fab Labs and other crafting initiatives to increase the application in the building industry. Various wood-based materials such as oriented strand board (OSB) and medium-density fiberboard (MDF) are preferred for work with CNC routers because they are more predictable and stable compared to natural wood. Many of the digitally manufactured systems are cut from standardized, flat wood panels whose joints and corners can interlock because of their geometric shape, with the concept of friction-fit joints at the core (Brandão, Paio and Antunes, 2018).
The merge of digital planning tools, for example, CAD (Computer-Aided-Design) and digital fabrication tools are referred to as the file-to-factory process. The process includes the transfer from a digital object of a 3D modeling software to a CNC machine. It aims to combine digital design and digital fabrication seamlessly. Digital Fabrication with CNC machines is used to create different kinds of shapes using subtractive techniques. This makes it possible to produce building parts from different scales and shapes. The file-to-factory workflow allows the planner to make use of non-standardised and free-form shapes in the design. This however can be used to enable mass customization including non standardised building parts for different kinds of variations (Oosthuis, Bier and Albers, 2004).

2.1 Potential of Digital Fabrication for a demountable Space Plan

The use of robots and machines for the manufacturing process is rapidly changing the way of producing in many industries. Therefore, industrial robots can be considered as an alternative technology for various manufacturing tasks and reconfigurable manufacturing systems (Iglesias, Sebastián and Ares, 2015). High precision is one of the main advantages of digital fabrication in comparison to manual work. CNC-routers can be used for high-precision tasks, with deviations ranging from ±0.0002" (±0.00508 mm) to ±0.0005" (±0.0127 mm). The outcome nevertheless depends on the skill of the machinist, the complexity of the parts, and the material that is used. Furthermore, CNC machining can provide high scalability for high-volume production, of the same product or variations with little intervention by the machine operator (Jablons, 2022). The economy of scale is also applicable for the work with CNC-routers since it is possible to increase the level of the output while reducing the cost per unit (Peterdy, 2022). The precision and the scalability of CNC milling therefore can make it possible to realize projects that would not be feasible because of its increased manual labor, complexity, and cost intensiveness (Scheurer, 2005). The innovation possibilities of digital fabrication tools on wood products and customization for a reduction of cost have moved different companies to fully focus on this way of building new houses e.g Wikihouse and others. Digital fabrication is presenting the possibility to rethink sophisticated Japanese joinery and implement it into a the reusable digitally fabricated joinery that can especially be used in the scle of partition wall systems (Brandão, Paio and Antunes, 2018). The high productivity of digital fabrication could therefore be a key aspect to increasing the overall productivity of the construction sector towards the level of other industries (García de Soto *et al*., 2018).

3. MEASURING THE EASE OF ASSEMBLY

To find a suitable methodology to measure the ease of assembly for partition walls some different methodologies were taken into account. One approach to creating a rating tool for demountability that can be applied to diverse items is the evaluation tool by Devdas Shetty and Ahad Ali (2015) which includes nine criteria for comparison, although this tool is more focused on the disassembly of electronic devices (Shetty and Ali, 2015). Another influence is the approach of Askıner Güngör (2005) which covers different aspects more precisely and is suitable for this research since it focuses more on product recovery and the connections of products. Another methodology DfR (Design for Remountability) that is relevant to this research is the DfR rating method prototype developed by S. Lammersen and three other students from TU Delft. The methodology is a combination of adjusted methods of Shetty and Ali and the Askiner Güngör assessment. This research paper will use the existing evaluation method of the student group of TU Delft. The method was developed by the four former TU Delft students including student Steven Lammersen. It measures the accountability of large building components and in this example of open building typologies on three different case studies of finished open building projects. The criteria nevertheless measure the building parts on a building scale and not on the partition wall scale as this paper does. In this case, the methodology will need adjustments on the scale and detailing. A more detailed description of the assessment will follow in the next paragraphs.

3.1 Type of evaluation method

This research uses a Multiple-Criteria-Decision-Making (MCDM) approach that can be described as „a branch of operational research dealing with finding optimal results in complex scenarios including various indicators, conflicting objectives, and criteria" (Kumar et al., 2017 p.1).
An often-used MCDM is the Analytic network process (ANP). Just as in the rating system of Askıner Güngör (2005), this research will follow the ANP approach developed by Thomas J. Saaty in the 1970s. A full Analytic Network Process (ANP) makes it possible to create alternative connections between the three focus concerns: (1) creating disassembly-friendly products; (2) efficiency of disassembly, (3) increasing the product's performance once it is in use. This illustrative way of insights into case studies or objects makes designers benefit from their own design choices for connectors or production approaches (Güngör, 2006). While this paper focuses on the second part of the process, identifying the efficiency of the assembly, the last sub-question aims to combine the first aspect of the Analytic Network Process.
Furthermore, this evaluation will include a Pair Comparison Chart (PCC). This enables the rating to give priority to certain criteria of the evaluation method (David, 1988).

3.2 Criteria

Since DfD is a topic that is applied in different industries and products the criteria that are used in this context can vary and do not always apply to the build context and the case study of partition walls this used assessment of the student group of Lammersen needs to be adjusted. Five criteria of the Lammersen assessment can be used without adjustment. Furthermore, the labor intensiveness and required operator qualification rating were adjusted for the framework of partition walls.
To increase the precision of the evaluation for the ease of assembly more criteria can be added to the existing methodology of Lammersen in the context of partition walls. Damage rating is separated into functional and aesthetical damage ratings. Since these two criteria are assessing the damage focused on the reuse of a system, a new criterion was added to assess possible damage during the assembly due to a high fragility of a system. If a system is can be damaged during the assembly the implemented "Fragility rating" will take it into account. Since the labor intensiveness rating is mainly assessing the weight of the single components of the partition wall system and is not assessing the number of components that need to be moved during the assembly, nor does the rating give information on how

many different component types there are in total. High repetitions and many crafting steps can decrease the ease of assembly due to more time investment during the assembly. The measurement of the disassembly time and the disassembly sequence is therefore closely connected to the type of connection between different components at each moment of the disassembly sequence (Favi and Germani, 2014).
The increased repetition of manual handling steps due to high numbers of components will therefore be taken into account in this rating and will take the simplicity of the concept and the possibility to save time during the assembly into account. For this reason, the criteria "Total number of components" will be added to the existing methodology of Lammersen.
A goal in the planning of assembly is to minimize human errors while assembling a system. Human assemblers use their skill, judgment, and dexterity to complete the assembly task. For this reason, parts and the assembly of a product should be planned to minimize the consequences and the chances of human error (Bayoumi, 2000). The different number of components have a correlation to the different tasks that need to be fulfilled during the assembly of a system. According to Martin Vares, less different components will prevent confusion resulting in less assembly problems (Vares, 2021). For this reason, the rating for the rating "Number of different component types" is added to the existing methodology of Lammersen to reward systems for a low number of different component types and less complexity.

3.3 Descriptive Rating

The assessment rating of Lammersen uses descriptions of processes during the construction and deconstructions and makes a grading between -2 and 9 possible. The score -2 is used as a reduction due to a detail of a system from the score of a the overall score of the criteria. The overall ratings of a criteria cannot be lower than 1. The overall score is then able to give insights into the demountability of a system. The Spreadsheet method used by Shetty and Ali was also used by Geoffrey Boothroyd in the Product Design for Manufacture and Assembly book (Boothroyd, 2010). Overall this method is very user-friendly and the displayed options are more relatable and can be applied by people that are not familiar with the built environment (Lammersen, 2020). The best possible rating in this context is a 9 and the worst possible rating is a (1). This rating makes it possible to identify the strengths and weaknesses of systems. The individual scores of the different systems are then multiplied with the connected *profile factor* that was assigned to the criteria using the Pairwise Comparison Chart (PCC) for every criterion of the assessment. The Pairwise Comparison chart is added to give specific criteria more weight in the rating than others. The weights added in this Pairwise chart are designed to be aligned with the overall design goal of the design project.

Workspace Accessibility The amount of access that is required to perform assembly or disassembly work.	
Process	**Rating**
The task can be done with hardly any space required (< 5 cm)	9
The task requires some space for hands or small hand tools (< 20 cm)	7
The task requires space for hand or powered tools	5
Special care/tools/techniques are needed	-1
Blind assembly/disassembly	-1
Significant time delay	-1
One element have to be removed to access the area	-1
Multiple elements have to be removed to access the area	-2

Table 1: Example for the descriptive rating

Criteria		Rating Score	%
1. Connection Type		**36,00**	21,11 %
2. Number of Component Types		**32,33**	18,96 %
3. Total number of Components		**26,75**	15,68 %
4. Connector Integration		**16,29**	9,55 %
5. Number of fasteners		**12,95**	7,59 %
6. Fragility		**12,70**	7,45 %
7. Workspace Accessibility		**11,48**	6,73 %
8. Tool Complexety		**8,51**	4,99 %
9. Labor intensiveness		**8,18**	4,79 %
10. Required Operator Qualifications		**5,37**	3,15 %

Table 2: Pairwise rating scores for each criteria

3.4 Selection criteria for Case Studies

The four case studies are selected because they are different from each other and therefore have different strengths and weaknesses. According to Seawright and Gerring, it is to choose representative and useful variations from theoretical interest. The most common approach in choosing case studies is therefore using typical, extreme, influential, and different case studies (Seawright and Gerring, 2008). The selection criteria behind the case studies are the different production processes, nevertheless, all are planned to be demountable. Two of them were produced using digital fabrication and the other two are built in a conventional way for partition walls. Both digitally fabricated ones are produced with a CNC-Mill and are still not widely used in the building practice, the other two systems are made using conventional carpeting tools. The main difference is therefore the production process. In the following paragraphs, the case studies will be described in more detail.

3.5 Case Studies

To compare the four case studies, basic conditions must be defined so that all cases have the same starting position. First, it is determined that a length of 2.4m is built with each of the four case studies. Secondly, it is determined that floor rails and ceiling rails are not included in the evaluation of the systems to generalize the component count. Thirdly, it is specified that all the systems must use the same demountable, metal fastening system by Fastmount system for the outer layer of the wall. (Fig. in App. H)

The first partition wall system is the FAAY system. It was chosen for its simplicity and sophisticated approach to demountability. The components are not made with a CNC router (Faay Vianen B.V., 2022). The second system is Wikihouse system. This is an open-source system for building houses in various scales and allows the planner to choose from various CNC-milled demountable building elements, e.g. a floor system, ceilings and modular wall systems with customizable openings (Wikihouse, 2022). The Wikihouse production flow includes a CNC router and the joints are based on the concept of a friction fit and use slots and butterfly joints to keep the elements in place but can also be screwed depending on the interior or exterior application. The third system is the X-Frame system. Walls, ceilings, and openings can be individually designed with twelve differently sized CNC-milled wooden parts placed. The system is also based on friction-fit connections for the interior but can involve a fastener depending on the robustness of the interior or exterior application (XFrame, 2022). The most common way of building a partition wall is the wood frame wall which is displayed here as a reference for the average performance on demountability for partition walls (Clarson Builders, 2022). With a screwed wood frame with wood studs an insulation in between and a wood board on each side.

4. RESULTS

The comparison of the four case study systems gave insights into the strengths and weaknesses of the systems and makes it possible to find correlations between systems and the sub-solutions. The Wikihouse and the X-Frame system have an alternative rating for their screw supported system, separated from the friction fit system. The general scores of the products are evenly separated over the range of results. In the categories Tool complexity, workspace accessibility, required operator qualification and fragility, all products scored high results. On other categories like connector integration, connection type, number of components types and number of total components different results were scored. The wood frame system scored the lowest with a total of 67,27% in comparison to a perfect score. The wood frame system scored lower than most systems on the criteria, connector integration, connection type and number of total components. Followed by the X-Frame alternative system with screws with an overall score of 73,00%. The next higher total score was assessed with the FAAY system with 79,33%. The system scored lower than the rest on connection type, connector integration and labor intensiveness. The Wikihouse alternative with screws scored 80,30% on the overall score. The X-Frame system scored 84,60%, the system scored lower than most of the other systems on the categories number of total components and number of component types. The highest score was assessed with the Wikihouse system. With lower scores in the categories of labor intensiveness, connector integration, number of component types and total number of components.

System	Total score	% of ideal Score
1. Wikihouse	1367,97	**89,11 %**
2. X-Frame	1298,75	**84,60 %**
3. Wikihouse (with screws)	1233,62	**80,36 %**
4. FAAY	1217,79	**79,33 %**
5. X-Frame (with screws)	1120,64	**73,00 %**
6. Woodframe	1032,63	**67,27 %**

Table 3: Results of the case study comparison

5. GUIDELINES

The methodology is nevertheless not suitable to create a system that enables the highest score on each system. This has to do with a clash of three criteria. The labor intensiveness criteria, the number of total components criteria and the number of different component types criteria. If a product has heavy panels like the FAAY or the Wikihouse system this has a negative impact on the weight measuring labor intensiveness rating but a positive influence on the number count of types and components, since it means the system includes few but large and heavy components. On the other hand a high number of smaller parts like the X-Frame system has a positive influence on the labor intensiveness rating but a negative on the number count of types and components. However the method can be used for creating general guidelines across various scales of architecture for designers with the emphasis that the decision has to be made depending on the circumstances of the design project. E.g. only small parts can be transported or labor intensiveness has a low priority due to robot assembly.
Out of the adjusted evaluation, a set of general guidelines will be reframed to assist in the future planning of demountable structures. The guidelines will then be implemented and combined with existing guidelines by Philip Crowtheron the "Environment Design Guide" (2009) and Nicolas Cialimbori on "DfD-Guide to Closed Loop Buildings" (2005) (Fig. in App. D) As their research did not state the ease of assembly as a criterium for their DfD guides, the criteria is added to the existing criteria for a more clear distribution of DfD categories and further research in this sector.

6. CONCLUSION

Design for disassembly is a fundamental part in many different industries such as electronics (Shetty and Ali, 2015) and automotive industry (Liu, 2010) but has difficulties of gaining traction in the building industry (Crowther, 2009), although it could be a key aspect for circularity in the building industry and the global waste reduction (Askar, Bragança and Gervásio, 2022). History shows that there used to be demountable buildings like the Glass Palast in London that was assembled, disassembled and relocated in 1851 (Crowther, 2009). However manual labor was paid less which was one reason to make these undertakings possible. Time is a relevant factor in the building industry and is one of the main reasons why buildings are not demounted because it can be labor and cost-intensive. This explains why the adjustments after the first tests of the adjusted evaluation method on the case study examples were made. The aspect of repetition of tasks was implemented with the criteria "Component types" and total "Number of total components" to reward systems for efficiency, which is an essential goal of the assembly and disassembly since its ability to reduce the assembly time (Vares, 2021). The labor intensiveness and high repetition over a long time is one of the reasons why robots are more included into today's workflows in architecture (Kramberger *et al.*, 2022). Since the evaluation method did not include these aspects due to the scale of the original framework, it was possible to go into more depth on this behalf in the scale of the space plan and the partition wall systems.

After the research has been conducted it is now possible to point out that positive correlations were found between CNC-Milling and the ease of assembly to answer the main research question. The comparison of the case study examples showed that the two CNC-milled products were able to achieve higher ratings than the products that were not CNC-milled. Even the CNC-milled Wikihouse system that was additionally rated with a screw supported system scored higher than the not digital fabricated ones. On the other hand, CNC-milled products did both not achieve high ratings on the number of component types and the total number of component criteria that were added during the research. Increased component types in the component number case of X-Frame can also increase the complexity and the potential for human error if the comprehensibility of the product if no manual is available. However the systems have this complexity for the reason of high modularity for openings sizes etc. Complexity can also lead to higher time investment for disassembly if there the points of assembly are not identifiable in the future (Crowther, 2009). From this aspect, the CNC-milled products have a decreased ease of assembly and score the same or even lower than the not CNC-milled products.

The overall scores of the CNC-milled products were higher than the products that were not CNC-milled using this methodology and this set of case study examples. For this reason, the main research question can be answered by explaining that there is a correlation that CNC-Milling increases the ease of assembly and disassembly. The results showed that one possible reason for that is the connection types, number of fasteners, and connector integration. All of these criteria can be rooted back to a CNC-milled workflow and the potential of friction fit connections. The precision of the CNC router plays an essential role and has advantages over manual-cut building parts that potentially need more fasteners to fix connections properly. To make optimal use of the demountable wood panelling of the walls, the products like the metal Fastmount mechanism has little deviation tolerance to function properly, and therefore a precise structure is necessary. In this sense demountable systems work with another demountable system only if high precision is guaranteed, therefore CNC-milling can also be an advantage for the use of ease of assembly and disassembly increasing products.

This assessment was established using the existing Design for Disassembly methods and partly including new criteria based on the insights from the case study examples and the efficiency of the existing methods. Because of few comparable ease of assembly and disassembly assessments on partition walls except a few examples just as a digitally fabricated wall system of Felipe J. S. Brandao, this assessment lacks scientific validation. Nevertheless, the method can give insights into correlations and design strategies that should be considered from a designer's perspective when designing for disassembly.

Further investigations towards more case studies and comparison to more evaluations and topic additions on the topic just as design for reuse would be useful to increase the evaluation for more disassembly in the space plan. A flexible and demountable space plan allows a building to be easily reconfigured to meet changing needs without the need for costly and wasteful renovations. This approach to building design can help create a more sustainable future for the built environment.

References

1. 3XN (2018) *Building a Circular Future 3rd Edition*. Available at: https://gxn.3xn.com/wp-content/uploads/sites/4/2018/09/Building-a-Circular-Future_3rd-Edition_Compressed_V2-1.pdf.
2. Askar, R., Bragança, L. and Gervásio, H. (2022) 'Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings', *Applied System Innovation*, 5, pp. 1, 24. Available at: https://doi.org/10.3390/asi5010024.
3. Bayoumi, A.M.E. (2000) 'DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA): CONCEPTS, BENEFITS AND APPLICATIONS', in M.F. Hassan and S.M. Megahed (eds) *Current Advances in Mechanical Design and Production VII*. Oxford: Pergamon, pp. 501–509. Available at: https://doi.org/10.1016/B978-008043711-8/50051-9.
4. Benachio, G.L.F., Freitas, M. do C.D. and Tavares, S.F. (2020) 'Circular economy in the construction industry: A systematic literature review', *Journal of Cleaner Production*, 260, p. 121046. Available at: https://doi.org/10.1016/j.jclepro.2020.121046.
5. Boothroyd, G. (2010) *Product Design for Manufacture and Assembly*. CRC Press. Available at: https://doi.org/10.1201/9781420089288.
6. Brand, S. (1994) *How buildings learn: what happens after they're built*. New York, NY: Viking.
7. Brandão, F., Paio, A. and Antunes, N. (2018) *Towards a Digitally Fabricated Disassemble-able Building System: A CNC fabricated T-Slot Joint*. pp. 12 Available at: https://doi.org/10.52842/conf.ecaade.2018.2.011.
8. Ciarimboli, N. and Guy, B. (2005) 'Design for Disassembly in the Built Environment: Dfda Guide to Closed-Loop Design and Building 0 9810X 02006 Foreword and Acknowledgements', *Docslib*, p. 5.
9. Clarson Builders (2022) *Our Guide On How To Build A Stud Wall*, *Clarkson*. Available at: https://www.clarksonbuilders.co.uk/news/how-to-build-a-stud-wall/ (Accessed: 2 January 2023).
10. CROWTHER, P. (2009) 'Designing for disassembly', in *Technology, Design and Process Innovation in the Built Environment*. Spon Press. p. 11
11. David, H.A. (1988) *The method of paired comparisons*. 2nd ed., rev. London, New York: C. Griffin ; Oxford University Press (Griffin's statistical monographs & courses). Available at: http://bvbr.bib bvb.de:8991/F?func=service&doc_library=BVB01&doc_number=003962593&line_number=0001&func_code=DB_RECORDS&service_type=MEDIA (Accessed: 27 December 2022).
12. Durmisevic, E. (2006) 'Transformable building structures: Design for dissassembly as a way to introduce sustainable engineering to building design & construction', p. 97.
13. Fastmount (no date) *Metal Range | Fastmount™ Panel Mounting*. Available at: https://fastmount.com/product-category/metal-range/ (Accessed: 8 January 2023).
14. Favi, C. and Germani, M. (2014) 'A Design for Disassembly Approach to Analyze and Manage End-of-Life Options for Industrial Products in the Early Design Phase', in E. Henriques, P. Pecas, and A. Silva (eds) *Technology and Manufacturing Process Selection*. London: Springer London (Springer Series in Advanced Manufacturing), p. 311. Available at: https://doi.org/10.1007/978-1-4471-5544-7_15.
15. García de Soto, B. *et al*. (2018) 'Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall', *Automation in Construction*, 92, pp. 297–311. Available at: https://doi.org/10.1016/j.autcon.2018.04.004.
16. Ghisellini, P., Ripa, M. and Ulgiati, S. (2018) 'Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review',

Journal of Cleaner Production, 178, pp. 618–643. Available at: https://doi.org/10.1016/j.jclepro.2017.11.207.

17. Grrenspec (2022) *Gypsum Plasterboard and the environment*. Available at: http://www.greenspec.co.uk/building-design/plasterboard-drylining-partition/ (Accessed: 4 December 2022).
18. Güngör, A. (2006) ‘Evaluation of connection types in design for disassembly (DFD) using analytic network process’, *Computers & Industrial Engineering*, 50(1–2), pp. 35–54. Available at: https://doi.org/10.1016/j.cie.2005.12.002.
19. Habraken, N.J. (2000) *The Structure of the Ordinary: Form and Control in the Built Environment*. MIT Press.
20. Iglesias, I., Sebastián, M.A. and Ares, J.E. (2015) ‘Overview of the State of Robotic Machining: Current Situation and Future Potential’, *Procedia Engineering*, 132, pp. 911–917. Available at: https://doi.org/10.1016/j.proeng.2015.12.577.
21. Jablons, J. (2022) *Precision CNC Machining*, *Metal Cutting Corporation*. Available at: https://metalcutting.com/knowledge-center/precision-cnc-machining/ (Accessed: 25 December 2022).
22. Kramberger, A. *et al*. (2022) ‘Robotic Assembly of Timber Structures in a Human-Robot Collaboration Setup’, *Frontiers in Robotics and AI*, 8. Available at: https://www.frontiersin.org/articles/10.3389/frobt.2021.768038 (Accessed: 5 January 2023).
23. Kumar, A. *et al*. (2017) ‘A review of multi criteria decision making (MCDM) towards sustainable renewable energy development’, *Renewable and Sustainable Energy Reviews*, 69, pp. 596–609. Available at: https://doi.org/10.1016/j.rser.2016.11.191.
24. Lammersen, S. (2020) ‘OB-DFD: Open Building - Designed for Disassembly’. Available at: https://repository.tudelft.nl/islandora/object/uuid%3A05e31a98-754c-41a8-b348-b7235176fd62 (Accessed: 7 December 2022).
25. Liu, Y. (2010) ‘Research on the Disassembly Design of the Used Cars’, *Key Engineering Materials*, 426–427, pp. 303–307. Available at: https://doi.org/10.4028/www.scientific.net/KEM.426-427.303.
26. Middelkoop, D. (2014) ‘SP54/SP70 - Faay Vianen b.v.’, 15 April. Available at: https://www.faay.com/product/sp54sp70/ (Accessed: 8 January 2023).
27. Melvin, J. (2019) *Launch of Open Building.co! An emerging group of Dutch architects who are devoted to radically changing the building industry*, *Marc Koehler Architects*. Available at: https://marckoehler.com/story/launch-of-open-building-co/ (Accessed: 26 December 2022).
28. Oosthuis, K., Bier, H. and Albers, C. (2004) ‘File to Factory and Real-Time Behavior in ONL-Architecture’. Available at: http://papers.cumincad.org/data/works/att/acadia04_294.content.pdf.
29. Peterdy (2022) *Economies of Scale*, *Corporate Finance Institute*. Available at: https://corporatefinanceinstitute.com/resources/economics/economies-of-scale/ (Accessed: 26 December 2022).
30. Scheurer, F. (2005) *From design to production: Three complex structures materialised in wood*. Available at: https://archive.arch.ethz.ch/caad-wiki/twiki/pub/D2p/ConferencesPublications/2005_Scheurer_FromDesignToProduction.pdf
31. Schittich, C. (2013) *Einfach Bauen Zwei*. Walter de Gruyter. Available at: https://books.google.nl/books?id=eYvTAAAAQBAJ
32. Seawright, J. and Gerring, J. (2008) ‘Case Selection Techniques in Case Study Research: A Menu of Qualitative and Quantitative Options’, *Political Research Quarterly*, 61(2), p. 296. Available at: https://doi.org/10.1177/1065912907313077.
33. Shetty, D. and Ali, A. (2015) ‘A new design tool for DFA/DFD based on rating factors’, *Assembly Automation*, 35(4), pp. 348–357. Available at: https://doi.org/10.1108/AA-11-2014-088.
34. Tahir, M. (2021) ‘Construction Waste and its Impact on the Environment’, *Graana.com Blog*, 27 October. Available at: https://www.graana.com/blog/construction-waste-and-its-impact-on-the-environment/ (Accessed: 3 November 2022).

35. Valencia-Barba, Y.E. *et al*. (2021) 'Life cycle assessment of interior partition walls: Comparison between functionality requirements and best environmental performance', *Journal of Building Engineering*, 44, p. 2. Available at: https://doi.org/10.1016/j.jobe.2021.102978.

36. Vares, M. (2021) 'Design for Assembly (DFA) Principles Explained', *Fractory*, 28 September. Available at: http://https%253A%252F%252Ffractory.com%252Fdesign-for-assembly-dfa%252F (Accessed: 2 January 2023).

37. Wikihouse (2022) *WikiHouse*. Available at: https://www.wikihouse.cc/blocks/wall-s (Accessed: 28 December 2022).

38. XFrame (2022) *Modular Office*, *XFrame*. Available at: https://xframe.com.au (Accessed: 28 December 2022).

Appendix A:

Pairwise Comparison Chart (PCC)

The overall design goal was the input for the PCC that is based on Saaty's rating scale and led to the following overview.

	Tool Complexety	Workspace Accessibility	Labor intensiveness	Connector Integration	Connection Type	Number of fasteners	Fragility	Required Operator Qualifications	Number of Component Types	Total number of Components	Rating Score	%
Tool Complexety		1	1	2	1/5	1	2	1	1/6	1/7	**8,51**	4,99 %
Workspace Accessibility	1		6	1/3	1/4	1/5	1	2	1/2	1/5	**11,48**	6,73 %
Labor intensiveness	1	1/6		1/5	1/3	1	3	2	1/3	1/7	**8,18**	4,79 %
Connector Integration	1/2	3	5		1/4	5	1/7	2	1/5	1/5	**16,29**	9,55 %
Connection Type	5	3	3	4		4	7	3	3	4	**36,00**	21,11 %
Number of fasteners	1	5	1	1/5	1/4		3	1	1/2	1	**12,95**	7,59 %
Fragility	1/2	1	1/3	7	1/7	1/3		3	1/7	1/4	**12,70**	7,45 %
Required Operator Qualifications	1	1/2	1/2	1/2	1/3	1	1/3		1/5	1	**5,37**	3,15 %
Number of Component Types	6	2	3	5	1/3	2	7	5		2	**32,33**	18,96 %
Total number of Components	7	5	7	1	1/4	1	4	1	1/2		**26,75**	15,68 %
											171	

Intensive of Importlance	Definition	Explaination
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one element over another
5	Strong Importance	Experience and judgment strongly favor one element over another
7	Very Strong Importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8		Intermediate values between two adjacent values

Table A1: Saaty´s rating chart

Appendix B:

Components	Case Study I: FAAY	Case Study II: Wikihouse	Case Study III: X-Frame	Case Study VI: Wood Frame	Case Study V: Wikihouse Alternati. (with screws)	Case Study VI: X-Frame Alternative (with screws)
Wood studs	5	8	0	5	8	0
Panels	4	8	0	0	8	0
Adding glue	6	0	0	0	0	0
Insulation Pieces	0	4	0	8	4	0
Screws	0	0	0	56	48	0
Metal Profiles	0	0	0	10	0	0
Cross bars	0	0	0	4	0	0
Butterfly Clips	0	18	0	0	18	0
X-Frame, diagonal	0	0	16	0	0	16
X-Frame, vertical (short)	0	0	8	0	0	8
X-Frame, vertical (long)	0	0	6	0	0	6
X-Frame, horizontal	0	0	12	0	0	12
X-Frame, connector (Triangle)	0	0	8	0	0	8
X-Frame, connector (Edge)	0	0	8	0	0	8
X-Frame, connector (Corner)	0	0	8	0	0	8
X-Frame, connector (Square)	0	0	14	0	0	14
X-Frame bolt	0	0	0	0	0	19
X-Frame screw nut	0	0	0	0	0	19
Total Component Types	3	4	8	5	5	10
Total Components	15	38	80	83	86	118

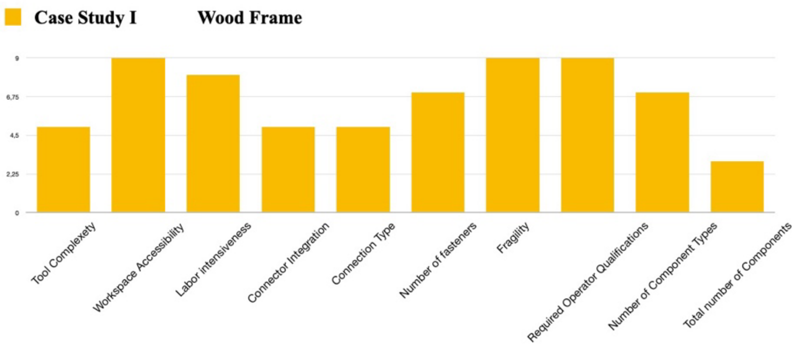
Table B1: Number count of the components and component types

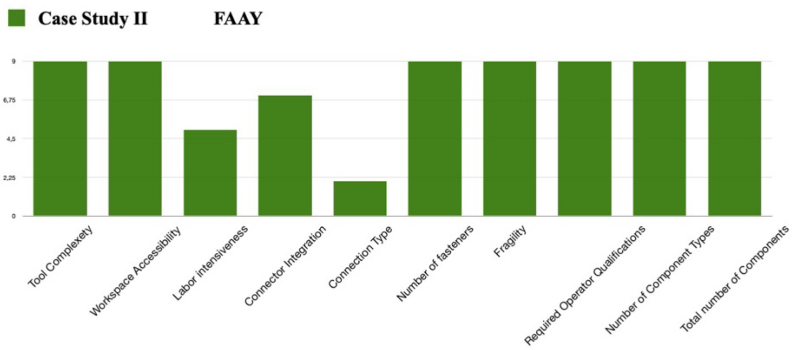
Appendix C:

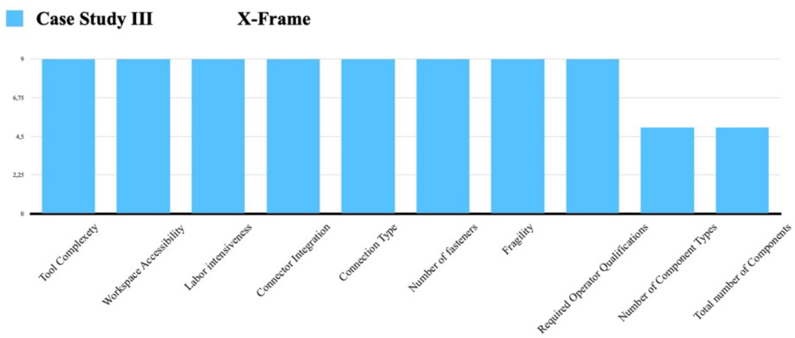
Criteria	Factor	Case Study I Wood Frame	SxF	Case Study II FAAY	SxF	Case Study III X-Frame	SxF	Case Study IV Wikihouse	SxF	Case Study V X-Frame (with screws)	SxF	Case Study VI Wikihouse (with screws)	SxF
Tool Complexety	8,51	5	42,55	9	76,59	9	76,59	9	76,59	5	42,55	5	42,55
Workspace Accessibility	11,48	9	103,35	9	103,35	9	103,35	9	103,35	9	103,35	9	103,35
Labor intensiveness	8,18	8	65,41	5	40,88	9	73,59	7	57,23	9	73,59	7	57,23
Connector Integration	16,29	5	81,46	7	114,05	9	146,64	7	114,05	9	146,64	9	146,64
Connection Type	36,00	5	180,00	2	72,00	9	324,00	9	324,00	9	324,00	9	324,00
Number of fasteners	12,95	7	90,65	9	116,55	9	116,55	9	116,55	7	90,65	7	90,65
Fragility	12,70	9	114,32	9	114,32	9	114,32	9	114,32	9	114,32	9	114,32
Required Operator Qualifications	5,37	9	48,30	9	48,30	9	48,30	9	48,30	9	48,30	9	48,30
Number of Component Types	32,33	7	226,33	9	291,00	5	161,67	7	226,33	3	97,00	7	226,33
Total number of Components	26,75	3	80,25	9	240,75	5	133,75	7	187,25	3	80,25	3	80,25
Total (Score x Factor)			1032,63		1217,79		1298,75		1367,97		1120,64		1233,62
% (of ideal score)			**67,27 %**		**79,33 %**		**84,60 %**		**89,11 %**		**73,00 %**		**80,36 %**

Table C1: Results of the Comparison

Graphic Overview of the Comparison Results







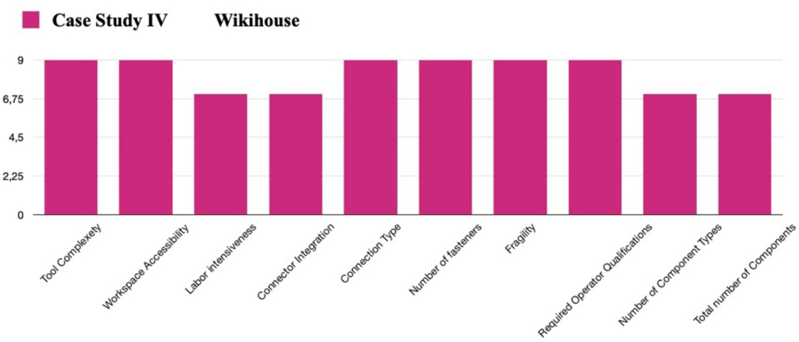


Table C2: Graphic overview of the results

Appendix E:

Combined Guidelines from the Evaluation and Crowther&Ciamboli

No.	Guideline	Material Recycling	Component Remonufaccture	Component Reuse	Building Relocation	Ease of Assembly	Reference
1.	Use recycled and recyclable materials	⬤	⬤	•	•	•	Combined Philip Crowther& Nicolas Cialimbori Guidelines
2.	Minimise the number of different types of material	⬤	⬤	•	•	•	
3.	Avoid toxic and hazardous materials	⬤	⬤	•	•	•	
4.	Provide identification of material types	⬤	⬤	•	•	•	
5.	Use an open building system not a closed one	•	•	•	⬤	•	
6.	Use modular design	•	•	•	⬤	•	
7.	Separate the structure from the cladding for parallel disassembly	•	•	•	⬤	•	
8.	Provide a means of handling and locating	•	•	⬤	⬤	•	
9.	Design joints and components to withstand repeated use	•	•	⬤	⬤	⬤	
10.	Allow for parallel disassembly	●	●	⬤	●	•	
11.	Provide identification of component type	●	●	⬤	●	•	
12.	Use a standard structural grid for set outs	•	•	•	⬤	•	
13.	Use lightweight materials and components	⬤	⬤	⬤	⬤	⬤	
14.	Identify points of disassembly	•	●	⬤	⬤	⬤	
15.	Provide spare parts and on site storage for them and parts	•	•	•	⬤	•	
16.	Retain all information of the building components	•	•	●	⬤	●	
17.	Minimise the number of different types of components	•	•	⬤	⬤	⬤	Combined Evaluation & Philip Crowther Guidelines
18.	Use mechanical not chemical connections	•	⬤	⬤	⬤	⬤	
19.	Design to use common tools,avoid specialist plant	•	●	⬤	⬤	⬤	
20.	Provide access to all parts and connection points	•	●	⬤	⬤	⬤	
21.	Make components sized to suit the means of handling	•	●	⬤	⬤	⬤	
22.	Use a minimum number of connectors	•	●	⬤	⬤	⬤	
23.	Use a minimum number of different types of connectors	•	●	⬤	⬤	⬤	
24.	Integrate connections into the Elements	•	•	⬤	•	⬤	
25.	Use Elements that withstand the Assembly and the disassembly	•	•	⬤	•	⬤	
26.	Minimise the total number of componentes	•	⬤	•	⬤	⬤	

Not normally relevant •	Relevant ●	Highly Relevant ⬤

Table E1: Summary of the guidelines from the evaluation and Philip Crowther and Nicolas Ciamboli

Appendix F:

1. Wood Frame Step Sequence

Criteria	Factor	**Case Study I:** Wood Frame	SxF
Tool Complexety	8,51	5	**42,55**
Workspace Accessibility	11,48	9	**103,35**
Labor intensiveness	8,18	8	**65,41**
Connector Integration	16,29	5	**81,46**
Connection Type	36,00	5	**180,00**
Number of fasteners	12,95	7	**90,65**
Fragility	12,70	9	**114,32**
Required Operator Qualifications	5,37	9	**48,30**
Number of Component Types	32,33	7	**226,33**
Total number of Components	26,75	3	**80,25**
Total (Score x Factor)			1032,63
% (of ideal score)			**67,27 %**

	Ideal Score
9	76,59
9	103,35
9	73,59
9	146,64
9	324,00
9	116,55
9	114,32
9	48,30
9	291,00
9	240,75
	1535,08

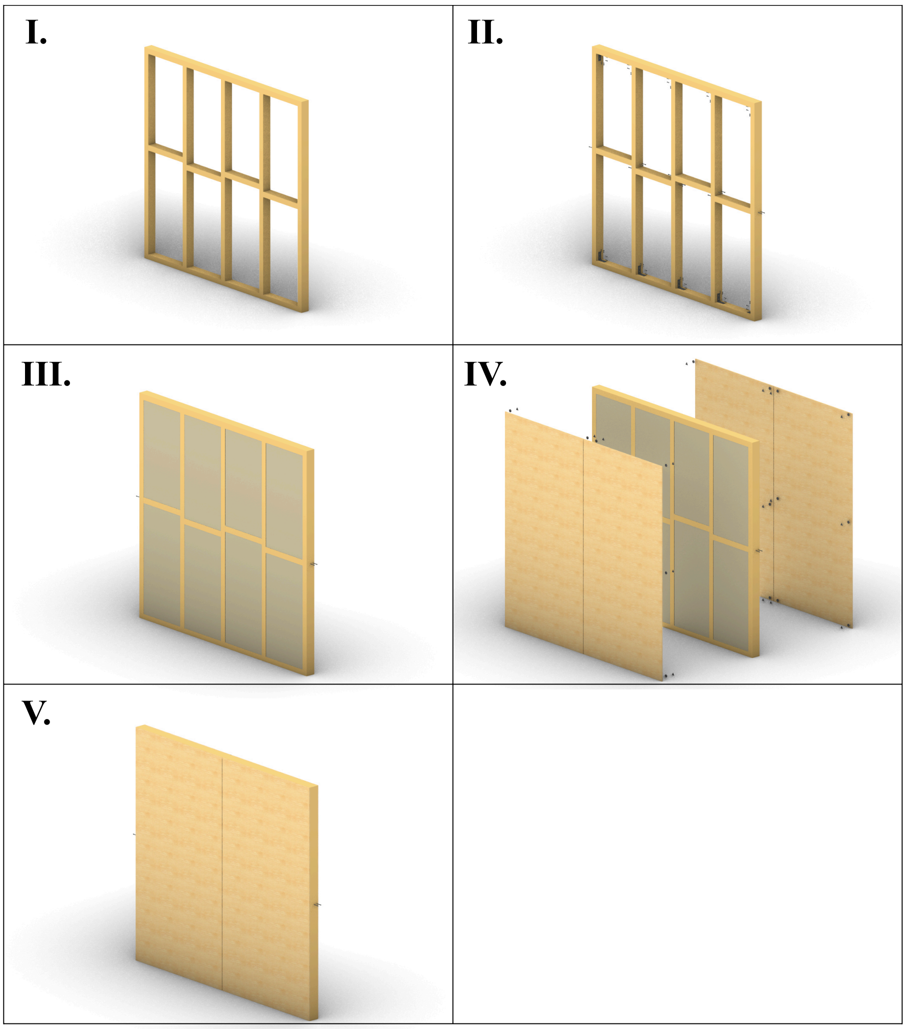


Table F1: Wood Frame step sequence

2. FAAY SYSTEM STEP SEQUENCE

Criteria	Factor	Case Study II: FAAY	SxF
Tool Complexety	8,51	9	76,59
Workspace Accessibility	11,48	9	103,35
Labor intensiveness	8,18	5	40,88
Connector Integration	16,29	7	114,05
Connection Type	36,00	2	72,00
Number of fasteners	12,95	9	116,55
Fragility	12,70	9	114,32
Required Operator Qualifications	5,37	9	48,30
Number of Component Types	32,33	9	291,00
Total number of Components	26,75	9	240,75
Total (Score x Factor)			1217,79
% (of ideal score)			79,33 %

	Ideal Score
9	76,59
9	103,35
9	73,59
9	146,64
9	324,00
9	116,55
9	114,32
9	48,30
9	291,00
9	240,75
	1535,08

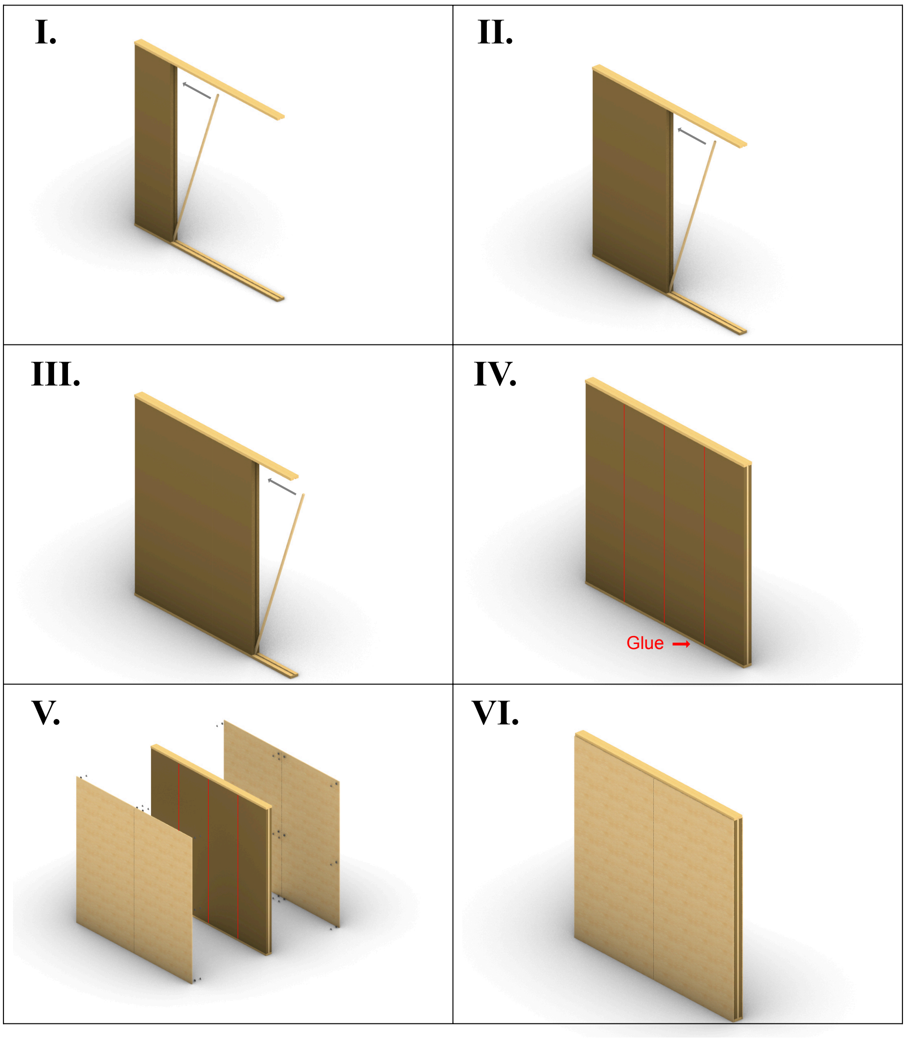


Table F2: FAAY System step sequence

3. X-FRAME STEP SEQUENCE

Criteria	Factor	Case Study III X-Frame	SxF
Tool Complexety	8,51	9	76,59
Workspace Accessibility	11,48	9	103,35
Labor intensiveness	8,18	9	73,59
Connector Integration	16,29	9	146,64
Connection Type	36,00	9	324,00
Number of fasteners	12,95	9	116,55
Fragility	12,70	9	114,32
Required Operator Qualifications	5,37	9	48,30
Number of Component Types	32,33	5	161,67
Total number of Components	26,75	5	133,75
Total (Score x Factor)			1298,75
% (of ideal score)			**84,60 %**

	Ideal Score
9	76,59
9	103,35
9	73,59
9	146,64
9	324,00
9	116,55
9	114,32
9	48,30
9	291,00
9	240,75
	1535,08

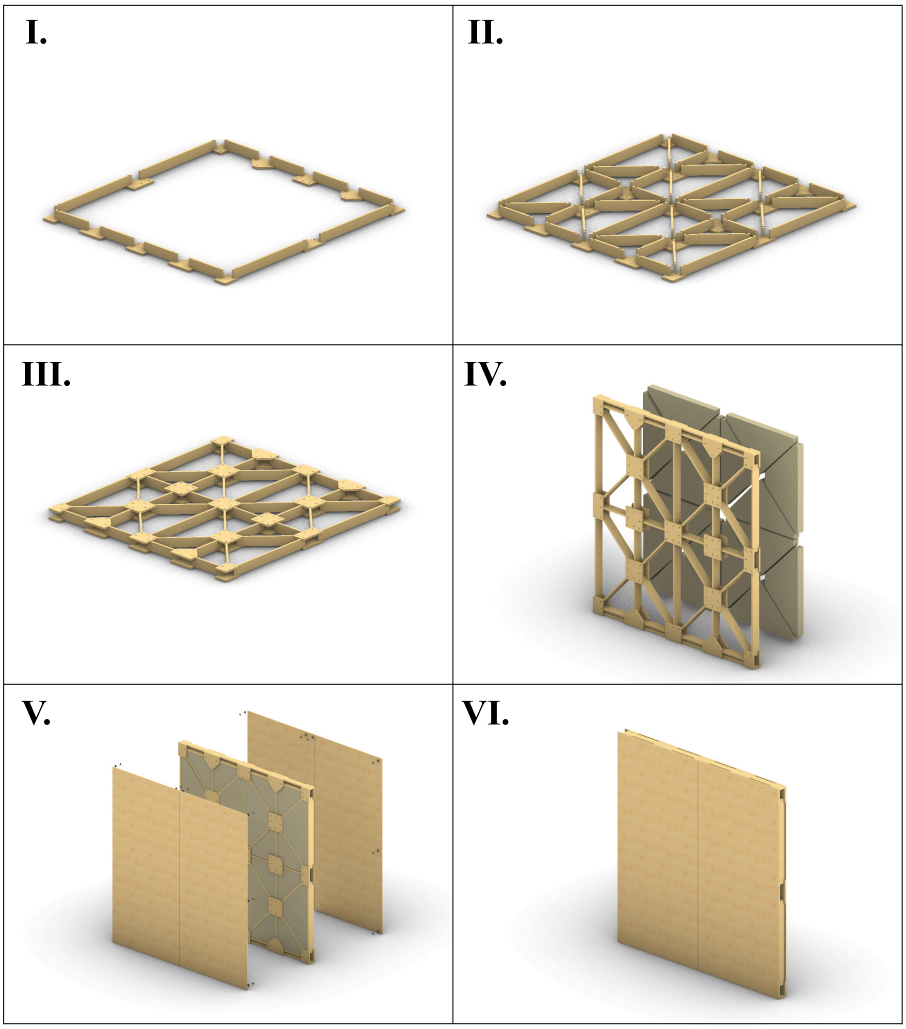


Table F3: X-Frame step sequence

4. WIKIHOUSE SYSTEM STEP SEQUENCE

Criteria	Factor	Case Study IV Wikihouse	SxF
Tool Complexety	8,51	9	76,59
Workspace Accessibility	11,48	9	103,35
Labor intensiveness	8,18	7	57,23
Connector Integration	16,29	7	114,05
Connection Type	36,00	9	324,00
Number of fasteners	12,95	9	116,55
Fragility	12,70	9	114,32
Required Operator Qualifications	5,37	9	48,30
Number of Component Types	32,33	7	226,33
Total number of Components	26,75	7	187,25
Total (Score x Factor)			1367,97
% (of ideal score)			**89,11 %**

	Ideal Score
9	76,59
9	103,35
9	73,59
9	146,64
9	324,00
9	116,55
9	114,32
9	48,30
9	291,00
9	240,75
	1535,08

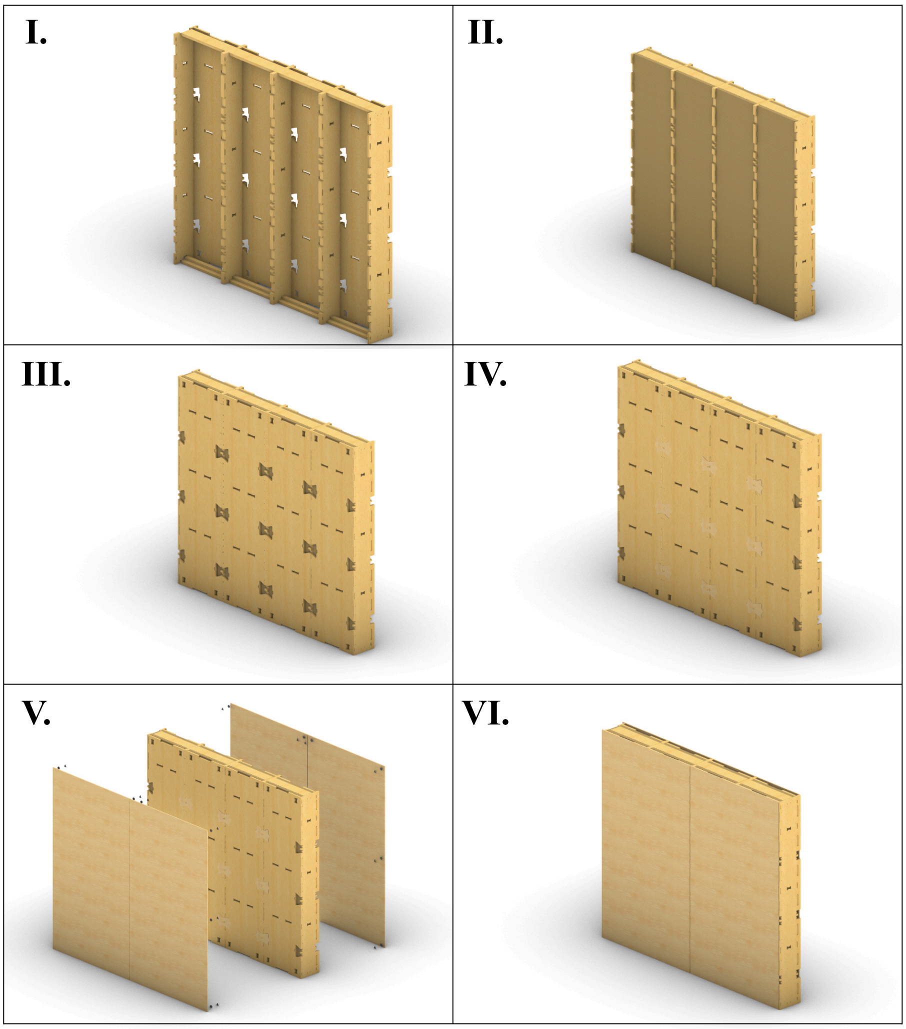
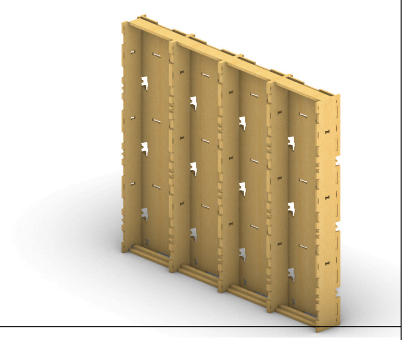


Table F4: Wikihouse step sequence

5. WIKIHOUSE ALTERNATIVE STEP SEQUENCE

Criteria	Factor	**Case Study VI:** Wikihouse Alternative (with screws)	SxF		Ideal Score
Tool Complexety	8,51	5	42,55	9	76,59
Workspace Accessibility	11,48	9	103,35	9	103,35
Labor intensiveness	8,18	7	57,23	9	73,59
Connector Integration	16,29	9	146,64	9	146,64
Connection Type	36,00	9	324,00	9	324,00
Number of fasteners	12,95	7	90,65	9	116,55
Fragility	12,70	9	114,32	9	114,32
Required Operator Qualifications	5,37	9	48,30	9	48,30
Number of Component Types	32,33	7	226,33	9	291,00
Total number of Components	26,75	3	80,25	9	240,75
Total (Score x Factor)			*1233,62*		*1535,08*
% (of ideal score)			**80,36 %**		

I.



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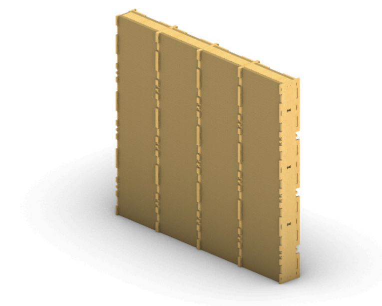

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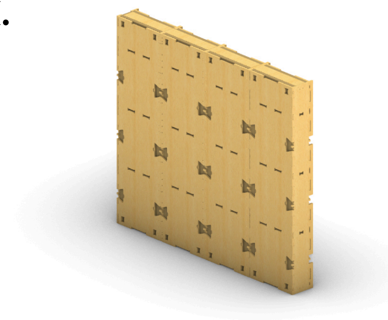

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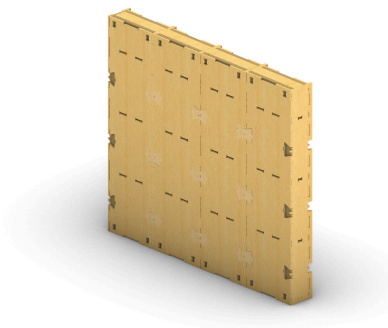

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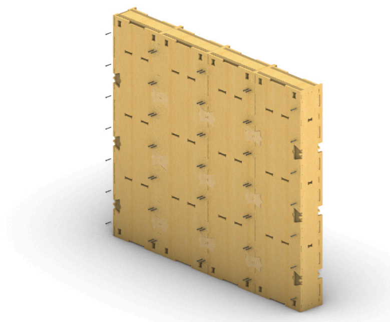

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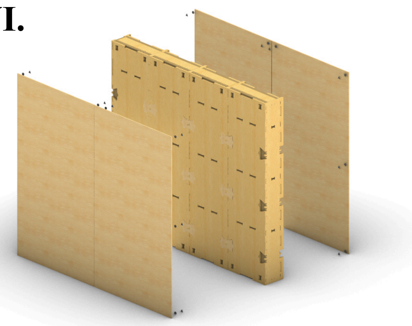


VII.

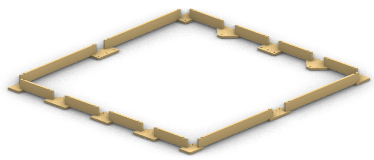
Table F5: Wikihouse Alternative step sequence

6. X-FRAME ALTERNATIVE STEP SEQUENCE

Criteria	Factor	**Case Study V:** X-Frame Alternative (with screws)	SxF
Tool Complexety	8,51	5	42,55
Workspace Accessibility	11,48	9	103,35
Labor intensiveness	8,18	9	73,59
Connector Integration	16,29	9	146,64
Connection Type	36,00	9	324,00
Number of fasteners	12,95	7	90,65
Fragility	12,70	9	114,32
Required Operator Qualifications	5,37	9	48,30
Number of Component Types	32,33	3	97,00
Total number of Components	26,75	3	80,25
Total (Score x Factor)			*1120,64*
% (of ideal score)			**73,00 %**

	Ideal Score
9	76,59
9	103,35
9	73,59
9	146,64
9	324,00
9	116,55
9	114,32
9	48,30
9	291,00
9	240,75
	1535,08

I.



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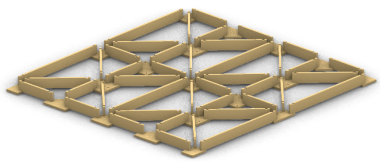

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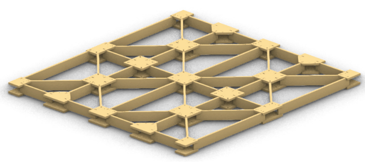

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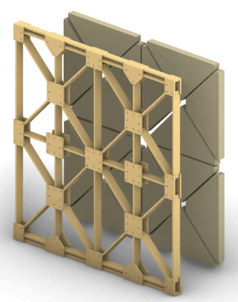

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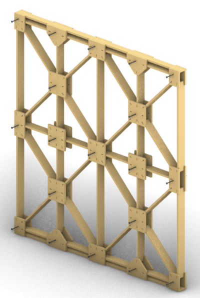

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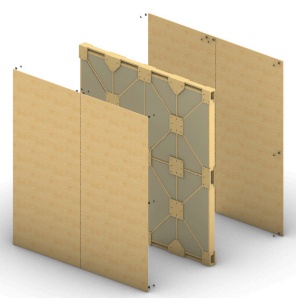


VII.

Table F6: X-Frame Alternative step sequence

Appendix G:

CRITERIA FOR EVALUATION OF EASE OF ASSEMBLY & DISASSEMBLY

Theoretical best- and worst-case scenarios are used as outlines of the rating list, with practical intermediate steps. There are some reasons to lower the score with some points, when special care, special tools or techniques are needed to accomplish the task.
The range depend on application of measure method and can therefore be changed.

Definitions:
Connector or fastener: A mechanical device for fastening together two or more pieces.

Element/Panel: A system part that is an essential part of the overall construction

1. Tool Complexety

Describtion:
Tool Complexity Rating evaluates the complexity of mechanical tools required to mount or demount the element.

Process	**Rating**
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Power tools are required	5
Special tools are required	3
Significant time delay (due to the tool complexity)	-2
Special care/techniques are needed	-1

2. Workspace Accessibility

Describtion:
The amount of access that is required to perform assembly or disassembly work.

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

3. Labor intensiveness

Describtion:
The physical intensity of work that is needed to handle the element

Process	Rating
The element is manageable with one hand (<5kg)	9
The element is manageable with two hands (5-10kg)	9
The element is liftable in accordance with working conditions (10-20kg)	7
The element requires two people to manage (20-40kg)	5
The element requires more than two people to manage (40-100kg)	3
The element is hard to grasp or manage (tool needed, flexible, slippery, long or similar)	-1
Placement above head, sitting or squatted while lifting	-1

Connectivity Rating

This criteria aims to implement more standardisation in prefabrication and therefore was implemented by the student group of Lammersen to increase the standardisation. Therefore three connectivity points were added. Connector integration, connection types and number of connectors.

4. Connectivity Rating: Connector Integration

Describtion:
The physical intensity of work that is needed to handle the element

Process	**Rating**
Connectors are fully integrated into the element	9
Connectors are partly integrated into the element, but separate connecting elements are needed	7
Connectors are not integrated into the element, but design allows for aided affixing of connectors	5
Connectors are not integrated into the element, and design does not allow for aided affixing of connectors	1

5. Connectivity Rating: Main connector type

Describtion:
The type of connector used between the elements.

Process	**Rating**
Elements are connected without dedicated fasteners (friction fit, puzzle joints)	9
Elements are connected with bolts or clips (or similar)	7
Elements are connected with screws (or similar)	5
Elements are connected with nails (or similar)	3
Elements are connected with a fixed connection, but can be detached with some difficulty (Glue or strong tape)	2
Elements are connected with a fixed connection, and cannot be detached without heavy damage	-1

6. Connectivity Rating: Number of fasteners

Describtion:
The average amount of connectors used to connect two elements to each other.

Process	**Rating**
No fasteners are needed to connect two components	9
One fastener is needed to connect two components	7
Two fasteners are needed to connect two components	5
Three fasteners are needed to connect two components	4
Four or more fasteners are needed to connect two components	1

(The range depend on application of measure method and can therefore be changed!)

Fragility rating

Fragility rating is a combination of the functional and asthetical damage rating his criteria is considering the fragility of the elements based on their detailing of the connections, material durability and geometry.

7. Damage Rating: Fragility

Describtion:
The amount of fragility the system has due to its shape, material or workflow.

Process	**Rating**
No noticeable damage when assembled	9
Assembly can cause scratches or screwholes that dont have a impact in the systems performance	7
Deep scratches or dents (or similar) which have some small impact on the performance	4
Systems is highly fragile and needs to be treated with a lot of caution due to complex shapes and deformable materials	1

8. Required Operator Qualifications

Describtion:
The Operator Qualifications rating is based on the type and amount of technical understanding and skills to work with tool complexety.

Process	**Rating**
Requires operators to have basic technical understanding and skills to operate with basic tools	9
Requires operators to have more than basic technical understanding to complete assembly	8
Requires operators to have advanced technical understanding for systems and crafting skills for handling tools	5
Requires operators to have advanced carpeting skills to finish the assembly	3

Rating factors related to number of components and repetition

High repetitions and many crafting steps can decrease the ease of assembly due to more time investment during the assembly. For this reason two more criteria will be added aiming to identify repetitions that decrease the ease of assembly due to time increase.

9. Number of Different Components

Describtion:
The exact number of different component types of a system

Process	**Rating**
Very low number of different components (≤3)	9
Low number of different components (3-5 component types)	7
High number of different components (6-8 component types)	5
Very high number of different components (9≤)	3

(The range depend on application of measure method and can therefore be changed!)

10. Total Number of Components

Describtion:
The exact number of all components of a product

Process	Rating
Very low number of total components (≤15)	9
Low number of total components (16-40)	7
High number of total components (41-80)	5
Very high number of totalcomponents (≤81)	3

(The range depend on application of measure method and can therefore be changed!)

Rating factors related to DfA and DfD

Closer descriptions of the criteria and reasons for their inclusion into the assessment and adaption to partition wall systems.

Process Description: Tool complexity
Tool complexity is a criteria that was used in the Lammersen Assessment, in the Shetty&Ali (2015) and the Güngör (2006) assessment. This criteria as adaptable for the assembly and the disassembly of a system. It describes how complex the tools that are needed for the process of mounting and demounting of a partition wall system.

Process description: Workspace accessibility
This criteria was used in the Lammersen and the Ali&Shetty (2015) assessment and refers to how well parts can be removed from an element without damaging it. Depending on the workspace accessibility a good or a bad accessibility can add or subtract time during the mounting or demounting process. In extreme cases, bad accessibility can lead to damage of the element due to potential fragility.

Process Description: Labor Intensiveness
The labor intensiveness rating was implemented by the student group of Lammersen from TU Delft. In the Shetty&Ali rating it is referred to as the "Handling rating" and relates to the graspability of an element. Building elements can be easy to work with due their lightness or very labor intensive due to their heavy weight. Therefore they should be considered during ease of assembly assessment. In the scale of partition walls the weight will be slightly adapted to lighter weights to fit into the weight range of the assessed building parts.

Rating factors related to Connectivity
This criteria aims to implement more standardisation in prefabrication and therefore was implemented by the student group of Lammersen to increase the standardisation. Therefore three connectivity points were added. Connector integration, connection types and number of connectors.

Process description: Connector Integration
Connector integration can be crucial to decrease assembly time and are a key aspect if the workflow will be automated in the future. (Lammersen, 2020) This criteria measures the degree on how

integrated the connector is into a element. In this criteria it will also be measured of additional connectors are necessary.

Process description: Connection Types
Chemical connections or not removable mechanical connections can have a negative impact on the ease of assembly. On the other hand simple mechanical connections can increase the ease of assembly and make the assembly sequence quicker. Since one of the listed case studies is including glue for the assembly, adding glue for a connection was assigned to the description “fixed connection, but removable with difficulty”.

Process description: Number of Fasteners
This criteria is the last criteria from the connectivity rating of the Lammersen assessment. This criteria refers to how many connectors are used to connect to elements with each other. A low amount of types is desirable since it leads to less assembly time.

Process description: Structure Fragility
This criteria is a combination of damage functional and aesthetical damage ratings from Lammersen research. Since this research is focusing on the ease of assembly the reuse aspect of the elements is not directly connected to this research. Therefore this criteria is considering the fragility of the elements based on their detailing of the connections, material durability and geometry. For instance will complex shapes with soft materials score lower on this criteria than a durable material with a straight forward geometry since it possible damage during the assembly which then leads to decrease of the ease of assembly.

Process description: Required Operator Qualification
The required operator qualification criteria was implemented by the Lammersen research and aims to identify the required skill of the builder or the system. Since the building industry is heavily dependent on manual labor this is a relevant criteria since it is possible that due to the shortage of skilled crafters it increases the ease of assembly if only little skill for the assembly is required so more people are able to assemble the system. It is therefore an important part of the evaluation of the ease of assembly. (Lammersen, 2020) In the case of partition walls no direct certificate is needed since the systems can be build without calculation or special carpeting skill. Therefore the description of the criteria will change towards a combination of the used tool complexity and the complexity of the system workflow.

Rating factors related to number of components and repetition

The existing labor intensiveness rating from the Lammersen research is mainly assessing the weight of the single components of the partition wall system it is necessary to take more aspects of the labor intensiveness into account in terms of repetition and handling steps.
High repetitions and many crafting steps can decrease the ease of assembly due to more time investment during the assembly. The measurement of the disassembly time and the disassembly sequence is therefore closely connected to the type of liaison between different components at each moment of the disassembly sequence. (Favi & Germani, 2014)
“Time is a common parameter used for the calculation of the indices proposed for selective disassembly. The indices also take into account cost and environmental and collateral aspects which effect the selection of a specific EOL (End of Life) scenario.” (Favi & Germani, 2014, p.311) Since time and the sequences of the assembly and disassembly are having a correlation as Favi & Germani stated it should be taken into account for the a rating for the ease of assembly.
Firstly the criteria “Number of different components” will be added to identify how many different kinds of components exist in a system.
Secondly the criteria “Number of total components” will be added. This rating will give reward systems that have a small number of components with a higher rating due to the correlation of time savings due to low repetition and the short step sequence, researched by Favi &Germani. (2014)

To create a rating for these three criteria numbers from the case studies are taken into account for creating the rating but aiming to be as general as possible for possible future use of the rating.

Process description: Number of different Components
A goal in the planning of assembly is to minimize human errors while assembling a system. Human assemblers use their skill, judgement and dexterity to complete a assembly task. For this reason parts and the assembly of a product should be planned to minimize the consequences and the chances of human error. (Bayoumi, 2000) The different number of components have a correlation to the different tasks that need to be fulfilled during the assembly of a system. According to Martin Vares, less different components will prevent confusion resulting in less assembly problems. (Vares, 2021) On the other hand a high number of different component types can possibly increase errors, for this reason the rating for the number of different component types is added to the existing methodology of Lammersen to reward systems for a low number of different component types.

Process description: Total number of Components
This criteria focusses on the correlation between step sequence and time savings explained by Favi &Germani. (2014) A lower number of total components will decrease the assembly time. (Vares, 2021) For this reason a criteria is added that will rate the total number of components of a system.

Appendix H:

FASTMOUNT.COM
PANEL MOUNTING SYSTEMS

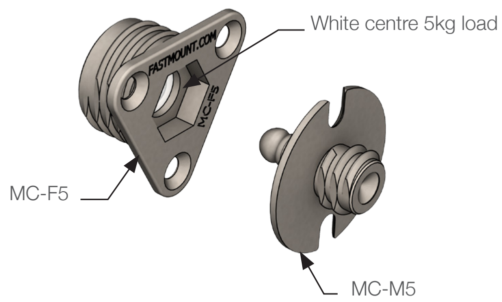
Setting the standard for panel mounting | PRODUCT SHEET

MC-05 Metal Clip Set MC-F5+MC-M5

INDUSTRY FIT:

SPECIFICATIONS: **METAL** MC RANGE

The Fastmount metal clip is designed for demanding applications that require fire protection and heavy load bearing. This versatile metal clip can be used in conjunction with our Standard range clips.



MATERIAL:
EZDA 3 triple plated, SS spring

MORE INFO:
Installation Guide FM IG_MC-05
Clip Layout Guide FM TD-02, 09, 12

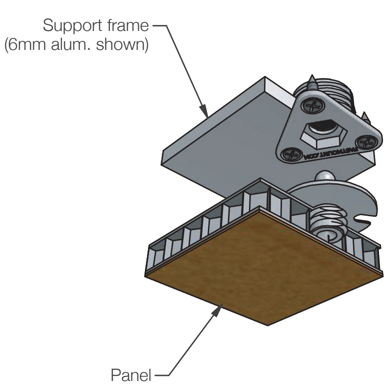
BENEFITS

- Metal clip to withstand high temperatures
- Allows for tolerance and panel flex (self centering)
- Provides acoustic and vibration isolation
- 5kg pull out load
- Self tapping and screw fit mounting options

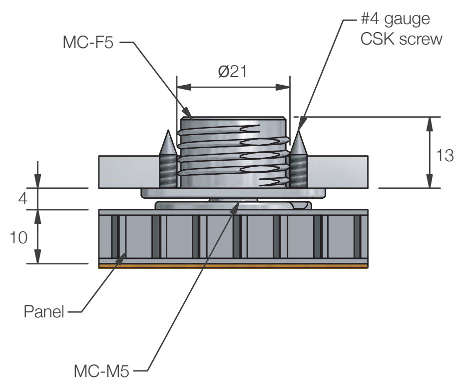
APPLICATIONS

- Fire rated panels
- Panels in fire egress paths
- Ceiling, wall and exterior panels
- Mounting of curved panels
- Variety of substrates

INSTALLATION: Partially exploded through section showing typical installation method



Cutaway exploded view (nts)



Typical section (1:1)

The Fastmount® multi-award winning system has revolutionized the mounting of panels. Panels can easily be removed and refitted in any sequence time after time. For further information or technical support contact: info@fastmount.com

www.fastmount.com

*Specification subject to change without notice, see website for updates.
PRODUCT SHEET MC-05 / DATE 0417.

PROUDLY DESIGNED & MANUFACTURED IN NEW ZEALAND

Figure H1: Fastmount click system detail