AN EVALUATION METHOD TO ASSESS DESIGN FOR SELF BUILDING OF TIMBER BUILDING SYSTEMS

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ABSTRACT

This research aims to provide information needed, regarding the implication of self building, in order to design a timber building system that is easily assembled by students. Therefore an answer is given to the question 'What is required from a timber building system to have students build their own housing' by the development of an evaluation method. Criteria are obtained from evaluation methods for Design for Assembly and Disassembly (DfA/DfD), user-friendliness, literature and interviews. Adjustments result in a new assessment method to evaluate the ease of self-building timber building systems. A multi-criteria-decision-making method is used that relies on a descriptive rating. By implementing a pair comparison chart the criteria are given value. To validate the new method several case studies are assessed. Based on this assessment can be conclude that ease of assembly, lightweight and manageable components, minimal tool complexity and safety and stability are required most from a building system that is meant for self-building.

KEYWORDS

Self-building, Assessment method, Timber building systems

1. INTRODUCTION

1.1 Problem statement

The housing deficit in the Netherlands has become a prominent problem, and projections indicate that this issue will only become more pressing in the future. Attributing to this problem are the costs of both materials and labor, which have increased. In response to these challenges, the trend of self-building has gained significant popularity over the past decade. This approach offers a potential solution to the housing crisis by enabling individuals to construct their own housing, thereby reducing dependence on traditional housing markets and associated costs.

The current housing shortage particularly affects students, especially in cities like Delft. TU Delft, a prominent university facing a rapidly expanding student population, has struggled to provide adequate on-campus housing. Despite recognising the issue, the university's efforts to address the housing shortage have been slow, with few new developments arising. Additionally, the housing crisis has not been sufficiently integrated into TU Delft's vision for a dynamic campus environment, leaving students dependent on slow third-party accommodation arrangements.

1.2 Scope and structure

This research addresses the need for feasible self-building solutions, particularly for non-professional builders such as students. The study focuses on developing and refining assessment methods to evaluate the ease of self-building timber building systems. The aim is to create a thorough and useful framework that can guide non-professionals in constructing their own homes, thereby lighten some of the housing pressures faced by students.

To achieve this, the research explores the main question *'What is required from a timber building system to have students build their own housing'* through several sub questions:

1. *What assessment methods can be used to quantify the ease of self-building?* This question involves reviewing existing methodologies in product design, such as Design for Assembly (DfA), Design for Disassembly (DfD) and Ready to Assemble (RtA), and adapting them for the built environment.
2. *How can criteria of existing methods be adjusted to be used for self-building?* Given the unique challenges of self-building, it is crucial to refine and modify the criteria used in traditional assessment

methods to suit the needs of non-professional builders. This will be done in collaboration with architects affiliated with the topic of self-building.

3. *What is required from an assessment method for Design for Self-building (DfSB)?* This question seeks to identify the essential components and considerations for developing a thorough yet user-friendly assessment tool designed especially for self-building.
4. *How useful is the assessment method for DfSB for creating guidelines?* Finally, the research evaluates the practical application of the developed assessment method in creating guidelines that can facilitate the self-building process for non-professionals.

The structure of this paper begins with a detailed review of existing assessment methods in the built environment and product design, focusing on their applicability to self-building scenarios. It then outlines the refined criteria and methodology developed for the Design for Self-building (DfSB) assessment. The paper concludes with case studies that validate the proposed assessment method, demonstrating its utility in assessing timber building systems on their ease of self-building.

All things considered, this research aims to contribute to the growing field of self-building by offering a methodical and useful evaluation method. This method offers a solution that can be adapted to various self-building contexts, potentially easing the broader housing crisis in the Netherlands.

2. ASSESSMENT METHODS

2.1 Assessment method for DfA/DfD and user-friendliness

Assessment methods in the built environment are a fairly new concept. However assessment methods regarding design for assembly and disassembly are commonly used in the field of product design. Literature shows these assessment methods are, with proper adjustment, applicable in the field of the built environment (Berends, 2021) (Lieser, 2022). However, the ability of self-building is subjective. Evidently, a licensed construction worker is able to construct housing with more ease than a non-professional. Since the design objective, related to this research, aims to have students (non-professionals) built their own housing, the ability to self build is directly related to the ease of assembly. Therefore the assessment method will be based on commonly used assessment methods for design for assembly and disassembly (DfA/DfD). To find a suitable methodology to measure the ability to self-build timber building systems different methods were taken into account.

One method for developing a rating tool for demountability that can be applied to a wide range of items is the evaluation tool of Shetty and Ali (2015). This tool includes nine different criteria for comparison. Despite the fact that this tool was designed for the field of product design is it still highly valuable, since the building systems that are tested in this research can be considered products on their own. The approach of Güngör (2006) has considerable influence for the assessment for self-building, since this method focusses on product recovery as well as connections. A combination of both approaches was proposed by Lammersen (2020) and three other former students from the TU Delft resulting in the DfR (Design for Remountability) rating method.

The methodologies that were mentioned before where influential in two methodologies designed by Lieser (2022) and Berends (2021). This research is based on these two methodologies that are designed to assess the design for assembly and disassembly of infill systems. Although both researches are based around a different scope, the criteria that derive from their literary studies can be applied to self-building. Furthermore, the introduction of Berends' topic of user-friendliness derived from assessment methods for RtA (Ready to Assemble), are highly valued for the evaluation method for design for self-building.

2.2 Criteria for DfA/DfD

Design for assembly and disassembly is a topic that is applied in different industries and products with criteria that are used in several different contexts. Therefore they can not directly be applied to the context of the case studies. Lieser (2022) mentioned this when assessing the DfR methodology from Lammersen. (2020) from the TU Delft. Five criteria can be used directly without adjustments. However due to the difference in scale between the methodology from Lammersen, Lieser's research and the context of this research several criteria, such as "Labor intensiveness" and "Required operator skill" needed adjusting. The "Labor intensiveness" rating assesses mainly the weight of individual components of a system, not the number of components to be moved during assembly or the total number of component types. High repetitions and many crafting procedures might reduce the ease of assembly by requiring more time to complete the task. The measurement of disassembly time and sequence is therefore closely related to the type of connection between various components at each stage of the disassembly process (Favi and Germani, 2014). The criterion "Total number of components" was added to the criteria to take the increased repetition of manual handling steps due to the hing number of components into account as well as the simplicity of the system and therefore the possibility to save time during assembly. Minimising the possibility of human errors while assembling a system plays a large part in design for assembly. Human assemblers use their skill, judgement and dexterity to complete the assembly. Therefore, components and the assembly of a product or system should be planned to minimise the consequences and the chances of human error (Bayoumi, 2000). Less different component will reduce the possible confusion resulting in less assembly problems (Vares, 2021). Related to the criterion "Total number of components", the "Total number of component types" rating is introduced to reward this system for a low number of different component types and the directly related complexity. Furthermore, damage can play a big role in the amount of time a system can be re-assembled. A new criterion has been introduced to assess the potential influence damage has related to the systems fragility. If during assembly the system gets damaged the "Fragility" rating will take it into account.

2.3 Criteria for user-friendliness

User-friendliness, is a new topic that was introduces by Berends (2021) in relation to design for assembly and disassembly. Interestingly this new topic provides insights on the user side of the assembly process. By exploring seven literary studies, Berends introduces a set of criteria derived from the field of usability and RtA furniture.

3. MEASURING SELF BUILDING

3.1 Assessment method design for Self-building

Since assessing self-building is a newly introduced topic, the assessment method derives from methodology related to design for assembly and disassembly and user-friendliness, as were introduced in the previous chapter. However, despite the criteria that were obtained from these methods, the hierarchy in criteria needs adjusting. In collaboration with architects M. van der Berg and C. Smink from self-building architecture firm Dondervink as well as architect Y. Warmerdam, the list of criteria were adjusted to fit the topic of self -building. Several different iterations were adopted and resulted in an average hierarchy of the criteria. Noted is that the criteria related to the user domain are prominently more important in the eyes of the self builder, see Appendix A.

3.2 Descriptive rating

To further develop the new assessment method the set of predetermined criteria needs to be converted to factors that can be rated. Factors related to the criteria were constructed the same way as was done in the research of Shetty and Ali (2015). Theoretical best- and worst-case scenarios were envisioned with practical and realistic steps in between. The method of Shetty and Ali make grading the factors between 1 and 9 possible. However, Lammersen's method that was adopted from the research from Shetty and Ali introduced a grading ranging from -2 to 9. The score -2 is used as a reduction due to a detail of a system from the score of the overall score of the criteria. See Appendix B for the descriptive rating of all criteria

Required operator skill: The required operator skill rating is based on the type and amount of technical understanding and skills to work with tool complexity.

Process	Rating
Requires operator to have no prior knowledge	9
Requires operator to have basic technical understanding and skills to operate with basic tools	7
Requires operator to have more than basic technical understanding and skills	5
Requires operator to have advanced technical understanding and skills	2
Requires operator to have advanced carpenter skills	-1

Table1: Example for the descriptive rating (image made by author)

3.3 MCDM/ PCC

Since criteria within the set can have correlation between another, either positively or negatively, the assessment has adopted a Multi-Criteria-Decision-Making (MCDM) approach, which can be described as "a branch of operational research dealing with finding optimal results in complex scenarios including carious indicators, conflicting objectives, and criteria" (Kumar et al., 2017, p.1). The Analytic Network Process (ANP) is a frequently utilised MCDM. As in Güngör's (2006) grading system, this study will adopt Saaty's ANP technique from the 1970s. Unlike the method of Shetty and Ali, a full Analytic Network Process (ANP) makes it possible to create alternative connections between criteria. Additionally, a Pairwise Comparison Chart (PCC) will also be a part of this assessment. This allows the rating to prioritise certain criteria of the evaluation method (David, 1988). This comparison chart provides each criteria with its own profile factor. This profile factor will be multiplied with the grade given to each criteria to determine its contribution to the overall score of the assessed building system. For the full pairwise comparison chart see Appendix C.

Criteria	Rating	%
Required operator skill	**64**	14,93
Tool complexity	**51,5**	12,02
Weight	**51,5**	12,02
Dimensions	**51,5**	12,02
Ability to grip	**51,5**	12,02
Workspace accessibility	**38,8**	9,05
Number of component types	**31,1**	7,26
Connector integration	**23**	5,37
Support integration	**23**	5,37
Number of fastener types	**16,6**	3,87
Connection type	**11,4**	2,66
Fragility	**7,40**	1,73
Number of components	**4,7**	1,10
Number of fasteners	**2,6**	0,61
Total	**428,6**	

Table 2: Rating for each criteria based on PCC (image made by author)

4. CASE STUDIES

4.1 Selection case studies

To validate the new assessment method, three case studies where selected. Two of the case studies have similarities and are both designed for easy assembly, even by non-professionals. The third case study acts as a reference study to validate the method even further. Despite the similarities of the systems they al show different strengths and weaknesses. These case studies were chosen because they are meant to be assembled easily as well as their use of materials, which is mainly timber. All of the chosen systems are constructed by connecting smaller components, and therefore look promising for self building. Two of the systems are produced by digital fabrication, which allows for a highly detailed innovative building system. Both are produced using a CNC-mill and both show the possibilities of this new technique that can create building systems that are easily constructed with minimal tools or knowledge. The last building system is built in a more conventional way using carpenter skills. This case study can therefore be seen as the control group, validating the different scores that were giving by the assessment.

4.2 Case studies

Basic conditions must the established so that each case has the same starting point in order to compare the three case studies. For the assessment a wall structure of approximately 3,5 x 3m (width x height) was determined. The thickness of the wall structure is inherent to the type of building system and does not influence the outcome of the assessment. Furthermore, all components and fasteners that contribute to the wall remaining upright have been included in the evaluation. And finally, the walls are not insulated or cladded in any way and are only comprised of the bare system. The full analysis can be seen in Appendix D. The first wall uses the KLIK-KLIK™ building system from CLT factory. KLIK-KLIK™ uses cross-laminated timber lightweight wall panels with unique screw-less joints, which are stronger than a traditional screw joint. The panels are made to be easy and fast to assembly even by yourself. Their so called real-world lego or DIY house walls can be assembled without any special tools, additional support construction, management or supervision in a matter of hours. (Klik-Klik – KLIK-KLIK™ Wall System, 2024). The second wall structure uses the Skylark 250 building system from Wikihouse. The open source modular building system makes it easy to design, manufacture and assemble high-performance buildings. The builder can choose from a wide array of CNC-milled building blocks, e.g. a floor system, ceiling or modular wall system with customisable openings. The building blocks are connected by CNC-cut “bowties" and slots that rely on friction to keep the components together. Depending on the use these connection can be assisted with additional screws (Wikihouse, 2023). The third wall uses a conventional timber frame construction. This system is most common to construct a simple tiber wall structure. The screwed timber frame with timer studs and bracing is clad on both sides with oriented strand board (OSB), a sheet material composed of different layers of wood chips. As mentioned before this case study was implemented as a reference for the average performance of assembly of a timber wall.

5. RESULTS

System	Total	% of ideal score
1. KLIK-KLIK™	2186.7	56,7%
2. WIKIHOUSE	3000.8	77,8%
3. TFC WALL	1755,3	43,8%

Table 3: Results of case study comparison (image made by author)

5.1 Case study assessment

The comparison of the three timber building systems give insights into the strengths and weaknesses and makes it possible to find correlations between the systems. For the full assessment with scores per criteria see Appendix E. KLIK-KLIK™ and Skylark 250 from Wikihouse are both designed with the non professional assembler in mind. Therefore these systems scored fairly high on the criteria related to the user, such as “Required operator skill”, “Tool complexity” and criteria that derive from labor intensiveness. However, Wikihouse’s take on the system results in an overall better score than KLIK-KLIK™. This is mainly because the building blocks from their skylark system are assembled from smaller parts and are therefore lighter, easier to handle by one person and easier to grip. Wikihouse scored lower for "Number of components" than KLIK-KLIK™ but the characteristics of these components resulted in a higher score for “Weight”, “Dimensions” and “Ability to grip” which are criteria that are more valued in this assessment as a result of the pairwise comparison of all criteria. So even though their is a negative correlation between these criteria, the outcome has a positive effect on the overall score as result. Furthermore the proper integration of a friction fit connection allowed Wikihouse to score higher on “connection integration” and “connector type”, evidently reducing the tool complexity and the needed skills for assembly. Resulting in the highest score for these criteria as well. Wikihouse scored highest of all systems with 77,8% of the perfect score. KLIK-KLIK™ came in second place with 56,7% of the perfect score. The conventional timber frame construction scored lowest with 43,8%, which is not that far behind KLIK-KLIK™. As mentioned before this last case was added to validate the assessment method. Interestingly the system was able to score fairly close to the second system. Despite some of the worst possible scores for “Required operator skill” and “Tool complexity” due to the fact of having to cut material to the right dimensions yourself, it score similar or higher for the next five criteria on the list. Furthermore it scored slightly higher in for “Number of fastener types”. Both systems are assembled with three different kinds of wood screws. Yet KLIK-KLIK™ also uses wedges which results in a lower score in for this criteria.

5.2 Criteria correlation

In the previous chapter 5.1 the ideal score was introduced. comparing the score of the case studies with this ideal score resulted in their percentages. Nevertheless the methodology is nog suitable to create a system that enables the highest score on each criterion resulting in an overall score of 100%. This is due to the intercorrelation of several criteria. Most criteria correlate in a similar manner. That means if it scores low on one criterion it will score low on the second criterion as well. However for some criteria this is not the case. As pointed out by Lieser (2022), the criteria derived from labor intensiveness, “total number of components” and “total number of component types” clash. For example, a systems labor intensive rating “weight" is negatively impacted by heavy panels like KLIK-KLIK™ uses, but is positively impacted by the number of types and components because it indicates the systems includes few but heavy components. A similar correlation can be seen for the other labor intensiveness criteria “Dimensions” and “Ability to grip”. Additionally few but heavy components indicate the use of specialty tools such as cranes e.g. to aid assembly. This results is a negative impact on the tool complexity rating as well as the required operator skills.

6. CONCLUSION

This research has explored the application of Design for Assembly (DfA) and Design for Disassembly (DfD) principles in the context of self-building timber housing systems. The study aims to provide a comprehensive assessment method that evaluates the ease of assembly for non-professionals, particularly students, who are involved in constructing their own housing. The methodology was adapted from established assessment tools in product design, emphasising the importance of user-friendliness and practical assembly considerations.

6.1 Key findings

The assessment methods traditionally used in product design, such as those by Shetty and Ali (2015) and Güngör (2006), were adapted to fit the context of the built environment. Lammersen's (2020) integration of these methods led to the development of a new design for remountability rating method. The criteria for DfA/DfD were refined to suit the unique demands for self-building. Adjustments were made to account for the scale and complexity of building systems, as compared to product design. Criteria were introduced or modified to ensure a comprehensive evaluation of the ease of assembly and the potential for human error minimisation. Berends’ notion to include user-friendliness as an important factor highlights the importance of considering the end-user’s experience in the assembly process. Implementing criteria derived from usability studies and Ready to Assemble (RtA) furniture design ensures the assessment to evaluate the systems not only on their technical assembly requirements but also on their user experience. The new assessment method for self-building integrates elements from different validated methodologies, creating a tool for evaluating timber building systems. The adoption of a Multi-Criteria-Decision-Making (MCDM) approach, particularly the Analytic Network Process (ANP) and Pairwise Comparison Chart (PCC), allows for a detailed assessment that prioritises criteria based on their connections and relative significance.

6.2 Validation through case studies

The validation of the assessment method was conducted through three case studies. Each case study was evaluated based on the newly refined criteria (see Appendix A), providing insights into the strengths and weaknesses of each system. *Wikihouse Skylark 250*: This system achieved the highest overall score, demonstrating high ease of assembly due to its lightweight, easy-to-handle components, and effective friction fit connections. The modular design and minimal tool requirements contributed to its user-friendliness and high overall score of 77.8%. *KLIK-KLIK™*: While also designed for easy assembly, this system scored lower than Wikihouse due to higher labor intensiveness and component complexity. Despite this, it performed well on criteria such as connector type and connection integration, resulting in a score of 56.7%. *Conventional Timber Frame Construction*: As the control group, this system scored the lowest (43.8%) due to the high skill and tool complexity required. However, it provided a useful check to validate the assessment method's ability to distinguish between systems designed for professional versus non-professional assembly.

6.3 Implications and Future Research

The findings from this research demonstrate that it is feasible to adapt product design assessment methods to the built environment, particularly for self-building scenarios. The developed assessment method provides a valuable tool for evaluating timber building systems, ensuring they are accessible and user-friendly for non-professionals.

Future research could explore further refinements to the criteria and weighting factors, as well as the application of this assessment method to a broader range of building systems and materials. Additionally, long-term studies on the practical implementation of these systems by non-professionals could provide deeper insights into the real-world effectiveness and user satisfaction of self-building solutions.

6.4 Conclusion

In conclusion, the adaptation and refinement of DfA/DfD assessment methods for the built environment have shown promising results in evaluating the ease of assembly for self-building timber systems. The integration of user-friendliness and the development of a comprehensive assessment tool offer significant potential to enhance the accessibility and practicality of self-building, contributing to more sustainable and user-centric housing solutions.

The new assessment method for Design for Self-Building (DfSB) provides the necessary information to answer the main question of this research *'What is required from a timber building system to have students build their own housing?'*. In order to have students, or non-professional, built their own housing the timber building system must meet several key requirements:

1. Ease of Assembly: The system should be designed with minimal complexity. This includes clear steps, pre-fabricated components and simple connection mechanisms.
2. Lightweight and manageable components: The components should be lightweight and easy to handle, ensuring that individual components can be moved and assembled by one or two people with our specialised equipment
3. Minimal tool requirements: The system should require none or only basic, easy accessible tools, reducing the need for specialised skills or equipment.
4. Safety and stability: The system must ensure structural integrity and safety, even when assembled by in-experienced builders, to prevent accidents and ensure long-term durability.

By fulfilling these requirements, a timber building system can effectively empower students to build their own housing, addressing both their immediate accommodation needs and contributing to broader housing solutions.

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APPENDIX A.

CRITERIA FOR DESIGN FOR SELF BUILDING (DFA/DFD/USER-FRIENDLINESS)

Dondervink (M. van der Berg & C. Smink)	Y. Warmerdam	G. de Graaf (author)	Average	Criteria for DfSB
1. Workspace accessibility	1. Required operator skills	1. Required operator skills	1. Required operator skills	1. Required operator skills
2. Connection integration	2. Labor intensiveness	2. Labor intensiveness	2. Tool complexity / Labor intensiveness	2. Tool complexity / weight / dimension / ability to grip
3. Required operator skills	3. Tool complexity	3. Tool complexity	3. Workspace accessibility	3. Workspace accessibility
4. Tool complexity	4. Number of component types	4. Workspace accessibility	4. Number of component types	4. Number of component types
5. Number of component types	5. Connection type	5. Number of component types	5. Connection integration	5. Connector integration / support integration
6. Labor intensiveness	6. Workspace accessibility	6. Connection integration	6. Connection type	6. Number of fastener types
7. Connection type	7. Connector integration	7. Connection type	7. Fragility	7. Connection type
8. Fragility	8. Fragility	8. Fragility	8. Number of components	8. Fragility
9. Number of components	9. Number of components	9. Number of components	9. Number of fasteners	9. Number of components
10. Number of fasteners	10. Number of fasteners	10. Number of fasteners		10. Number of fasteners

The average of the criteria was established in collaboration with three architects. The criteria used for this came from methods for design for assembly and disassembly (DfA/DfD). However since the introduction of Berend's (2021) topic of user-friendliness more criteria were adopted and used for the development of the assessment for design for self-building.

Labor intensiveness has been divided into three criteria; weight, dimensions, ability to grip. This was done to include more of the users experience. Furthermore the connection integration also includes support integration. And finally, similar as the criteria number of component types that derives from number or components a new criteria derives from number of fasteners, namely number of fasteners types.

APPENDIX B.

DESCRIPTIVE RATING CRITERIA FOR DESIGN FOR SELF BUILDING

The criteria of this evaluation method are based on prior evaluation method regarding design for assembly, design for disassembly and user-friendliness. From these methods several criteria were adopted to construct the evaluation method for self building. The criteria can be divided in two groups. The first being criteria related to the end user or builder in this scenario and the second being criteria related directly to the building system.

User perspective criteria

1. Required operator skill

The required operator skill rating is based on the type and amount of technical understanding and skills to work with tool complexity.

Process	Rating
Requires operator to have no prior knowledge	9
Requires operator to have basic technical understanding and skills to operate with basic tools	7
Requires operator to have more than basic technical understanding and skills	5
Requires operator to have advanced technical understanding and skills	2
Requires operator to have advanced carpenter skills	-1

2. Tool complexity

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

Process	Rating
Tools are not required; task can be done by hand	9
Common hand tools are required	8
Power (hand)tools are required	6
Power tools are required	3
Special tools are required	-1
Special care/techniques are required	-1
Heavy machinery is required	-2

Labor intensiveness
Since labor intensiveness can be rated in many ways, usually it is measured only regarding the weight the end user has to lift. To be more precise, this evaluation method introduces 3 criteria regarding labor intensiveness; weight, dimension and ability to grip or hold components.

3. Weight
Physical insensitivity of work that is needed to handle one component

Process	Rating
Component is liftable with one hand (<5kg)	9
Component is liftable with two hands (5-10kg)	8
Components is liftable in accordance with working regulation (10-25kg)	7
Component requires two people to lift (20-42,5kg)	5
Component requires more than two people to lift (42,5-100kg)	1
Component requires machinery to lift (101kg≤)	-2

4. dimensions components
Ease of handling derived from the scale of an average adult

Process	Rating
Component is movable be hand easily (≤1000x600x100, lxbxd)	9
Component is movable by one person (≤2600x600x100, lxbxd)	7
Component is movable by two people	5
Component is movable by three to four people	3
Component is only movable with machinery	-1

5. Ability to grab/hold components
Ease of handling due to available grip on component

Process	Rating
Components are easy to grip by themselves	9
Components are easy to grip, handles or lifting facilities are integrated	7
Components are not so easy to grip and have to be handled carefully	5
Components are hard to grip, small equipment is needed (gloves or similar)	3
Component are very hard to grip, large equipment is needed (supporting structure or similar	1

6. 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 (<5cm)	9
The task requires space or hands or small hand tools (<20cm)	7
The task requires space for (powered) hand tools	5
The task requires space for specialty tools	-1
The task has to be performed blind	-1
One element has to be removed to access area	-1
Multiple elements have to be removed to access area	-2

7. Support integration

The physical intensity of work that is needed to support the component before fixing

Process	Rating
Support is integrated into component	9
Support is added to component to fix second component	7
Components have to be held by assembler before fixing, this can be easily done	5
Components have to be held by assembler before fixing, this can be hard to do	3
Components have to be held by assembler, extra people are needed to fix it in place	1

System criteria

8. Connector integration
The physical intensity of work that is needed to handle the element

Process	**Rating**
Connectors are fully integrated	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	3
	1

9. Connection type
The type of connector used between components

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

10. Number of component types
Exact number of different components used for 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 depends on the application of measure method and can therefore be changed

11. Number of components
Exact number of all components in a system*

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

*The range depends on the application of measure method and can therefore be changed

12. Number of fastener types
Exact number of all fastener types in a system*

Process	Rating
No fasteners are needed to connect the system	9
One type of fastener is needed to connect the system	7
Two types of fasteners are needed to connect the system	5
Three fasteners are needed to connect the system	3
Four or more fasteners are needed to connect the system	1

*The range depends on the application of measure method and can therefore be changed

13. Number of fasteners
Exact number of all fastener in a system*

Process	Rating
No fasteners needed	9
Very low number of total fasteners (≤15)	7
Low number of total fasteners (16-40)	5
High number of total fasteners (40-80)	3
Very high number of total fasteners (81≤)	1

*The range depends on the application of measure method and can therefore be changed

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

Process	Rating
No noticeable damage when assembled	9
Minor damage that has no impact on systems performance	7
Damage that has small impact on systems performance	4
System is highly fragile, damage will have major impact on systems performance	1

APPENDIX C.

PAIRWISE COMPARISON CHART

	Workspace accessibility	Tool complexity	Required operator skill	Ability to grip	Weight	Dimensions	Connector integration	Support integration	Number of components	Number of component types	Number of fasteners	Number of fastener types	Connection type	Fragility	**Rating**	%
Workspace accessibility		1/2	1/3	1/2	1/2	1/2	3	3	7	1/2	8	4	5	6	**38,8**	9,05
Tool complexity	2		1/2	1	1	1	4	4	8	3	9	5	6	7	**51,5**	12,02
Required operator skill	3	2		2	2	2	5	5	9	4	9	6	7	8	**64**	14,93
Ability to grip	2	1	1/2		1	1	4	4	8	3	9	5	6	7	**51,5**	12,02
Weight	2	1	1/2	1		1	4	4	8	3	9	5	6	7	**51,5**	12,02
Dimensions	2	1	1/2	1	1		4	4	8	3	9	5	6	7	**51,5**	12,02
Connector integration	1/3	1/4	1/5	1/4	1/4	1/4		1	5	1/2	6	2	3	4	**23**	5,37
Support integration	1/3	1/4	1/5	1/4	1/4	1/4	1		5	1/2	6	2	3	4	**23**	5,37
Number of components	1/7	1/8	1/9	1/8	1/8	1/8	1/3	1/3		1/6	2	1/4	1/3	1/2	**4,7**	1,10
Number of component types	1/2	1/3	1/4	1/3	1/3	1/3	2	2	6		7	3	4	5	**31,1**	7,26
Number of fasteners	1/8	1/9	1/9	1/9	1/9	1/9	1/4	1/4	1/2	1/7		1/5	1/4	1/3	**2,6**	0,61
Number of fastener types	1/4	1/5	1/6	1/5	1/5	1/5	1/2	1/2	4	1/3	5		2	3	**16,6**	3,87
Connection type	1/5	1/6	1/7	1/6	1/6	1/6	1/3	1/3	3	1/4	4	1/2		2	**11,4**	2,66
Fragility	1/6	1/7	1/8	1/7	1/7	1/7	1/4	1/4	2	1/5	3	1/3	1/2		**7,40**	1,73
														Total	**428,6**	

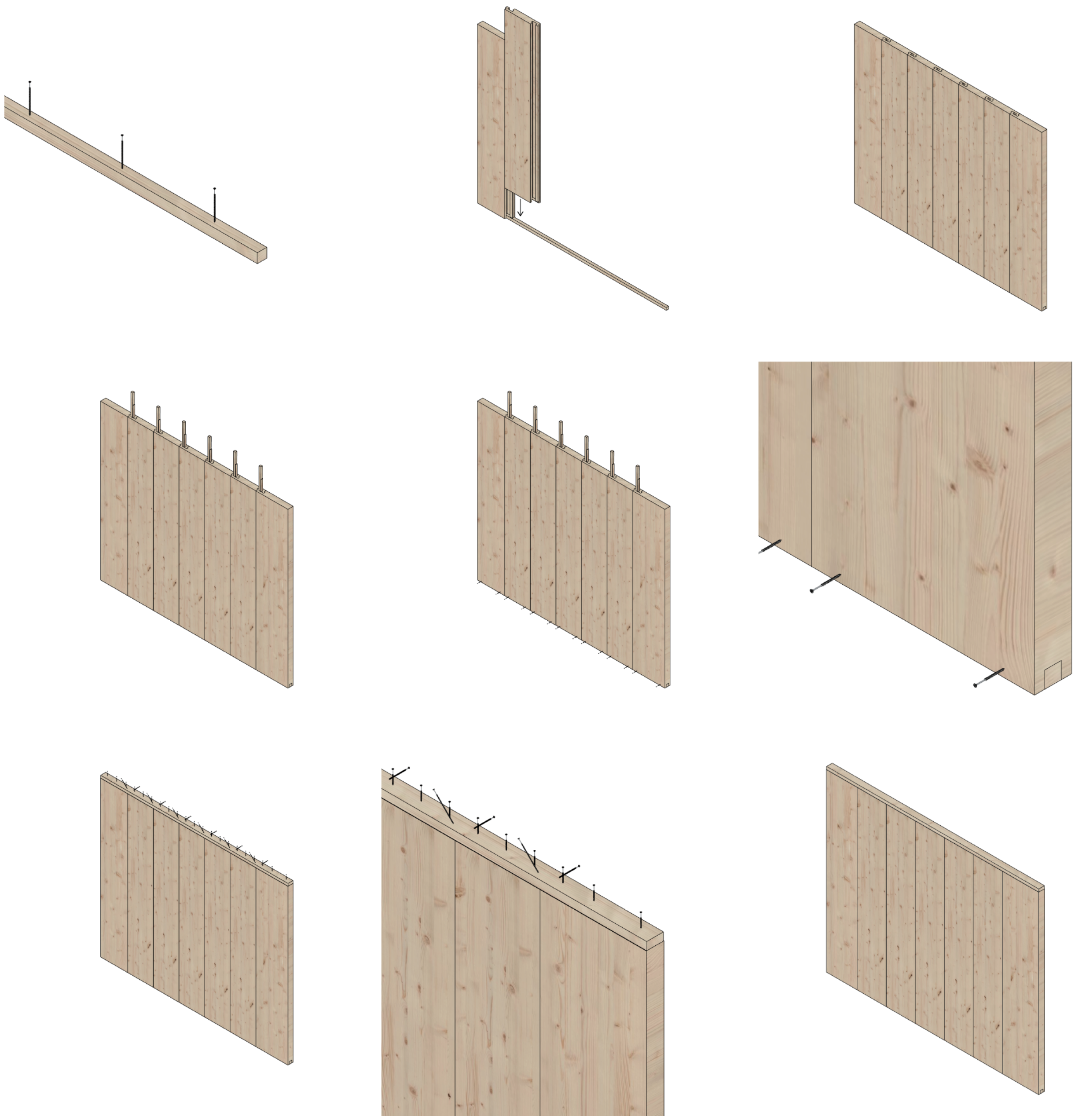
Intensive of importance	Definition	Eplanation
1	Equal importance	Two criteria contribute equally to the objective
3	Moderate importance	One criteria is slightly favoured over another
5	Strong importance	One criteria is strongly favoured over another
7	Very strong importance	One criteria is very strongly favoured over another
9	Extreme importance	One criteria is favoured over the another in the highest possible order of affirmation
2,4,6,8		Intermediate values between two adjacent values

APPENDIX D.
CASE STUDY ANALYSIS

1. KLIK-KLIK™

KLIK-KLIK by CLT factory brings CLT, a material that is very popular currently, to the hands of the non professional. The system of KLIK-KLIK comprises of 16 CLT panels that can be used to construct housing to the user needs. For the case study comparison a wall was tested with the approximate measurements of 3,5 x 3m (width x height).
First a 45x45mm batten is anchored to the floor with eight 8x140mm wood screws. Next the wall panels can be placed on top of this batten. The starting and ending panel is the CLT-15 and the five panels between are the CLT-01. Both panels range between 65.5 and 72.5 kg. Next the panels are pulled together by using 12 wedges, 2 for every connection. The wedges are hammered from the top to create a tight friction fit between two panels. After the wedges are in place, the excess can be cut flush with a saw. Then for extra security every panel gets attached to the batten with two 6x80mm wood screws on each side. Finally a 95x45mm roof batten is attached using the same 6x80mm wood screws. Every panel gets fastened with three screws. To complete the wall structure, every seem between two panels gets two extra 8x160mm wood screws fastened on a 45 degree angle to ensure a tight connection.

To sum up; for this wall the KLIKKLIK system uses 9 components of 4 different types and 81 fasteners of again 4 different types.

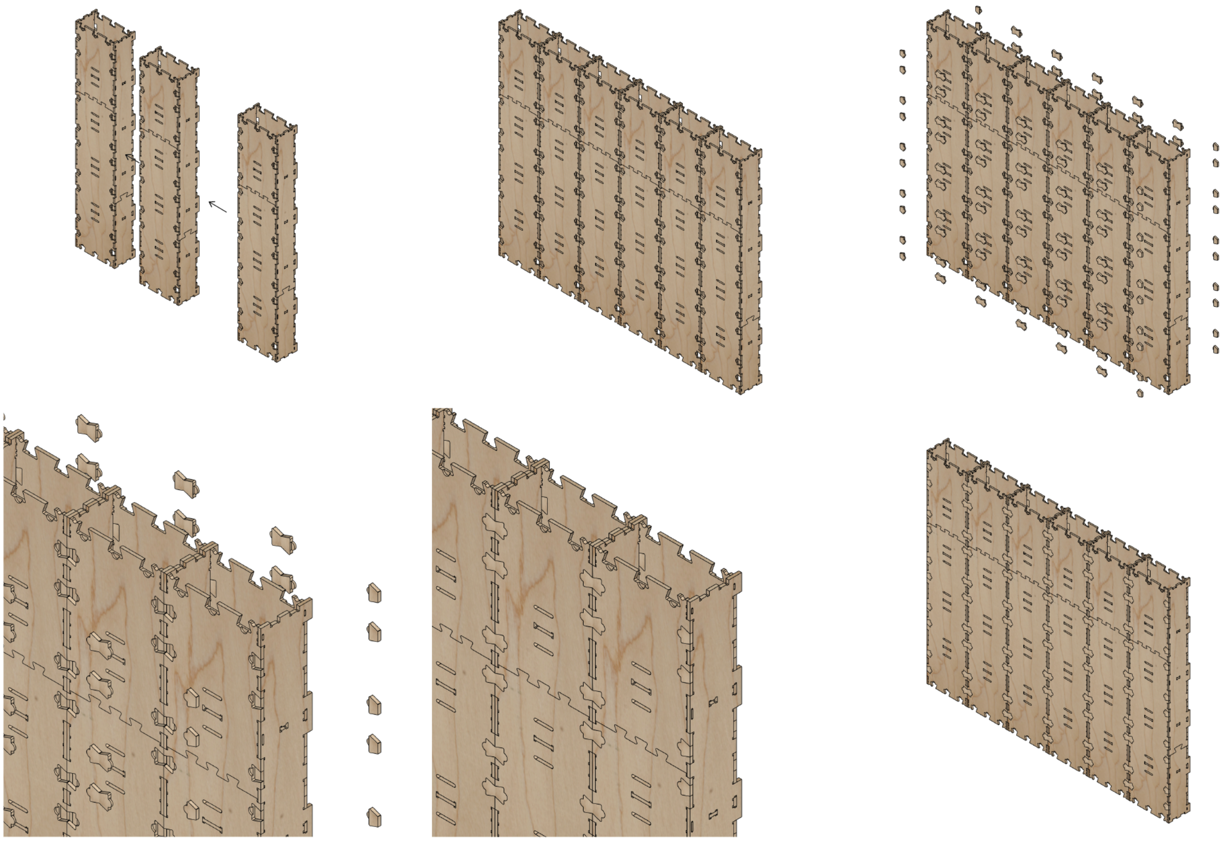


2. WIKIHOUSE

The skylark 250 system of wikihouse is comprised of a wide array of building block that comprise of CNC-milled spruce plywood panels. The system includes roof, floor and modular wall systems that can be used to design stand alone houses up to two stories. For the case study comparison a wall was tested with the approximate measurements of 3,5 x 3m (width x height).

First the wall blocks are stacked next to each other. Every building block is made from 8 panels of 4 different types and is circa 40kg. Next the building block are connected with bowties that rely on friction to join the wall blocks to each other. Every seem gets 10 bowties, which resulted in 100 bowties for this wall structure. Additionally the ends of the wall blocks were closed of with 40 half-bowties.

To sum up; for this wall the skylark 250 system of wikihouse uses 6 wall blocks, which are made from 8 components of 4 different types and 140 fasteners of 2 different types.

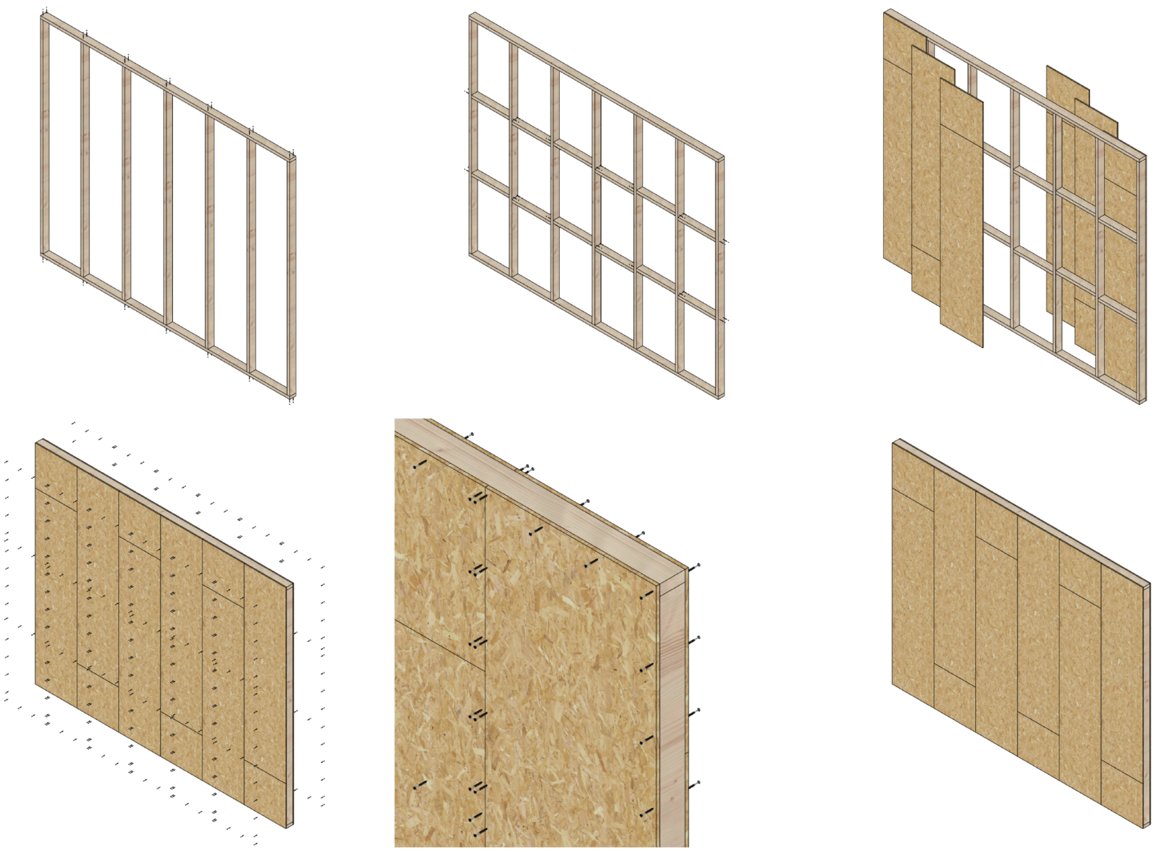


3. TFC WALL

The conventional timber frame construction is not a system. Prior to installing al component need to be cut to size. Therefore this wall requires some carpenter skills that are not necessary for the other two wall systems. For the case study comparison a wall was tested with the approximate measurements of 3,5 x 3m (width x height).

First a frame is constructed using two 39x89mm horizontal beams and seven vertical slats with the same dimensions. This frame is screwed together using wood screws, two for every joint. Secondly, the frame is reinforced with bracing that is staggered a little to allow for screws on each side and secured in place using the same screws as before. Just as the KLIKKLIK wall the frame is anchored to the floor using similar wood screws. Then the frame is cladded on both sides with 12mm oriented strand board (OSB). The OSB has a tongue and groove which allows for staggering of the sheet material. The 24 OSB components are fastened alongside its edges with wood screws every 15-20cm. The sheets OSB are the largest and heaviest components of this wall structure with dimensions of 600x2440x12mm and a weight of approximately 10kg.

To sum up; for this wall the conventional timber frame construction uses 45 components of 2 types and 564 fasteners of 3 different types.



APPENDIX E.
ASSESSMENT RESULTS

	Factor	%
Required operator skill	**64**	14,93
Tool complexity	**51,5**	12,02
Weight	**51,5**	12,02
Dimensions	**51,5**	12,02
Ability to grip	**51,5**	12,02
Workspace accessibility	**38,8**	9,05
Number of component types	**31,1**	7,26
Connector integration	**23**	5,37
Support integration	**23**	5,37
Number of fastener types	**16,6**	3,87
Connection type	**11,4**	2,66
Fragility	**7,40**	1,73
Number of components	**4,7**	1,10
Number of fasteners	**2,6**	0,61
Total	**428,6**	
Ideal score (428,6 x 9)	**3857.4**	

KLIK-KLIK™	Factore	Score	SxF
Required operator skill	**64**	7	448
Tool complexity	**51,5**	6	309
Weight	**51,5**	1	51,5
Dimensions	**51,5**	5	257,5
Ability to grip	**51,5**	5	257,5
Workspace accessibility	**38,8**	5	194
Number of component types	**31,1**	7	217,7
Connector integration	**23**	7	161
Support integration	**23**	5	115
Number of fastener types	**16,6**	1	16,6
Connection type	**11,4**	5	57
Fragility	**7,40**	7	51,8
Number of components	**4,7**	9	42,3
Number of fasteners	**2,6**	3	7,8
Total (score x factor			2186,7
% (of ideal score			**56.7%**

WIKIHOUSE	Factor	Score	SxF
Required operator skill	**64**	9	576
Tool complexity	**51,5**	9	463,5
Weight	**51,5**	5	257,5
Dimensions	**51,5**	5	257,5
Ability to grip	**51,5**	7	360,5
Workspace accessibility	**38,8**	7	271,6
Number of component types	**31,1**	7	217,7
Connector integration	**23**	9	207
Support integration	**23**	5	115
Number of fastener types	**16,6**	7	116,2
Connection type	**11,4**	9	102,6
Fragility	**7,40**	4	29,6
Number of components	**4,7**	5	23,5
Number of fasteners	**2,6**	1	2,6
Total (score x factor			3000,8
% (of ideal score			**77.8%**

TFC WALL	Factor	Score	SxF
Required operator skill	**64**	-1	-64
Tool complexity	**51,5**	-1	-51,5
Weight	**51,5**	8	412
Dimensions	**51,5**	7	360,5
Ability to grip	**51,5**	5	257,5
Workspace accessibility	**38,8**	5	194
Number of component types	**31,1**	9	279,9
Connector integration	**23**	3	69
Support integration	**23**	3	69
Number of fastener types	**16,6**	3	49,8
Connection type	**11,4**	5	57
Fragility	**7,40**	4	29,6
Number of components	**4,7**	5	23,5
Number of fasteners	**2,6**	1	2,6
Total (score x factor			1688,9
% (of ideal score			**43,8%**