An Evaluation method to assess User-friendly Design for Assembly and Disassembly of Modular infill systems

A research towards the direct involvement of residents in circular building systems

Research paper

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Contents

AN EVALUATION METHOD TO ASSESS USER-FRIENDLY DESIGN FOR ASSEMBLY AND DISASSEMBLY OF MODULAR INFILL SYSTEMS

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ABSTRACT

This research aims to increase the demand for a circular built environment by taking a user-perspective. To achieve this goal, building components should become part of the intrinsic motivation of the user. Therefore, an answer is given to the question 'What are the preconditions for user-friendly design for assembly and disassembly of modular infill systems?' by the development of an evaluation method. First, the criteria for Design for Assembly & Disassembly (DfA/DfD) and user-friendliness are defined by means of literature. Secondly, existing methods within these fields are studied as a starting point for the development of the evaluation method. The method is then tested on partitioning wall systems and improved based on practical experience. As a result, the evaluation method proved usable. Therewith the method provides first insights into a modular infill system's ease of DfA/DfD by the unskilled end-user and serves as concrete guidelines in circular product development.

KEYWORDS

Circularity, design for assembly & disassembly, user-friendliness, evaluation method

I. INTRODUCTION

The shift from a sustainable built environment to a sustainable and circular environment becomes increasingly important. Studies, literature and media address manufacturers and companies to increase knowledge around circular solutions and process integration. The, most of the time, not-part-of-the-building-process end-user is overlooked. As Geldermans, Tenpierik, and Luscuere state in their research in 2019: 'As long as residents feel not sufficiently incentivized to demand more co-creative power, the building sector does not feel inclined to contest traditional methods, and authorities refrain from implementing legally binding measurements.' This, together with the fact that the end-user causes the demand of the buildings that are built, points out that awareness among this group is needed. In sustainable solutions such as solar panels on the contrary, user-integration to raise awareness, knowledge and show potential benefits, is far more common. Next to this, studies on Ready-to-Assemble (RtA) furniture in the field of product design show that when the assembly is experienced as pleasant, these kinds of designs can add value to a product (Norton, Mochon, Ariely, 2012). This so-called 'IKEA-effect' will then enhance the intrinsic motivation of people to adopt such systems.

Modular infill systems have a great potential to connect the two key aspects of circularity and the ability to be assembled by the end-user. Geldermans et al. (2019) already started with the study of the synergistic potential between the circular design of flexible partitioning systems and user-benefits. However, no in-depth study was done on how end-users could engage with the system to make it part of their intrinsic motivation. The research therefore focuses on both circularity, in the field of DfA/DfD, and the user-friendliness of such systems. As a result, the research aims to develop an evaluation method to provide product developers of modular infill systems first insights of a products ease of DfA/DfD by the unskilled end-user. Subsequently, the evaluation method could then serve as concrete guidelines in circular product development.

1.1 Definitions

During the research, it appeared that different terms were used for the same definition. To provide clarity, the terms and the corresponding definitions that are used within the paper are described below.

- Modular infill system – an interconnected set of elements that define the interior within the different spaces of a building. More important, the elements can be easily assembled as well as disassembled without damage and are interchangeable. The system refers to all elements that belong to the fixed interior of a building. For an apartment it would include partitioning walls, the kitchen and sanitary.
- System - an interconnected set of components that is coherently organized in a way that achieves something. A system must consist of three kinds of things: components, interconnections, and purpose (adapted from Meadows, 2008; in Geldermans 2020).
- Product – a separately available set of components and connectors that is part of a system (for example: one module of a partitioning wall system or one module of a kitchen).
- Component – part of a product other than a connector.
- Connector – a part of a product that connects two or more components.
- Parts – referring to both components and connectors.

1.2 Scope of the research

The research aims to support the transition towards a circular built environment taking a user-perspective. This approach let to the following frames:

- The research has its focus on a product level and specifically modular infill systems. These are part of what Habraken (1961) called the 'infill' and will be changed every 3 till 30 years.
- Within the circular life cycle of a product as defined by the European Commission in 2020, the research focuses on the consumption and waste prevention phase. The consumer is addressed by studying the topic of user-friendliness in RtA furniture and usability. Waste prevention is dealt with by the topic of circularity concerning DfA/DfD.

1.3 Research structure

To give the end-user the opportunity to make modular infill systems part of their intrinsic motivation and to get started with these products, the aim of the research is to give an answer to the question: *'What are the preconditions for user-friendly design for assembly and disassembly of modular infill systems?'* Based on the development of an evaluation method, a first attempt is made to formulate concrete guidelines for designers, product developers and manufacturers. This is done in six steps:

1. Identification of the criteria for DfA/DfD and user-friendliness on the basis of literature.
2. Exploration of existing evaluation methods for circularity or user-friendliness in literature.
3. Development of the evaluation method by the conversion of the criteria into rating factors with a corresponding score.
4. Performing a first attempt for validation of the method by testing various partitioning walls.
5. Refinement of the method with the results from the evaluation of the partitioning walls.
6. Reflection on the method and formulation of recommendations for future research.

II. CRITERIA FOR DFA/DFD AND USER-FRIENDLINESS

2.1. Design for Assembly and Disassembly

2.1.1. Development of DfA/DfD

The first subtopic of this paper that was studied, comprised the field of DfA/DfD. First research within this area focused on the design for assembly. To decrease manufacturing costs, guidelines and methods for measurement were developed to minimize manual or machinal operations (Boothroyd, Alting, 1992). When environmental concerns raised, Boothroyd and Alting (1992) noticed a shift towards approaches that address DfA as well as DfD. This enabled products to be part of recycling processes due to easier maintenance and the possibility for dismantling. The new approach considered not only

the design and the manufacturing phase of a product, but included all life-cycle phases, affecting the end-user as well as the society. With the current shift from sustainable design towards sustainable and circular design, the topic of 'the design for disassembly' gets more prominent. The possibility to dismantle an object after its operational phase facilitates in the preservation of objects and its resources within life cycles (Van Vliet, Van Grinsven, Teunizen, 2019).

2.1.2. Criteria for DfA/DfD of building products

The criteria that are required for DfA/DfD were found by comparing ten different literature studies. These studies were found via co-students and tutors within the faculty of Architecture, colleagues in the field of Architecture, the online databases TU Delft Repository, Research Gate and Science Direct and within the literature itself. Because the paper focuses on the use- and the reuse-phase of a product, the literature was filtered for the criteria specifically related to this (see appendix A).

During the selection, it appeared that to a large extent the criteria were related and interconnected to each other. This made the selection of a set requirements harder to define. First, it was noted that some criteria that were mentioned as a requirement for the DfA/DfD, were criteria that primarily belong to material-use. Since the scope of the research focuses on DfA/DfD, these criteria were omitted from the list of criteria that can be found in appendix B.

Secondly, seven of the requirements could be seen as a direct result of other criteria and were therefore also left out of the final list. An example of this is 'simplify the product structure' that is covered in the criteria aiming for 'minimizing the number and variety of components and connectors', 'the use of market-standard connections and dimensions' and within 'the use of modular systems'.
The criteria concerning 'damage resistant connectors and components' were mentioned only three times in the found literature. Since they will help maximize the potential of the object to be reassembled without a decrease in functional or aesthetic value, they are part of the final list.

Lastly, a difference was made within the studies concerning the number of components and the number of connectors. Research that studied the criteria for DfA/DfD related to the built environment did not mention the first aspect as opposed to studies done in the field of product development. Because the research focuses on a product level, this aspect does apply. Similar, criteria regarding to the building as a whole, formulated in for example Guy and Ciriamboli (2005), were not included.

To provide a clear overview, the criteria were subdivided into two categories, based on the three categories identified by M. van Vliet (2018). Herein, technical aspects refer to the characteristics of the design. Process-related aspects refer to the conditions that secure the (dis)assembly of a design and financial aspects relate to the financial feasibility of the process (Van Vliet et al. 2019). Since the research focuses itself on the use-aspects of the design, financial aspects were left out.

2.2. User-friendliness

The second topic that is addressed in the research, and newly introduced in the field of circularity, is user-friendliness. First, the topic is explored in literature in the field of Usability and RtA furniture. These literature studies were found in the online databases TU Delft Repository, Research Gate and Science Direct. Based on the acquired knowledge, a set of criteria is composed out of seven literature studies (see appendix C&D).

2.2.1. Development of Usability

In literature, 'user-friendliness' can be originally found as the term 'usability'. Although it is referred to as the usability of products, it is mainly associated with user interfaces of computer systems. Usability is considered as a quite fuzzy and subjective concept to work with (Van Kuijk, Van Driel, Van Eijk, 2015; Quesenbery, 2001; Seffah, Donyaee, Kline, Padda, 2006). In scientific literature, the term 'usability' is often split into several subtopics to provide guidance on how to apply the term to a particular system or product. For each of these subtopics, corresponding goals, criteria and requirements can be formulated, each of which can be assessed.

2.2.2. Criteria for Usability

The set of subtopics formulated by Nielsen (1993) clarifies best how usability can be related to circular and user-friendly modular infill systems. The set divides usability in the five quality attributes 'learnability', 'efficiency', 'memorability', 'errors' and 'satisfaction'. The studies researching 'usability' are looking for ways how a system could be used most easily repeatedly. Similar, a circular use of modular infill systems asks not only for the ease of assembly and disassembly just once, but especially to be reassembled several times. This requires the end-user to become familiar with composing the system. The system itself should provide in easy to learn and easy to remember assembly and disassembly principles, tolerances for error recovery and promote satisfaction (figure 1). Evaluating the formulated criteria with these subtopics adds value to the research. This will provide in a deeper and better understanding of the process-related aspects of the concept and will help to formulate the corresponding rating factors in the next section.

promote	**Learnability**	-	ease to master features required for assembly and disassembly
promote	**Efficiency**	-	speed to perform the task
promote	**Memorability**	-	the ease to perform assembly and disassembly again after a period in which it was not performed
prevent	**Errors**	-	mistakes that are made during assembly and disassembly
promote	**Satisfaction**	-	the amenity the user experience before, during and after assembling or disassembling the object

Figure 1. The five quality attributes that define 'usability', formulated by Nielsen in 1993 and adjusted to fit with the subjects of assembly, disassembly and reassembly (image made by the author).

2.2.3. Development of Ready-to-Assemble furniture

Secondly, user-friendliness is found in research that studies the ease of assembly of RtA furniture by reducing complexity. Although this is only about assembly just for once, the studies focus on the target group chosen for this research; the unskilled end-user. Next to this, the studies relate to the scale of products the paper is searching for. Finally, the steady environment in which the assembly of RtA furniture takes place, corresponds with the setting the modular infill systems will be assembled, disassembled and reassembled in.

2.2.3. Criteria for Ready-to-Assemble furniture

Comparing the criteria of RtA furniture with the criteria for DfA/DfD, the criteria relating to the characteristics of the product are mostly the same. New criteria mainly apply to the process of assembling and so to the characteristics of the user. Human factors principles recognized by Richardson, Jones and Torrance in respectively 1998 and 2006 and Helander and Willen in 1999, are converted into criteria that can be applied to the physical object. This concerns information processing, diagrams and illustrations in instructions and human cognition. An example of a criteria this applies to is 'minimizing the variety of parts'. When achieving this, the cognitive load, defined as the required working memory of a user to complete a task, will be reduced. Also, minimizing the variety of parts means that parts and corresponding operations are repetitive. This will accelerate the time the assembly and disassembly process is learned, recognized and memorized for a next time.

These links between the criteria for user-friendliness and the five quality attributes of usability can also be established with the criteria for DfA/DfD. For instance, 'minimize the number of components' can decrease assembly time and required working memory. It can increase efficiency as well as learnability and memorability, causing the user to be more satisfied with the result. The different criteria touch upon different combinations of attributes. As a natural consequence, the promotion of user satisfaction is achieved by all criteria. The interrelations between the criteria for DfA/DfD and user-friendliness are documented in appendix E.

2.3. Criteria for DfA/DfD and User-friendliness

Finally, the criteria relating to the topics of DfA/DfD and user-friendliness are combined in one set of criteria. This was done by joining both sets together and removing double criteria. It was noticed that

some of the requirements found in literature for DfA/DfD were not mentioned in the studies for RtA furniture. An example of this is 'connections are accessible'. Because assembling furniture is based on accessible connections, a criteria like this was not found. However, this is a significant aspect again when reviewing building products on its ability to be assembled, disassembled and reassembled.

Fuzzy criteria found in one of the two topics were replaced by concrete guidelines described in the other topic. To provide a clear overview, the criteria were divided into two categories that could be distinguished in the literature: 'Object domain - technical aspects' and 'User domain - process related aspects' (see appendix F).

III. EXISTING EVALUATION METHODS

To develop a method to assess user-friendly DfA/DfD, some preconditions can be defined. These will help to make a selection out of methods that have been applied in previous studies (appendix G).

Firstly, the research aims to build upon existing methods to contribute to a broadly supported and harmonized tool with outputs that can be compared. Secondly, the research aspires to develop a method that gives insight into the extent of user-friendly DfA/DfD of modular infill systems as a guidance tool for designers. Since the designer will not always be an expert within this area and to provide in a quick-scan tool that can be used in every design and in-use phase, the method should be easily understandable and accessible.

When the method meets these preconditions, the outcome will be a score that designers help in making deliberate choices concerning to user-friendliness in circular design. Next to this, the outcome will be easy to interpret and provide in knowledge on the principles of such designs in general. For the end-user, the score can give guidance to the extent of which the modular infill system can be assembled and disassembled easily, with regard to the experience someone has with RtA furniture.

3.1. Existing methods for DfA/DfD

The first methods developed in the area of DfA/DfD focused on design for assembly. The objective was to reduce manufacturing costs by simplifying the product structure (Boothroyd, Alting, 1992). A quantitative approach was taken, concluding that merely guidelines are too general and insufficient to be practically applied by the designer to improve the design. The methodologies were composed of ratings, scoring the products on factors such as the number of parts and the weight and size of parts. The resulted ratings were used as guidance for redesign.

With the growth of environmental concerns, a shift was made from the consideration of DfA towards DfD (2.1.1.). Compared to the evaluation methods for DfA, first studies regarding to DfD mainly conclude with a set of guidelines. Shetty and Ali (2015) developed a method again based on rating factors, assessing both DfA and DfD. The factors with a corresponding score can also be found more extensive in recent studies that focus on DfD as a subtopic of circularity.

3.2. Existing methods for RtA furniture and Usability

As could be read in the previous chapter, user-friendliness in literature can be found within the two subareas of usability and RtA furniture. Existing evaluation methods for usability define the topic into factors that could be measured with formulas or counting data.

Secondly, little research was done on methodologies to assess the user-friendliness of RtA furniture. The evaluation methods developed in the available studies differ from just countable data to complex formulas. They do not fit quantitative as well as qualitative data. In the end, the research of Richardson (2011) comes closest to the methodology of rating factors that was found in the literature of DfA/DfD.

IV. DEVELOPMENT OF THE EVALUATION METHOD

4.1. Method for the assessment of User-friendly DfA/DfD

As a result of evaluating existing assessment methods, the method based on rating factors fits the preconditions that were set for this study best. Compared to the various and few methods that were

found in the literature of RtA furniture, the method based on rating factors was found in almost all studies of DfA/DfD. Moving on with this method will contribute to the need for a widely supported and harmonized key measurement method (Platform CB'23, 2020, p. 7). Also, both qualitative and quantitative criteria can be implemented in the method and scores can be compared. Finally, the method based on rating factors is easy to understand, does not need specific numbers from databases and fits the scope of the research. A first version of the evaluation method is included in appendix H.

4.2. Rating factors

The next step in the development of the evaluation method is the conversion of the set criteria to factors that can be rated. Part of the criteria and the translation to rating factors can already be found in the literature for DfA/DfD. Since these factors are used identical in the different literature, they were copied in their entirety within the first version of the evaluation method. The factors related to the remaining criteria were constructed the same as was done in the research of Shetty & Ali in 2015. Theoretical best- and worst-case scenarios were envisioned with practical and realistic steps in between. As was determined in chapter II, the five quality attributes relating to usability are of significant value regarding to user-friendliness and the circular aspect of reassembly. These attributes were used to refine four of the formulated factors. This is explained in the next paragraphs.

4.2.1. Rating factor: Motions to Assemble/disassemble

The notion of maximizing the success of assembly and disassembly could be addressed by looking at the working memory capacity (WMC) within the field of cognition. WMC refers to the amount of information one could process at the time (Bozarth, 2010 in Cortés, 2014). When the workload is too much, the working memory starts to falter and information is degraded (Cepelewicz, 2018). This could cause the assembly or disassembly to fail, due to misunderstanding and the end-user being annoyed and unsatisfied. The number of items that fit within our WMC was first determined by Miller (1956) on an average of seven. Subsequent studies identified this limit closer to four to five items. These numbers are used to determine the steps within the rating factor 'motions to assemble or disassemble'.

4.2.2. Rating factor: Perceived length of assembly/disassembly

To promote learnability and efficiency and prevent from errors, the workload to assemble or disassemble an object should be minimized. Exceeding the WMC should be avoided (4.2.1.). However, there is an actual workload, that is determined by for example the complexity of connectors, and there is a perceived workload. The perceived workload affects the perceived investment in time for assembly or disassembly. This can be influenced by simple adjustments of the characteristics of the instructions. One of these characteristics is the division of the instructions in steps (Agrawala et al. 2003; Cortés, 2014). To decrease the perceived workload even more, the instructions should provide in a larger step at the beginning (Cortés, 2014). Next to this, studies show that people prefer when each step contains the assembly of one significant part (Agrawala et al. 2003). With this in mind, the rating factors for the parameter 'perceived length of assembly and disassembly' were established.

4.2.3. Rating factor: Instructions for assembly / disassembly

Within the literature for RtA furniture, instructions were found as a requirement for user-friendly design. However, different from conventional instructions, the instructions searched for in this research are instructions that provide the user to complete the assembly and disassembly of an object several times. To address this aspect of circularity, it is important that the instructions promote the learning of the assembly and disassembly principles of a product.

The instructions referred to in the literature of RtA furniture are paper instructions. However, literature that studied different types of assembly instructions, concluded that active assembly instructions scored best for inexperienced people (Wouters, 2007; Busck, Svensson, 2017). Because of this, the highest score of the rating factor for instructions consists of the inclusion of video instructions before paper instructions, followed by possibilities when instructions are missing.

4.2.4. Rating factor: Repetition of assembly operations

The repetition of assembly operations as a requirement for DfA/DfD was just once mentioned in the literature of RtA furniture. However, with the preconditions set for this research regarding to reassembly together with the connection with usability, it becomes an important rating factor.

The building products to which the evaluation method applies, will most likely be assembled and disassembled in a period between 3-30 years. To make sure that assembly and disassembly can be done easily, efficient and repeating over these different time spans, knowledge to carry out the operations should move from the short-term memory (STM) to the long-term memory (LTM). The STM is also referred to as 'working memory', as explained in paragraph 4.2.1. To make the shift from STM to LTM, three possible methods can be found in literature: urgency, association and repetition (Schmelzer, 2015). Repetition is stated as the activity that creates the strongest and most learning. This corresponds with the rating factor based on the criteria 'minimize the variety of components and connectors' that asks for as much of the same components and connectors as possible to complete the assembly. However, a clash occurs with the criteria 'minimize the number of components and connectors'. Suggesting that a minimum of components and connectors should be present. Because of this, the three aspects should after scoring be reviewed in relation to each other. Finally, exact numbers of repetitions required to enhance learning and remembering were not found in literature. As a starting point, the numbers in the rating scores are now based on the method of mega-drilling. This method proved especially powerful and requires information to be repeated 30 times to be memorized (Cooke in Oaklander, 2015). Further research and testing should confirm or modify this number.

4.3. Score tables

The method described by Shetty and Ali was also used to determine the score tables for each factor. This was done, because most of the scores found in literature that already translated criteria into rating factors, used this method. Based on practical properties of the element, every step of a rating factor was given a score between 1 and 9 points. The step with the most preferred scenario received 9 points, whereas the least preferred scenario was given 1 point (Shetty, Ali, 2015; Beem, 2020). Min-points that were added in some of the rating factors determined by Beem (2020) were omitted. No clear explanation was found on how these were formulated. In other evaluation methods based on rating factors, min-points were not included.

Next to this, the assessment methods based on rating factors found in the literature on circularity did not use a 1-9 scale, but a 0,10-1,00 scale. To convert these scores to the 1-9 scale, the 0,10-1,00 scores were multiplied with a factor 10. After this, the factors rated 10 were seen as a score 9. To keep the right ratio between the scores, these were again evaluated. Scores that were given to similar rating factors found in the research of Shetty and Ali (2015) and Beem (2020), were compared and refined. Finally, some of the similar factors consisted of more steps in the score tables found in the literature on circularity. In this case the formulated score tables were extended with these measures.

V. TESTING AND IMPROVING THE EVALUATION METHOD

To make a first evaluation of the developed method, five partitioning walls were tested. Although the walls are part of a system or a composition of products, the test was carried out on product level. This was done because the extent of certain systems is dependent on factors as the dimensions of a building or home and personal preferences of the end-user. A system level approach could then lead to significant incorrect differences between the scores of various products.

The partitioning walls that were tested, were chosen based on mainly practical reasons. First, an attempt was made to obtain the partitioning walls from companies that could deliver a sample or a whole product. Secondly, walls were added that had all data available which was required to rate all factors. To make a first reflection on the validation of the tool, both products were chosen that either labelled itself as circular as well as traditional products (appendix I). The 'circular' partitioning walls should result in a higher score, for in particular technical aspects, comparing to traditional products.

After different walls and the corresponding data was collected, the factors were rated for all products. The experience obtained during testing together with the outcomes of the tests, resulted in several points for improvement. These are described in general in the next paragraphs and in detail in appendix J.

5.1. Results of the tests with partitioning walls

Testing the method on the different partitioning wall systems resulted in a positive outcome. Traditional systems scored lower on technical aspects than new systems that were specially designed for circular purposes. The structure as it was developed in the first stage of the research can therefore be seen as usable. Although further testing and discussion will have to prove the methods scientific validation, the method will already provide first insights of a products ease of DfA/DfD regarding to user-friendliness.

During testing, most of errors found in the evaluation method had to do with the formulation of the factors. In some cases, ambiguity existed among the field of application of a rating factor (part of the product, product, system). Secondly, certain properties of the products resulted in the need for the addition of extra information within a rating factor. Finally, it was found that some factors were formulated fuzzy. Their subjective basis causes difficulty in defining concrete measurements. A uniform use of definitions and the reformulation of a part of the content of the rating factors will enhance the clarity of the method and promote same application between different users.

In addition, it occurred that more than one subfactor applied. When this happened, the lowest score was included to calculate the total score. Finally, an improved version of the evaluation method is included in appendix K.

VI. CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

6.1 Conclusion

To address the notion of the shift towards a circular built environment from the perspective of the end-user, the aim of the research was to answer the question *'What are the preconditions for user-friendly design for assembly and disassembly of modular infill systems?'* This was done by the development of an evaluation method based on rating factors, assessing the user-friendliness of the assembly, disassembly and reassembly of modular infill systems. The method based on rating factors was chosen, because it was found most common in previous studies and builds upon the method used in recent studies on circularity. Whereas guidelines were found fuzzy, rating factors convert guidelines into concrete measurable parameters that could directly be applied when designing or reflecting on a design. The rating factors developed in the research, were formulated on the basis of the criteria found in literature of DfA/DfD and RtA furniture. The term user-friendly was also found in research in the area of 'Usability'. The five quality attributes 'Usability' consists of, specifically relate to reassembly and re-use. Hence, the knowledge of these five aspects was used to refine the rating factors.

After the definition of the criteria, each step of a rating factor was given a score between 1-9 based on practical properties of the element. This was done to stick with the score tables found in most of the literature. Criteria that were adopted from literature and rated by a score table from 0,10-1,00 were converted to the 1-9 score table.

The evaluation method was tested with partitioning wall systems. During the research it was remarkable that more than half of the criteria for both subjects overlapped. As a consequence it was expected that during testing, the circular systems that were designed for DFA/DFD scored better on the part of the rating factors related to user-friendliness. However, out of the evaluated systems only one of the traditional wall systems passed the test and one of the circular wall systems just barely passed the test on this aspect.

Improvements resulted from practical experience were incorporated in a final version. Although the evaluation method proved usable based on the firsts tests on partitioning wall systems and is based on previously carried out research, the method should be further tested and discussed to prove its scientific validation. Especially related to the rating factors, since both quantitative as well as qualitative rating factors can still be found in the evaluation method. This should be done with experts in the field of product development and all people that have experience with assembling and/or disassembling products in the same category as modular infill systems. In the end, as a first result, the evaluation method provides product developers first insights of a products ease DfA/DfD by the unskilled end-user. Subsequently, the method could serve as concrete guidelines in circular product development.

6.2 Discussion and Recommendations

With the developed method, a first attempt was made to define concrete guidelines for user-friendly DfA/DfD. Although first tests proved the method usable, further research and tests should be conducted in several areas to improve and validate the method on a scientific level.

First, user-friendliness is mainly a subjective topic. Rating factors and subfactors were determined on the basis of literature, previous studies, practical properties and product tests and provide in a main structure. Corresponding scores, defined by means of similar sources and personal interpretations by the author, should be confirmed and supported by discussions and user tests. Next to this, modular infill systems belong to the layers of a building that will be changed approximately every 3-30 years (Habraken, 1961). Together with the conditions required to promote usability and the physical characteristics of products, the best-case scenario for testing would be to test a system among a group of end-users and do this similarly a couple of years later. Along with this, the method would benefit from tests with other modular systems such as kitchens. Also preferred are tests to find out if the addition of, for example installations or doors, still fit within the requirements for user-friendly design.

In addition, the inclusion of material-use as a second key aspect of circularity is interesting for future research. A combination of both DfA/DfD and material-use into one tool would provide in a clear and complete method to assess the circularity performance of products. Since circular material-use was one of the main aspects of the tested products, a greater difference will then occur between the scores.
Finally, interrelations between the criteria and the five quality attributes of usability were identified in the research. These connections question the weight of each rating factor score. Together with user tests, the identified cross-references could help to structure the rating factors and determine their weight in the total score in novel studies. This could be done by means of the method of pairwise comparison.

In the end the evaluation method has its potential in different fields and in different levels of depth. For example, in the first stages of product design, the factors of each criteria with the highest score could be extracted and used as guidelines to aim for in a new design. Also within this stage one could evaluate and compare existing products of the same category and see how these score as another level of input. After this, the method could be used to test and review intermediate results of different designs. The rating that is given to a product could then also be interpreted by people who would like to purchase or use such a product. For instance, a designer like an architect that would like to integrate such systems in his or her project could evaluate if the rating of a product fits it target group he or she is designing for. Or a couple who are designing their own home could select a modular infill system fitting to their skills of assembling to save money.

By applying the method in these various ways, it could not only be a helpful tool in product development, but also in every other field. It would help in selecting the fitting building products on the aspects that fit not only the preferred performance and appearance, but also the skills of the assembler and disassembler.

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Appendix A – Literature: Criteria for the Design for Assembly and Disassembly

Source	Year	Criteria
G. Boothroyd, L. Alting - 'Design for assembly and disassembly'	*1992*	• simplify the product structure • minimize the number of parts (A parts - demanded by the design specification; B parts - required by that particular design solution) • minimize the number of motions to assemble / disassemble / reassemble • minimize the variety of parts and subassemblies • use standard parts • use standard joining techniques • connections that are accessible • easy identification of separate materials
B. Guy, N. Ciarimboli, K. Hendrickson - 'Design for disassembly in the built environment'	*2005*	• document materials • document methods for deconstruction • use products with materials considered for future impacts / high quality • connections that are accessible; provide adequate tolerance • minimize or eliminate chemical connections (binders, sealers, glue, adhesives, resins, coatings in or on materials) • use standard connectors / joining techniques • use dry connections (bolted, screwed and nailed connections) • minimize the variety of connectors • minimize the number of connectors and fasteners • separate mechanical, electrical and plumbing systems • design to the worker and labor of separation (human-scale)(lightweight materials / use of smaller equipment) • simplify the product structure • simplify the form of the product / components • use standard sizes • use of interchangable components; modular, independent and standardized • product can be assembled and disassembled in a safe way; avoid toxic and hazardous materials • minimize the different types of materials / separation processes • avoid secondary finishes to materials that cover connection points • minimize the number of different types of components
A. Güngör - 'Evaluation of connection types in design for disassembly (DFD) using analytic network process'	*2006*	• minimize the number of parts • minimize the number of connectors and fasteners • use standard connectors / joining techniques • use connectors that require easy motions; fasteners assembled in the same direction • use of damage resistant fasteners and connectors (human errors, heat, humidity, vibration, sunlight) • minimize the number of steps to complete the fastening process of a connector • when necessary, use of simple and generic tools
D. Shetty, A. Ali - 'A new design tool for DFA/DFD based on rating factors'	*2015*	• design to the worker and labor of separation (human-scale)(lightweight materials / use of smaller equipment) • connections that are accessible; provide adequate tolerance • when necessary, use of simple and generic tools • minimize or eliminate chemical connections • use dry connections (bolted, screwed and nailed connections) • use of damage resistant fasteners and connectors (human errors, heat, humidity, vibration, sunlight) • disassembly process can be completed without damaging components • product can be assembled and disassembled in a safe way; avoid toxic and hazardous materials
PIANOo (expertisecentrum aanbesteden)	*2019*	• disassembly process can be completed without damaging components • components are arranged independent of eachother • minimize the number of connectors and fasteners • use standard joining techniques

Source	Year	Criteria
		• components that are accessible • connections that are accessible • use dry connections • minimize or eliminate chemical connections • provide in usable and up-to-date disassembly instructions • minimize the number of motions to assemble / disassemble / reassemble • product can be assembled and disassembled in a safe way • design to the worker and labor of separation • time of assembly and disassembly in balance with effort and result
M. van Vliet, J. van Grinsven, J. Teunizen - 'Circular buildings'	*2019*	• use dry connections • minimize or eliminate chemical connections • connections that are accessible • connections can be accessed without damaging components (life-span) • components are arranged independent of eachother • components that are accessible (from at least one side) • provide in disassembly instructions
A. Beem - 'Research towards and prototyping of an evaluation method for design for reuse for building products in the design phase'*	*2020*	• minimize the use of tools • minimize the required space for (de)mounting • minimize the equipment needed to move a product to or from its place of assembly/ disassembly; design for human-scale • minimize the physical intensity of labour that is required to handle the product; design for human-scale • integrate connectors into the product • minimize the number of connectors and fasteners • use dry connections • minimize or eliminate chemical connections • product can be detached without damaging individual components (life-span) • use of market standard dimensions • use of market standard connection-system • (maximize the circular potential of a product at the end of its functional life-cycle) • use of damage resistant components (human errors, heat, humidity, vibration, sunlight) • design to the worker and labor of separation (human-scale)(lightweight materials / use of smaller equipment / minimize required knowledge)
E. Durmisevic - 'Transformable Building Structures'	*2006*	• show the possibilities of reconfiguration; provide in disassembly instructions • components are arranged independent of eachother • use of modular dimensionial systems • design to the worker and labor of separation (human-scale)(lightweight materials / ease of handling and transport) • minimize the variety of fasteners and connectors • minimize the number of connectors and fasteners • connections that are accessible; provide adequate tolerance • use dry connections • minimize or eliminate chemical connections • document materials • components that are accessible (from at least one side) • components/materials are exchangable
Brussels Hoofdstedelijk Gewest	*2017*	• components are exchangable • use of market standard dimensions • use of market standard connection-system • use dry connections • minimize or eliminate chemical connections

Source	Year	Criteria
		• document characteristics of components to know what can be done in future use • components are arranged independent of eachother • components that are accessible • connections that are accessible • minimize the variety of fasteners and connectors • minimize the variety of components • when necessary, use of simple and generic tools • product can be assembled and disassembled in a safe way • minimize the number of connectors and fasteners • minimize the number of components • document methods for deconstruction • document materials and components
C. Poli - 'Manual Assembly'	*2001*	• combining parts • minimize the number of parts • minimize the number of fasteners • minimize the variety of fasteners • integrate connectors into the product • parts that can be easily handled • parts that can be easily inserted • parts that are easy to grasp • minimize the mass, size and thickness of parts • avoid the use of tools • parts that can be manipulated with one hand • parts can be seen • parts are accessible • fasteners are self-locating

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APPENDIX B – A SET OF CRITERIA FOR THE DESIGN FOR ASSEMBLY AND DISASSEMBLY

1. Technical aspects
- minimize the variety of components
- integrate connectors into the product
- minimize the number of connectors
- minimize the variety of connectors
- use of market-standard connections
- use of market-standard dimensions
- design to the worker and labor of separation
- use of modular systems / components can be interchanged
- connections are accessible
- use of dry connections / avoid chemical connections
- components are arranged independent of eachother
- components can be recognized
- use of damage resistant connectors
- use of damage resistant components

2. Process-related aspects
- minimize the number of motions to assemble and disassemble
- document methods for deconstruction
- minimize required knowledge for assembly and disassembly
- when necessary, use of simple and generic tools

APPENDIX C – LITERATURE: CRITERIA FOR THE DESIGN FOR USER-FRIENDLINESS

Based on literature studying Ready to Assemble furniture

Source	Year	Criteria
J. Casanova-Cortés - 'Re-Thinking The Image and Assembly Process Of Ready To Assemble Furniture'*	*2014*	• minimize assembly operations; integration of components • facilitate orientation; include orientation surfaces, make components symmetrical or increase asymmetry • facilitate insertion; make insertion unambigious, design components with guiding surfaces • minimize perception time: - visible parts; - tactile discrimination, texture, size; - visual discrimation, color, size • minimize decision time: - visible parts; - minimize the number of parts; - collocation of associated parts • minimize manipulation time: - fixture to hold parts - parts that are easy to grip and do not tangle; - fasteners that are easy to use; self-locating parts; - increase tolerances; new product similar to old • repetition of assembly operations • minimize the number of components/ fastenings • minimize the variety of components/ assemblies • easy steps in assembly instead of one big complex step • minimize the perceived length of the steps; first a big step • use of standard operations • group parts that should be assembled at the same time or in sequence one after another (max. 6) • Provide instructions: present the assembly task in a sequence of diagrams, in the context of previous assembled components
K. Wärmefjord, L. Lindkvist, R. Söderberg, A. Dagman - 'Non-Rigid Variation Simulation for Ready-to-Assemble Furniture'	*2019*	• avoid the use of complex tools • provide in tolerance at points of joints • minimize the number of components/ fixtures • allow for a simple and smooth joining process
B. Geldermans, M. Tenpierik, P. Luscuere - 'Circular and Flexible Infill Concepts: Integration of the Residential User Perspective'	*2019*	• freedom of choice in availability • freedom of choice in variation • user investment in time is low • user investment in money is low
M. Richardson - 'Assembly Complexity and the Design of Self-Assembly Products'	*2011*	• avoid assembly operations; integrate components • facilitate orientation; include orientation surfaces, make components symmetrical or increase asymmetry • facilitate insertion; make insertion unambigious, design components with guiding surfaces • Provide instructions that: - group /order parts - step-by-step instructions, presenting repetitive actions into one diagram - have structural and action diagrams - orientation of parts is recognizable - new components of a step are visible • minimize perception time: - visible parts; - tactile discrimination, texture, size; - visual discrimation, color, size

Source	Year	Criteria
		• minimize decision time: - visible parts; - minimize the number of parts; - collocation of associated parts • minimize manipulation time: - fixture to hold parts - parts that are easy to grip and do not tangle; - fasteners that are easy to use; self-locating parts; - increase tolerances; new product similar to old • minimize the variety of components • minimize the number of components • minimize the total number of components available to select at each step • provide in orientation guidelines or symmetrical components • minimize the number of fastening points / fastenings • provide in easy identifiable and distuingishable fastening points
M. Richardson, G. Jones, M. Torrance - 'Identifying the task variables that predict object assembly difficulty.'	*2006*	• minimize the total number of components available to select at each step • provide in orientation guidelines or symmetrical components • provide in easy identifiable and distuingishable fastening points • minimize the number of fastening points / fastenings • minimize the variety of assemblies • minimize the number of components • group/order parts
R.P. Sundarraj, T. Bramorski, M.S. Madan - 'The Effects of Grouping Parts of Ready-to -assemble Products on Assembly Time: An Experimental Study.'	*1995*	• grouping components into bags (max. 12)
M.G. Helander, B.A. Willen - 'The Occupational Ergonomics Handbook'	*1999*	• minimize perception time: - visible parts; - tactile discrimination, texture, size; - visual discrimation, color, size • minimize decision time: - visible parts; - minimize the number of parts; - collocation of associated parts • minimize manipulation time: - fixture to hold parts - parts that are easy to grip and do not tangle; - fasteners that are easy to use; self-locating parts; - increase tolerances; new product similar to old

**Student research*

APPENDIX D – A SET OF CRITERIA FOR THE DESIGN FOR USER-FRIENDLINESS

Object domain

- minimize assembly operations
- facilitate orientation of parts
- facilitate in components with guiding surfaces for insertion points
- integrate connectors into the product
- minimize the number of connectors
- minimize the variety of connectors
- minimize the number of components
- minimize the variety of components
- provide in a fixture to hold parts
- provide in parts that are easy to grip and do not tangle
- provide in tolerance at points of joints
- use of repeating systems; new product similar to old
- use of standard operations

User domain

- collocate associated parts
- freedom of choice in availability
- freedom of choice in variation
- user investment in time is low
- user investment in money is low
- provide in instructions; action and structural diagrams
- provide in step-by-step instructions
- minimize the perceived length of steps; first a big step
- group parts that should be assembled at the same time or in sequence one after another
- avoid the use of complex tools
- repetition of assembly operations (memorability, minimize variety)

APPENDIX E – INTERRELATIONS BETWEEN THE QUALITY ATTRIBUTES OF USABILITY AND THE CRITERIA FOR USER-FRIENDLY DFA/DFD

Object domain - technical aspects	*Learnability*	*Efficiency*	*Memorability*	*Errors*	*Satisfaction*
facilitate orientation of parts	x	x	x	x	x
facilitate in components with guiding surfaces for insertion points	x	x	x	x	x
integrate connectors into the product	x	x		x	x
minimize the number of connectors		x			x
minimize the variety of connectors	x		x	x	x
minimize the number of components		x			x
minimize the variety of components	x		x	x	x
provide in a fixture to hold parts	x			x	x
provide in parts that are easy to grip and do not tangle				x	x
provide in tolerance at points of joints	x			x	x
use of market-standard connections	x	x	x	x	x
use of market-standard dimensions		x			x
design to the worker and labor of separation; size + weight	x				x
connections are accessible	x			x	x
use of dry connections / avoid chemical connections		x			x
components are arranged independent of eachother	x			x	x
use of damage resistant connectors		x			x
use of damage resistant connectors		x			x
use of modular systems/ parts can be interchanged		x			x

User domain - process related aspects	*Learnability*	*Efficiency*	*Memorability*	*Errors*	*Satisfaction*
collocate associated parts	x	x		x	x
freedom of choice in availability					x
freedom of choice in variation					x
user investment in money is low					x
provide in instructions; action and structural diagrams	x	x	x	x	x
provide in step-by-step instructions	x	x	x	x	x
minimize the perceived length of steps; first a big step					x
group parts that should be assembled at the same time or in sequence one after another	x	x		x	x
avoid the use of complex tools	x	x		x	x
repetition of assembly operations	x	x	x	x	x
minimize the number of motions to assemble and disassemble	x	x	x	x	x
document methods for disassembly	x	x	x	x	x
minimize required knowledge for assembly and disassembly	x	x	x	x	x

APPENDIX F – CRITERIA FOR THE DESIGN FOR USER-FRIENDLY DFA/DFD

Object domain - technical aspects

- facilitate orientation of parts
- facilitate in components with guiding surfaces for insertion points
- integrate connectors into the product
- minimize the number of connectors
- minimize the variety of connectors
- minimize the number of components
- minimize the variety of components
- provide in a fixture to hold parts
- provide in parts that are easy to grip and do not tangle
- provide in tolerance at points of joints
- use of market-standard connections
- use of market-standard dimensions
- design to the worker and labor of separation (size + weight)
- connections are accessible
- use of dry connections / avoid chemical connections
- components are arranged independent of eachother
- use of damage resistant connectors
- use of damage resistant components
- use of modular systems/ parts can be interchanged

User domain - process related aspects

- freedom of choice in availability
- freedom of choice in variation
- user investment in money is low
- provide in instructions; action and structural diagrams
- provide in step-by-step instructions
- minimize the perceived length of steps; first a big step
- group parts that should be assembled at the same time or in sequence one after another
- avoid the use of complex tools
- repetition of assembly operations
- minimize the number of motions to assemble and disassemble
- document methods for disassembly
- minimize required knowledge for assembly and disassembly

APPENDIX G – EXISTING EVALUATION METHODS

Source	Year	Subject	M. to Assess / M. for Measurement
D. Shetty, A. Ali - 'A new design tool for DFA/DFD based on rating factors'	*2015*	Product design: Design for Assembly / Design for Disassembly	Rating 0 (difficult) till 9 (easy)
Based on M. Schumacher - 'Design for disassembly technique based on rating factors on access, re-use, tool, task and time, recycle and removal'*	*2002*	Product design: Design for Disassembly	
A. Beem - 'Research towards and prototyping of an evaluation method for design for reuse for building products in the design phase'*	*2020*	Building products: Design for Reuse	Rating -2 (worst case scenario) till 9 and possibility for +2 (best case scenario)
Based on D. Shetty, A. Ali - 'A new design tool for DFA/DFD based on rating factors'	*2015*	Product design: Design for Assembly / Design for Disassembly	Rating 0 (difficult) till 9 (easy)
M. van Vliet, J. van Grinsven, J. Teunizen - 'Circular buildings'	*2019*	Building design: Design for dissassembly	Scoring 0,10 (worst value) till 1,00 (best value) Including environmental impact, using the MPG (milieuprestatie gebouwen) as a standardization factor in the end to come to a total score.
Based on E. Durmisevic - 'Transformable Building Structures'	*2006*	Building structural design: Design for dissassembly	
E. Durmisevic - 'Transformable Building Structures'	*2006*	Building structural design: Design for dissassembly	Scoring 0,00 (worst value) till 1,00 (best value) brought together in a knowledge matrix
A. Güngör - 'Evaluation of connection types in design for disassembly (DFD) using analytic network process'	*2006*	Product design: Design for dissassembly	Analytic network process: Method to structure interactions an dependencies between elements in a network and calculate the elements priority within the network.
PIANOo (expertisecentrum aanbesteden)	*2019*	Building products: Design for dissassembly	Scoring 0,10 (worst value) till 1,00 (best value)
Based on M. van Vliet - 'Disassembling the steps towards building circularity.' * and J. Verberne - 'Building Circularity Indicators.' *	*2018* *2016*	Building design: Design for dissassembly	
Alba concepts - 'Building circularity Index'	*2018*	Building design: Circular material-use and design for disassembly	Material-use: % DfD: rating factors

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APPENDIX H – EVALUATION METHOD USER-FRIENDLY DFA/DFD VERSION 1.0

Object Domain - *Technical Aspects*

1 ***Criteria:*** facilitate in components with guiding surfaces for insertion points

Guiding surfaces for insertion points	**rating**
Components have pre-fabricated holes of insertion points	9
Insertion points are marked on the components	7
Insertion points are not given, position has to be established from the instructions	2
Insertion points are not given, position has to be established by the assembler/disassembler	1

2 ***Criteria:*** components can be recognized

Recognition of components	**rating**
Components of the product can be recognized easily	9
Components of the product can be recognized when focused	7
Components of the product can be recognized with help of an instruction booklet	5
Components of the product are hard to recognize, despite the help of an instruction booklet	1

3 ***Criteria:*** integrate connectors into the product

Connector integration	**rating**
Connectors are fully integrated into the product	9
Connectors are partly integrated into the product, but separate connecting products are needed	7
Connectors are not integrated into the product, but design allows for aided affixing of connectors	5
Connectors are not integrated into the product, and design does not allow for aided affixing of connectors	1

4 ***Criteria:*** minimize the number of connectors

Number of connectors	**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

5 ***Criteria:*** minimize the variety of connectors

Variety of connectors	**rating**
One type of fastener is needed to connect two components	9
Two types of fasteners are needed to connect two components	7
Three types of fasteners are needed to connect two components	5
Four or more types of fasteners are needed to connect two components	1

6 ***Criteria:*** minimize the number of components

Number of components	**rating**
The product consists of 1-4 components	9
The product consists of 5-7 components	7
The product consists of 8-10 components	5
The product consists of 11-15 components	3
The product consists of >16 components	1

7 ***Criteria:*** minimize the variety of components

Variety of components	**rating**
The product comprises of one type of component	9
The product comprises of 2-4 types of components	7
The product comprises of 5-7 types of components	4
The product comprises of more than 7 types of components	1

8 ***Criteria:*** provide in a fixture to hold parts

Fixtures supporting assembly/disassembly	**rating**
A fixture component is provided to hold parts	9
Different fixture components to hold groups of parts	7
Parts have to be holded by the assembler/disassembler by him/herself, this can be done easily during assembly/disassembly	5
Parts have to be holded by the assembler/disassembler by him/herself, this is hard to be done during assembly/disassembly	2
Parts have to be holded by the assembler/disassembler by him/herself, extra people are needed to help	1

9 ***Criteria:*** provide in parts that are easy to grip

Grabability of parts	**rating**
Parts are easy to grip by themselves	9
Parts are easy to grip, handles or lifting facilities are integrated	8
Parts are not so easy to grip and have to be handled carefully	7
Parts are hard to grip, small equipment is needed (for example gloves)	5
Parts are hard to grip, large equipment is needed (for example a supporting structure)	1

10 ***Criteria:*** provide in parts that do not tangle

Independency of elements	**rating**
Components are arranged independent of eachother, assembly and disassembly can be completed easily	9
Components cross eachother, assembly and disassembly can be completed with a little difficulty	7
Components cross eachother, assembly and disassembly can fail (by frustration of the assembler/disassembler)	3
Components cross eachother, assembly/disassembly is likely to fail (by causing frustration by the assembler/disassembler)	1

11 ***Criteria:*** provide in tolerance at points of joints

Tolerances	**rating**
Double the size of the fastener is provided as tolerance	9
One and a half time the size of the fastener is provided as tolerance	8
1,5<1 the size of the fastener is provided as tolerance	7
No tolerance is provided, fasteners are easy to insert	5
No tolerance is provided, fasteners are difficult to insert and can only be done when handled with care	2
No tolerance is provided, damage is likely to happen	1

12 *Criteria:* use of market-standard dimensions

Degree of standardization	**rating**
Product has market standard dimensions	9
Product can be easily altered to market standard dimensions or can be easily used along-side market standard products	7
The product can be further dismantled and individually altered to market standard dimensions	4
Product cannot be standardized in dimensions and cannot be easily used along-side market-standard products	1

13 *Criteria:* use of market-standard connection-system

Degree of standardization	**rating**
Product has a market standard connection-system	9
Product can be easily altered to a market standard connection-system or can be easily used along-side market standard products	7
The product can be further dismantled and individually altered to market standard connection-systems	4
Product cannot be standardized in connection-systems and cannot be easily used along-side market-standard products	1

14 *Criteria:* use of components of the size that can be handled by the scale of one average adult

Product placement/ removal	**rating**
The product is movable by hand (<2000x100x600 (lxbxd))	9
A hand truck is needed to place/ remove the product	7
A pump truck is needed to place/remove the product	4
A forklift truck is needed to place/ remove the product	3
A crane with 2t power is needed to insert/ extract the product	1

15 *Criteria:* use of components of the weight that can be handled by the scale of one average adult

Labour intensiveness	**rating**
The product is manageable with one hand (<7.5kg)	9
The product is manageable with two hands (7.5-12kg)	8
The product is liftable in accordance with working conditions (12-23kg)	7
The product requires two people to manage (23-50kg)	6
A hand truck is needed to place/ remove the product	4
A pump truck is needed to place/remove the product	3
A forklift truck is needed to place/ remove the product	2
A crane with 2t power is needed to insert/ extract the product	1

16 ***Criteria:*** connections are accessible

Accessibility of connections	**rating**
Connection is freely accessible, ample space for hands and/or tools	9
Connection has restricted access for hands or tools	7
Connection is accessible after removing parts, not damaging objects	6
Connection is accessible after removing parts, causing repairable damage of objects	3
Connection is not accessible, irreparable damage of objects	1

17 ***Criteria:*** use of dry connections / avoid chemical connections

Connector type	**rating**
Products are connected without dedicated fasteners (dry connection)	9
Products are connected with added elements (clips, velcro, magnets)	8
Products are connected with added elements (bolts and nuts, suspension, corner joints, screws), that can be easily kept intact during disassembly	7
Products are connected with a direct integral connection (pins, nails), during disassembly it is hard to keep the connector intact	4
Products are connected with a fixed connection, but can be detached with some difficulty (soft chemical compounds like kit connection, foam connection like PUR)	2
Products are connected with a fixed connection, and cannot be detached without heavy damage to the product or its host (hard chemical compounds like adhesives, concrete pouring, welding, cement, chemical anchors,)	1

18 ***Criteria:*** use of damage resistant connectors/ components

Damage during Assembly/ Disassembly/ Reassembly	**rating**
No damage that hinders the function of the product in any way	9
Small damage that does not hinder the function of the product	8
Small damage that hinders the function of the product in a small way, but does not require immediate repair	6
Significant damage that hinders the function of the product, repair is required after disassembly	3
Extensive repair and/or replacement of several parts is required after disassembly	2
point where the product is	1

19 ***Criteria:*** use of modular systems / components can be interchanged

Interchangeability of components	**rating**
Components can be interchanged with eachother and other systems	9
Components can be interchanged with eachother	8
Part of the components can be interchanged with eachother	5
Components can not be interchanged with eachother	1

User Domain – *Process Related Aspects*

20 ***Criteria:*** freedom of choice in availability

Availability of parts	**rating**
Components are separately available by different suppliers	9
Components are separately available by one supplier	6
Components are not separately available, but only as a whole product	3
Products have to be bought in quantities	2
Components are not available for private sale	1

21 ***Criteria:*** freedom of choice in variation

Variation of the product	**rating**
Product is available in a variety of models, serving all preferences of different end-users (size, color, texture)	9
Product is available in a limited variety of models, serving the preferences of the average end-user (size, color, texture)	7
Product is available in standard model(s), personal preferences can be implemented with separate materials and/or tools (size, color, texture)	5
Product is available in a limited variety of models, serving the preferences of just a small group of end-users (size, color, texture)	3
Product is available in standard model(s), personal preferences can not be implemented (size, color, texture)	1

22 ***Criteria:*** user investment in money is low

Perceived investment in money	**rating**
User investment in money is perceived low	9
User investment in money is perceived as moderate	7
User investment in money is perceived as mid-high	5
User investment in money is perceived high	3
User investment in money is perceived as too high	1

23 ***Criteria:*** minimize the number of motions to assemble and disassemble

Number of motions	**rating**
<4 motions are required to assemble/ disassemble	9
5-7 motions are required to assemble/ disassemble	7
8-10 motions are required to assemble/ disassemble	5
11-15 motions are required to assemble/ disassemble	3
>16 motions are required to assemble/ disassemble	1

24 *Criteria:* minimize required knowledge for assembly and disassembly

Required operator qualifications	**rating**
Does not require operator to have any offical qualifications	9
Requires operator to acquire a single certificate	7
Requires operator to acquire multiple certificates	5
Requires operator to have completed the equivalent of a three year long full-time education, but no additional qualifications	3
Requires operator to have completed the equivalent of a three year long full-time education, and acquire an additional certificate	1

25 *Criteria:* when necessary, use of simple and generic tools

Tool complexity	**rating**
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Powered tools are required	5
Special tools are required	1

26 *Criteria:* repetition of assembly operations

Repetition of assembly operations	**rating**
Assembly/disassembly operations of one type of fastener with related components is repeated >30 times	9
Assembly/disassembly operations of one type of fastener with related components is repeated 20<x<30 times	7
Assembly/disassembly operations of one type of fastener with related components is repeated 10<x<20 times	5
Assembly/disassembly operations of one type of fastener with related components is repeated 1<x<10 times	3
Assembly/disassembly operations of one type of fastener with related components is conducted just one	1

27 *Criteria:* provide in instructions

Instructions for assembly	**rating**
Instructions for assembly are available as a movie where an expert shows how assembly should take place	9
Instructions on paper for assembly are added to the product	7
Instructions for assembly are not added to the product, assembly can be done with common sense	5
Instructions for assembly are not added to the product, assembly is hard to be done	3
No instructions are added to the product, assembly can be done only with expert knowledge	1

28

Instructions for disassembly	**rating**
Instructions for disassembly are available as a movie where an expert shows how disassembly should take place	9
Instructions for disassembly are added to the product	8
Instructions for assembly are added to the product, disassembly can be done with assembly instructions in mind	7
Instructions for assembly are added to the product, disassembly is hard to be done	4
No instructions are added to the product, assembly and disassembly can be done with common sense	3
No instructions are added to the product, assembly and disassembly can be done only with expert knowledge	1

29 *Criteria:* action and structural diagrams

Kind of diagrams	**rating**
Instructions are provided with structural and action diagrams from one point of view	9
Instructions are presented with action diagrams from one point of view	8
Instructions are presented with structural diagrams, from one point of view	6
Instructions are provided with structural and action diagrams from different point of views	4
Instructions are presented with action diagrams from different point of views	3
Instructions are presented with structural diagrams, from different point of views	2
Instructions are provided with illustrations other than structural and/or action diagrams	1

30 *Criteria:* provide in step-by-step instructions

Perceived length of assembly / disassembly	**rating**
Instructions are presented in a step-by-step sequence, first a large step is given	9
Instructions are presented in a step-by-step sequence, steps require the same amount of operations	7
Instructions are presented in a step-by-step sequence, alternation of small and large steps	3
Instructions are presented in a step-by-step sequence, the last step is a big step compared to the former ones	2
Instructions are presented in a single illustration	1

Total score /30 criteria	

APPENDIX I – ADJUSTMENTS MADE TO THE EVALUATION METHOD USER-FRIENDLY DFA/DFD VERSION 1.0

The feedback gained from the tests, resulted in adjustments that are described in detail below. The numbers correspond with the numbers that were given to the rating factors in version 1.0.

1. Change in description and/or content

Five rating factors required a change in description and/or content:

4 - The factor 'number of connectors' referring to the total amount of connectors of the product instead of the connectors needed to connect two components. Exact numbers were given to each step derived from the theory of the working memory capacity and the number of connectors that were identified for each product during testing.
5 - 'Variety of connectors' applying to all different connectors instead of the ones used to connect two components. Exact numbers were determined in the same way as was done for 'number of connectors'.
7 - The numbers determined for the 'variety of components' were adjusted. During testing, it was noted that a product consisted of at least two types of components. Therefore, the formulation of the best-case scenario 'the product comprises of one type of component' was practically not realistic.
10 - The best-case scenario for 'independency of elements' was reformulated, since on a product level, connected components will cross each other at all times.
27 - In case of ready-to-assemble furniture, the addition of paper instructions was common, for building components this was not. 'Added' was therefore replaced by 'available'.

2. Addition of subfactors

In response to the tests, subfactors were added to the rating factors:

11 - Tolerances
14 - Product placement/removal
19 - Interchangeability of components
23 - Number of motions
27 - Instructions for assembly
28 - Instructions for disassembly
29 - Kind of diagrams
30 - Perceived length of assembly/disassembly

3. Splitting up factors

During the performance of the tests, it was noted that the factors 'Accessibility of connections' (16) and 'Damage during assembly/disassembly/reassembly' (18) could be rated differently for assembly/reassembly and disassembly and are therefore split. Similar, rating factor 'Variation of the product' (21) was split into a parameter for size and a parameter for aesthetics.

4. Adjustment: replacement or removal

Because of its subjective basis and the inexperience of the end-user with the costs of building components, the rating factor 'Perceived investment in money' (22) was removed from the evaluation method.

The factor 'repetition of assembly operations' (26), on the contrary, was replaced. This was done because of the clash with the rating factor based on the criteria 'minimize the number of motions to assemble and disassemble'. Also, as was noticed during testing, the required repetitions of (dis)assembly operations depends on the difficulty of the connector. This relates to the term 'association' that was found in literature as the second-best method to improve learnability and memorability (Schmelzer, 2015). People will better remember things that are part of an already existing neural connection. Meaning that people can associate these things with something they already know. It is then very likely that when a connection looks like a connection used in RtA furniture, the corresponding operation is experienced easier. When association does occur, the number of repetitions that was defined for the best-case scenario on at least 30, does not correspond anymore.

APPENDIX J – THE PARTITIONING WALLS THAT WERE TESTED IN THE EVALUATION METHOD VERSION 1.0

Circular products

1. Faay VP54

Object domain – Technical related aspects: 7,0/9
User domain – Process related aspects: 5,9/9
Total: 6,6/9

2. BIA Spanell Fermacell Greenline

Object domain – Technical related aspects: 7,1/9
User domain – Process related aspects: 5,0/9
Total: 6,4/9

3. Wall-linQ

Object domain – Technical related aspects: 7,1/9
User domain – Process related aspects: 2,0/9
Total: 5,5/9

Traditional products

4. Knauf W111 kamer scheidende wand

Object domain – Technical related aspects: 6,5/9
User domain – Process related aspects: 7,0/9
Total: 6,6/9

5. Gyproc classic kamer scheidende wand

Object domain – Technical related aspects: 5,6/9
User domain – Process related aspects: 4,7/9
Total: 5,3/9

APPENDIX K – EVALUATION METHOD USER-FRIENDLY DFA/DFD VERSION 2.0

Object Domain - *Technical Aspects*

1 ***Criteria:*** facilitate in components with guiding surfaces for insertion points

Guiding surfaces for insertion points	rating
Components have pre-fabricated holes of insertion points	9
Insertion points are marked on the components	7
Insertion points are not given, position has to be established from the instructions	2
Insertion points are not given, position has to be established by the assembler/disassembler	1

2 ***Criteria:*** components can be recognized

Recognition of components	rating
Components of the product can be recognized easily	9
Components of the product can be recognized when focused	7
Components of the product can be recognized with help of an instruction booklet	5
Components of the product are hard to recognize, despite the help of an instruction booklet	1

3 ***Criteria:*** integrate connectors into the product

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

4 ***Criteria:*** minimize the number of connectors

Number of connectors	rating
The product consists of 1-4 connectors	9
The product consists of 5-7 connectors	7
The product consists of 8-10 connectors	5
The product consists of 11-15 connectors	3
The product consists of >15 connectors	1

5 ***Criteria:*** minimize the variety of connectors

Variety of connectors	**rating**
The product comprises of 1-2 types of connectors	9
The product comprises of 3-4 types of connectors	6
The product comprises of 5-7 types of connectors	3
The product comprises of more than 7 types of connectors	1

6 ***Criteria:*** minimize the number of components

Number of components	**rating**
The product consists of 1-4 components	9
The product consists of 5-7 components	7
The product consists of 8-10 components	5
The product consists of 11-15 components	3
The product consists of >15 components	1

7 ***Criteria:*** minimize the variety of components

Variety of components	**rating**
The product comprises of 1-2 types of components	9
The product comprises of 2-4 types of components	7
The product comprises of 5-7 types of components	5
The product comprises of 8-10 types of components	3
The product comprises of more than 10 types of components	1

8 ***Criteria:*** provide in a fixture to hold parts

Fixtures supporting assembly/disassembly	**rating**
A fixture component is provided to hold parts	9
Different fixture components to hold groups of parts	7
Parts have to be holded by the assembler/disassembler by him/herself, this can be done easily during assembly/disassembly	5
Parts have to be holded by the assembler/disassembler by him/herself, this is hard to be done during assembly/disassembly	2
Parts have to be holded by the assembler/disassembler by him/herself, extra people are needed to help	1

9 ***Criteria:*** provide in parts that are easy to grip

Grabability of parts	**rating**
Parts are easy to grip by themselves	9
Parts are easy to grip, handles or lifting facilities are integrated	8
Parts are not so easy to grip and have to be handled carefully	7
Parts are hard to grip, small equipment is needed (for example gloves)	5
Parts are hard to grip, large equipment is needed (for example a supporting structure)	1

10 ***Criteria:*** provide in parts that do not tangle

Independency of elements	**rating**
Components are arranged independent of/cross eachother, assembly and disassembly can be completed easily without damage to the product	9
Components cross eachother, assembly and disassembly can be completed with a little difficulty, causing no damage to the product	7
Components cross eachother, assembly and disassembly causing no damage has to be done with special care	5
Components cross eachother, assembly and disassembly can fail (by frustration of the assembler/disassembler), likely to cause damage	3
Components cross eachother, assembly and disassembly is likely to fail (by causing frustration by the assembler/disassembler), causing damage	1

11 ***Criteria:*** provide in tolerance at points of joints

Tolerances	**rating**
Double the size of the connector is provided as tolerance	9
One and a half time the size of the connector is provided as tolerance	8
1,5<x<0 the size of the connector is provided as tolerance	7
No tolerance is provided, connectors are easy to insert	5
No tolerance is provided, connectors can be inserted when handled with care	4
No tolerance is provided, connectors are difficult to insert and can only be done when handled with special care, damage can occur	2
No tolerance is provided, damage is likely to happen	1

12 ***Criteria:*** use of market-standard dimensions

Degree of standardization	**rating**
Product has market standard dimensions	9
Product can be easily altered to market standard dimensions or can be easily used along-side market standard products	7
The product can be further dismantled and individually altered to market standard dimensions	4
Product cannot be standardized in dimensions and cannot be easily used along-side market-standard products	1

13 ***Criteria:*** use of market-standard connection-system

Degree of standardization	**rating**
Product has a market standard connection-system	9
Product can be easily altered to a market standard connection-system or can be easily used along-side market standard products	7
The product can be further dismantled and individually altered to market standard connection-systems	4
Product cannot be standardized in connection-systems and cannot be easily used along-side market-standard products	1

14 ***Criteria:*** use of components of the size that can be handled by the scale of one average adult

Product placement/ removal (dimensions of the product)	**rating**
The product is movable by hand easily (≤1000x600x100, lxbxd)	9
The product is movable by hand (≤2600x600x100, lxbxd)	7
The product is movable by two people	6
A hand truck is needed to place/ remove the product	5
A pump truck is needed to place/remove the product	3
A forklift truck is needed to place/ remove the product	2
A crane with 2t power is needed to insert/ extract the product	1

15 ***Criteria:*** use of components of the weight that can be handled by the scale of one average adult

Labour intensiveness	**rating**
The product is manageable with one hand (<7.5kg)	9
The product is manageable with two hands (7.5-12kg)*	8
The product is liftable in accordance with working conditions (12-23kg)*	7
The product requires two people to manage (23-50kg)*	6
A hand truck is needed to place/ remove the product (50-150kg)**	4
A pump truck is needed to place/remove the product (150-2000kg)**	3
A forklift truck is needed to place/ remove the product	2
A crane with 2t power is needed to insert/ extract the product	1

** according to the law for working conditions in the Netherlands*

*** derived from the average capacity of market standard products*

16 ***Criteria:*** connections are accessible during assembly

Accessibility connections (assembly)	**rating**
Connection is freely accessible, ample space for hands and/or tools	9
Connection has restricted access for hands or tools	7
Connection is accessible after removing parts, not damaging objects	6
Connection is accessible after removing parts, causing repairable damage of objects	3
Connection is not accessible, irreparable damage of objects	1

17 ***Criteria:*** connections are accessible during disassembly

Accessibility connections (disassembly)	**rating**
Connection is freely accessible, ample space for hands and/or tools	9
Connection has restricted access for hands or tools	7
Connection is accessible after removing parts, not damaging objects	6
Connection is accessible after removing parts, causing repairable damage of objects	3
Connection is not accessible, irreparable damage of objects	1

18 ***Criteria:*** use of dry connections/ avoid chemical connections

Connector type	**rating**
Products are connected without dedicated connectors (dry connection)	9
Products are connected with added elements (clips, velcro, magnets)	8
Products are connected with added elements (bolts and nuts, suspension, corner joints, screws), that can be easily kept intact during disassembly	7
Products are connected with a direct integral connection (pins, nails), during disassembly it is hard to keep the connector intact	4
Products are connected with a fixed connection, but can be detached with some difficulty (soft chemical compounds like kit connection, foam connection like PUR)	2
Products are connected with a fixed connection, and cannot be detached without heavy damage to the product or its host (hard chemical compounds like adhesives, concrete pouring, welding, cement, chemical anchors,)	1

19 ***Criteria:*** use of damage resistant connectors/ components

Damage during Assembly/Reassembly	**rating**
No damage that hinders the function of the product in any way	9
Small damage that does not hinder the function of the product	8
Small damage that hinders the function of the product in a small way, but does not require immediate repair	6
Significant damage that hinders the function of the product, repair is required after disassembly	3
Extensive repair and/or replacement of several parts is required after disassembly	2
Significant damage to the point where the product is unusable after disassembly	1

20 ***Criteria:*** use of damage resistant connectors/ components

Damage during Disassembly	**rating**
No damage that hinders the function of the product in any way	9
Small damage that does not hinder the function of the product	8
Small damage that hinders the function of the product in a small way, but does not require immediate repair	6
Significant damage that hinders the function of the product, repair is required after disassembly	3
Extensive repair and/or replacement of several parts is required after disassembly	2
Significant damage to the point where the product is unusable after disassembly	1

21 ***Criteria:*** use of modular systems / components can be interchanged

Interchangeability components	**rating**
Components can be interchanged with eachother and other systems (developed by other companies)	9
Components can be interchanged with eachother and other systems within the company it was developed	8
Components can be interchanged with eachother	7
Part of the components can be interchanged with eachother	4
Components can not be interchanged with eachother	1

User Domain – *Process Related Aspects*

22 ***Criteria:*** freedom of choice in availability

Availability of parts	**rating**
Parts are separately available by different suppliers	9
Parts are separately available by one supplier	6
Parts are not separately available, but only as a whole product	3
Products have to be bought in quantities	2
Parts are/product is not available for private sale	1

23 ***Criteria:*** freedom of choice in variation in size

Variation of the product in sizes	**rating**
Product is available in a variety of sizes, all kind of dimensions are possible	9
Product is available in a limited variety of sizes, covering the average requested dimensions	7
Product is available in standard sizes, the product can be easily adjusted to preferred dimensions	6
Product is available in standard sizes, the product can be adjusted to preferred dimensions with difficulty	4
Product is available in a limited variety of sizes, covering just a small part of requested dimensions, adjustments can not be made	2
Product is available in standard sizes, adjustments can not be made	1

24 ***Criteria:*** freedom of choice in variation in aesthetics

Variation of the product in aesthetics	**rating**
Product is available in a variety of models, serving all preferences of different end-users (color, texture)	9
Product is available in a limited variety of models, serving the preferences of the average end-user (color, texture)	7
Product is available in standard model(s), personal preferences can be implemented with separate materials and/or tools (color, texture)	5
Product is available in a limited variety of models, serving the preferences of just a small group of end-users (color, texture)	3
Product is available in standard model(s), personal preferences can not be implemented (color, texture)	1

25 ***Criteria:*** minimize the total number of motions to assemble and disassemble

Number of motions	**rating**
<4 motions are required to assemble/disassemble	9
5-7 motions are required to assemble/disassemble	8
8-10 motions are required to assemble/disassemble	6
11-15 motions are required to assemble/disassemble	4
16-20 motions are required to assemble/disassemble	3
20-25 motions are required to assemble/disassemble	2
>25 motions are required to assemble/disassemble	1

26 ***Criteria:*** minimize required knowledge for assembly and disassembly

Required operator qualifications	**rating**
Does not require operator to have any offical qualifications	9
Requires operator to acquire a single certificate	7
Requires operator to acquire multiple certificates	5
Requires operator to have completed the equivalent of a three year long full-time education, but no additional qualifications	3
Requires operator to have completed the equivalent of a three year long full-time education, and acquire an additional certificate	1

27 ***Criteria:*** when necessary, use of simple and generic tools

Tool complexity	**rating**
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Powered tools are required	5
Special tools are required	1

28 ***Criteria:*** repetition of assembly operations

Repetition of assembly operations	**rating**
Assembly/disassembly operations of one type of connector with related components is similar to daily life operations (hanging a painting, assembling technical devices etc.), or the operation is repeated $\geq$30 times	9
Assembly/disassembly operations of one type of connector with related components can be associated with ready-to-assemble furniture, or is repeated $20<x<30$ times	7
Assembly/disassembly operations of one type of connector with related components can hardly or not be associated and is repeated $10<x<20$ times	5
Assembly/disassembly operations of one type of connector with related components can hardly or not be associated and is repeated $1<x<10$ times	3
Assembly/disassembly operations of one type of connector with related components can hardly or not be associated and is conducted just once	1

29 ***Criteria:*** provide in instructions for assembly

Instructions for assembly	**rating**
Instructions for assembly are available as a movie where an expert shows how assembly should take place	9
Instructions on paper comprised of text + illustrations for assembly of the product are available	8
Instructions on paper comprised of illustrations for assembly of the product are available	7
Instructions on paper comprised of descriptions for assembly of the product are available	5
Instructions for assembly of the product are not available, assembly can be done with common sense	3
Instructions for assembly of the product are not available, assembly is hard to be done	2
No instructions are added to the product, assembly can be done only with expert knowledge	1

30 ***Criteria:*** provide in instructions for disassembly

Instructions for disassembly	**rating**
Instructions for disassembly are available as a movie where an expert shows how disassembly should take place	9
Instructions on paper comprised of text + illustrations for disassembly of the product are available	8
Instructions on paper comprised of illustrations for disassembly of the product are available	7
Instructions on paper comprised of descriptions for disassembly of the product are available	5
Instructions for assembly of the product are available, disassembly can be done with assembly instructions in mind	4
Instructions for assembly of the product are available, disassembly is hard to be done	3
No instructions of the product are available, assembly and disassembly can be done with common sense	2
No instructions of the product are available, assembly and disassembly can be done only with expert knowledge	1

31 ***Criteria:*** action and structural diagrams

Kind of diagrams	**rating**
Instructions are provided with structural and action diagrams from one point of view	9
Instructions are presented with action diagrams from one point of view	8
Instructions are presented with structural diagrams, from one point of view	6
Instructions are provided with structural and action diagrams from different point of views	5
Instructions are presented with action diagrams from different point of views	4
Instructions are presented with structural diagrams, from different point of views	3
Instructions are provided with illustrations other than structural and/or action diagrams from one point of view	2
Instructions are provided with illustrations other than structural and/or action diagrams from different points of view	1

32 ***Criteria:*** provide in step-by-step instructions

Perceived length of assembly / disassembly	**rating**
Instructions are presented in a step-by-step sequence, first a large step is given	9
Instructions are presented in a step-by-step sequence, steps require the same amount of operations	7
Instructions are presented in a step-by-step sequence, alternation of small and large steps	3
Instructions are presented in a step-by-step sequence, the last step is a big step compared to the former ones	2
Instructions are presented in a single illustration or as separate individual steps	1

Total score /32 criteria	

Reflection: Research towards design

Modular infill systems for unskilled future residents

Based on the master 3 paper: *'An evaluation method to assess user-friendly design for assembly and disassembly of modular infill systems.'*

Where the aim of the research was to develop an evaluation method to assess existing and new designs of modular infill systems on their ability to be assembled and disassembled by unskilled residents, the design phase of the graduation project aimed to design such a system. As was suggested in the end of the research, first the factors out of each criteria with the highest score were taken apart. These formed a list of guidelines as the ultimate goal for a new design (figure 1).

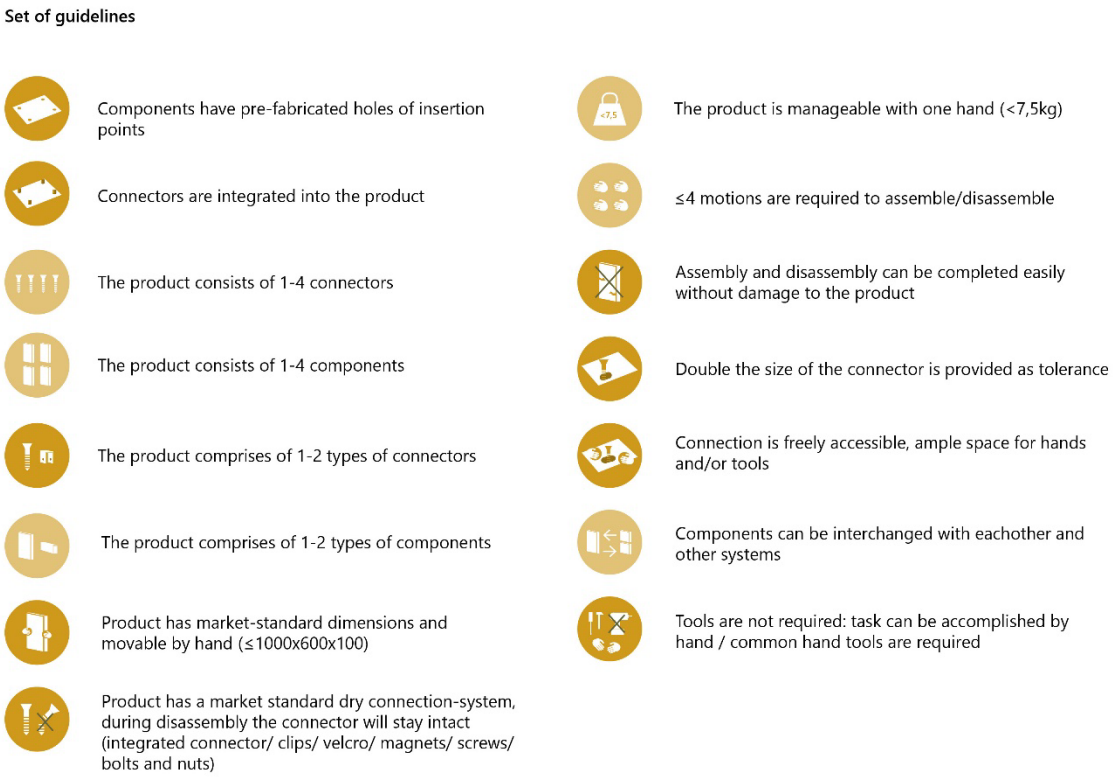


Figure 1. A set of guidelines as the base for the design of modular infill systems that can be assembled and disassembled by unskilled residents (own illustration).

After the formulation of the set of guidelines, I defined the elements that I needed for a complete infill system for the apartments I wanted to design. Where I first only looked at the fixed interior of the home, including partitioning walls, the bathroom and the kitchen, soon in the design process I figured out that the system should be something more. As I did not yet mention it, the piping systems are also part of all three aspects defined above and should be included in the new design and composition of the infill system. Next to this, the project focuses on starters, the target group that experience a lot of difficulty in finding a home that they can afford and at the same time is in line with their residential preferences. The 'extra' preferences that came to the front in different surveys among starters include 3-rooms, a garden and a house on the ground floor. So then I was thinking, which of the three preferences that are now mostly not feasible for starters can I solve with the modular infill system? So then I bumped into some interesting solutions in the design of Tiny houses. One of them was a bed that could be slid under the elevated bathroom to make place for a desk that could be folded out. This meant that one room could be used for two different functions instead of needing two separate rooms as can be mostly seen in average apartments. After this, the elements of a modular infill system comprised for me not only the fixed interior but also furniture. More important, the design of the

system should not only aim for the possibility of being changed in a view years in new preferred compositions, but with an active attitude of residents be changed during the day, fitting to their different activities (figure 2).

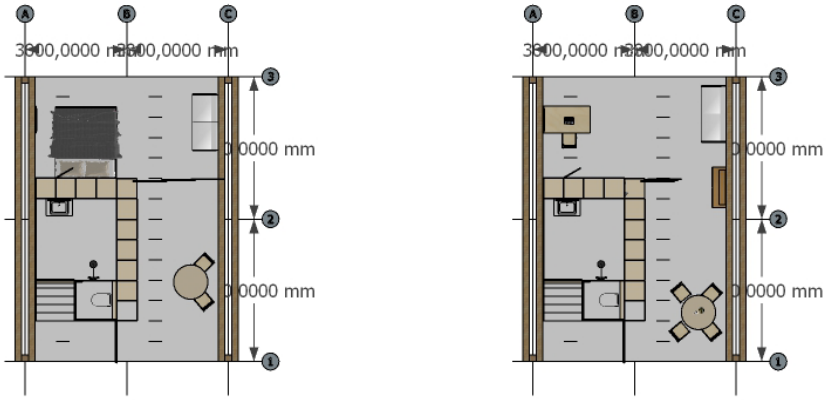


Figure 1. First models of a modular infill system that could be adapted during the day (own illustration).

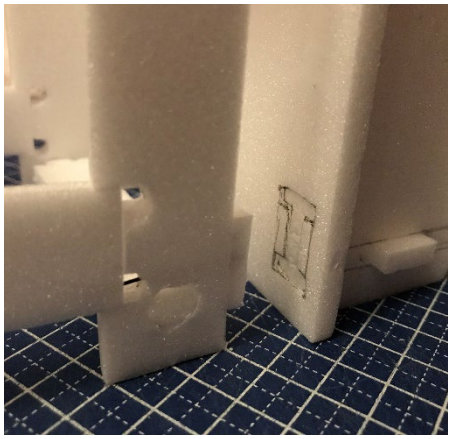
When I made the first sketches for such an infill system and did some calculations, I already noticed during the design that I could not comply to six of the fifteen guidelines. These are the amount of connectors, the amount of components, the amount of types of components and connectors, the weight that meet the load that one person is allowed to carry and the minimum amount of motions for assembly and disassembly (colored light yellow in figure 1).

When evaluating them, the last two are not a problem within the concept. The elements that are designed will not weigh less than 23 kilograms, but do weigh less than 50 kilograms. This is the weight two persons can carry together. The concept of the whole project is to see how residents can be involved in circular building design. This because we have to make the change from a sustainable towards a circular and sustainable built environment to save the world's climate and its material resources. To involve residents in circular building solutions by literally let them help building their homes, knowledge around this topic is provided and the potential of these solutions is made visible. By literally involving them in the building process by letting them build up their own infill, the circular solutions become part of the intrinsic motivation of the residents. As a result, awareness of circularity and support for a circular built environment will be increased, encouraging the parties, like the municipality and manufacturers, that should make it happen. So with two people that are needed to assemble and disassemble the system, due to the weight of some components, knowledge about the now unknown system will be spread faster between residents.

Secondly, the amount of motions for assembly and disassembly is way exceeded when designing a whole infill system. A rough count of a first design resulted in 163 components and 31 installations that will require even more motions to fully assemble or disassemble. The research ended in the guideline 'less than four motions are required to assemble and disassemble' based on literature and the assumption that this would avoid people's resistance to the assembly process. However, within the research it was also appointed and described that a minimum of 30 motions will enhance learning and remembering the operations. Since the aim of the infill is to not only be assembled for once, but to be disassembled and reassembled over time, this could help in learning and remembering the operations needed for the next times.

As the two above mentioned aspects still fit the guidelines when they are reformulated in line with the concept of the project, the first four did not. So for these four I looked for the best fitting solution. First for the amount of types of connectors, I evaluated different circular infill designs to expand the knowledge that was gained from the research. I analyzed the circular design of the kitchen developed by the TU Delft and the bathroom/cabinet/kitchen unit and circular walls of The New Makers. Here I noticed that all three products, that were designed to be easily assembled and disassembled, used connections that can be related to acts in daily life. The Circular kitchen makes use

of a click-connection, which can be related to closing a food container or press studs. The circular products of The New Makers make use of dry connections that are CNC-milled into the wooden components. No extra elements are added in terms of connectors. The connections itself are based on a push/slide motion, that can be related to opening or closing a cabinet or drawer. To get a grip on these connections and see how they work and how they could work together, I made a 1:4 scale model of the products (see images 1, 2 and 3). In this study I also analyzed the rotating mechanism that is needed to realise the folding bed. The mechanism for both the folding bed as well as the sliding bed are mechanisms that are also used in a lot of Ikea-furniture and it is most likely that people are familiar with the assembly method of these connectors. Because to be honest, in the first phase of implementing the research into the design, I had the feeling that I needed to invent something new. However, after these studies I found out that I do not have to reinvent connections or components, but combining the best of what already exists to fit the project's strategy and the goals I pursue within the concept.


Images 1,2 & 3. Exploration of the components and connectors in 1:4 scale models of existing systems that can be assembled and disassembled. The left image shows the modular wall of the New Makers. The centre image shows the kitchen frame and the possible connection to the wall with the similar dry connection that was used for the wall. On the right a picture of the rotating mechanism can be seen, that could be applied to a bed (own images).

In contrary to the amount of types of connectors, the amount of components and connectors far exceeded the number that was determined in the research. A solution related to the design of the system in accordance to the requirement of less than five components and less than five connectors, was hard to find, or so to say impossible. Therefore I looked for another strategy. I decided to evaluate the importance of the guidelines. This was also mentioned in the discussion and recommendations in the last section of the research as an important part for the validation and sharpening of the evaluation method that can be done in future research. I already noted it myself when moving to a new home and assembling Ikea furniture. Some of the guidelines were experienced more important than others. Some could cause annoyances and reluctance. Next to this, I could at a guideline: 'Components are hold by a frame, the components cannot tip over during assembly'.

To make a first attempt to validate these findings, I did a questionnaire among a small group of people who all had Ikea-assembly experience, but no (building-related) construction skills. The people had to pick five out of the entire list of guidelines that they find most important during assembly and order them according to their importance (see Appendix A). The number of five was chosen, since it is just enough to gain a clear distinction between the importance of certain guidelines, but not too much so people get confused, find it hard to order all the guidelines causing frustration or think that it costs too much time so that the rushing through it. The option was open to the respondents to add more than five guidelines/requirements to their top list. As a result, I could make a first estimation if the two guidelines should be taken into account as a priority.

The results of the questionnaire showed that among the first ten people that answered, already 7 mentioned in their top 5 'the product consists of a minimum amount of components' and/or

‘the product consists of a minimum amount of connectors’ (see Appendix B). A minimum amount of components was slightly preferred compared to a minimum of connectors (6:4). However, although I explained in the text of the questionnaire, it is likely possible that the respondents sometimes have mixed up the different definitions. Secondly, interesting to see is that also five out of the nine respondents included in their top five the requirement ‘the product consist of a minimum amount of different components’ and/or ‘the product consist of a minimum amount of different connectors’. Two of the respondents that had this guideline in their top list, did not have the amount of components of connectors included. Next to this, when a respondent included the guideline ‘connectors are integrated into the product’, it was remarkable that it was always noted on the first or second place.
A third point that stood out was that eight of the ten respondents noted the guideline ‘The product is manageable by one person’. I am still wondering if they have the idea that assembling alone would go faster because they do not have to check their companion. Nevertheless, that is the first thing that came to my mind. A side note that one of the respondents wrote, showed however that the guideline was maybe interpreted different and focuses on the ability to move the product or elements in case they would change its position. The main message of this note included also something else. It says: ‘during the first assembly, for me it wouldn’t matter if I have to carry out a lot of motions to assemble. However, when I need to disassemble the product to be able to move it to another position, I do not want to have to carry out the same amount of motions.’ This keen observation of one’s feelings and thoughts during assembly and disassembly is the reason to split the guideline for the number of motions into one for assembly, one for disassembly and one for reassembly. Another suggestion made by one of the respondents, was to show in the instruction video or paper instructions also what could go wrong during assembly or disassembly. This idea was likewise found in the research and resulted in the addition of video instructions as the highest rating factor in the criteria ‘provide in instructions’.

To conclude, this small survey and first attempt to involve the unskilled residents, showed that when integrating the connectors to the components and so avoiding a bunch of individual connectors, most of the reluctance, concerns or possible difficulty will be taken away before and during assembling or disassembling. Comparing to the analyzed wall system, the circular kitchen and the rotation and sliding mechanism, only the rotation and sliding mechanism are not yet regularly integrated into the component. The dry connection of the wall system is part of the component itself and the click-connection of the circular kitchen is already integrated into the components during production. Just as with the click-connection, the rotation and sliding mechanism could also be already fixed on one of the components if preferred. Do we link this to the bigger picture of processes and the roles that different people will have in this, is that the infill system would cost a little bit more due to extra operations of the people at the workshop. Finally, to prevent overwhelming the residents with a large amount of components, the same strategy as mentioned above could be applied. For example, the finishing of a kitchen could already be applied in the workshop. However, components like walls and installations do not have that possibility. Note the assumption is made that installations are all plug-and-play when the infill system is realized in the near future. With this solution, the installation part of the infill system will be at the same assemble and disassemble level as the other components: resident-prove!

In the end I learned a lot from both the transition from the research towards the integration of it into the concept of the whole project as well as the small questionnaire. Although the first steps are made on paper and some physical models, to prove the modular system’s success or failure among unskilled residents, it should be realized 1:1 and tested within different groups of residents, age, gender, work background, etc. A dream that I hope to realize in the near future. Overall my vision is that, independent of skills and what kind of guidelines these system follow, we need people that are enthusiastic about the concept and would like to involve in it to see what we could achieve with the infill system and how it could be improved. That is why I chose starters as the target group of the project. The group of young people that are part of the generation that would like to roll up their sleeves and intervene to ensure the earth’s health and so their future.
To conclude, the concept has the potential to be integrated in all different residential buildings and become a national system. All building would have their own local material bank with the elements which can be easily exchanged between the different projects due to their size. A platform will keep all the stock information, the possibility to upload new designs or vote for these and the personal

accounts of residents in which they can see and change their designed infill. So although the modular infill system is an infill system tailored by each resident, the concept can be implemented in each, for now residential project. The size of the elements encourages users to think about new smart elements and stimulate efficient use through exchange.

Appendix A

The questionnaire as it was asked to a group of unskilled Dutch residents.

Richtlijnen voor het ontwerp van een modulair invulsysteem voor in de woning

Hoi allemaal,

Voor mijn afstudeerproject heb ik gekeken naar hoe ik bewoners kan betrekken in circulaire bouwoplossingen. Dat zijn bouwoplossingen die ofwel te monteren maar ook te demonteren zijn en zo weer hergebruikt kunnen worden elders of bouwoplossingen die gebruik maken van hernieuwbare materialen zoals hout. Materialen die na de gebruikslevensduur weer in de natuur gecomposteerd kunnen worden. Ik kwam uit op een modulair invulsysteem voor de woning. Dit omhelst de wanden binnen de woning, maar ook de keuken, de badkamer, de kasten en eventueel een bed en bureau. In een onderzoek heb ik gekeken naar hoe ongeschoolde bewoners dit systeem zelf kunnen samenstellen en in elkaar kunnen zetten om zo te leren over circulariteit en wat het kan betekenen voor de woning. Uit dit onderzoek kwamen 15 richtlijnen naar voren voor het ontwerp van een bewoners-vriendelijk invulsysteem. Na mijn verhuiservaringen en Ikea-meubels heb ik deze vanuit mijn eigen ervaring nog wat aangescherpt. Mijn vraag aan jullie is of jullie vanuit de op de volgende pagina beschreven 14 richtlijnen de voor jullie 5 belangrijkste op een rij kunnen zetten en deze naar mij terug kunnen mailen. Het liefst op nummer 1 de voor jou belangrijkste, op nummer 2 de iets minder belangrijke enzovoort. Mocht je er maar 3 hebben, dan is dat ook prima, heb je er 7 ook goed! Goed om van te voren te melden is dat binnen het invulsysteem onderscheid is gemaakt tussen onderdelen, denk aan de planken van een kast, en verbindingselementen, denk aan schroeven, deuvels, spijkers etc. Mocht je nog vragen of aanvullingen hebben dan hoor ik dat graag.

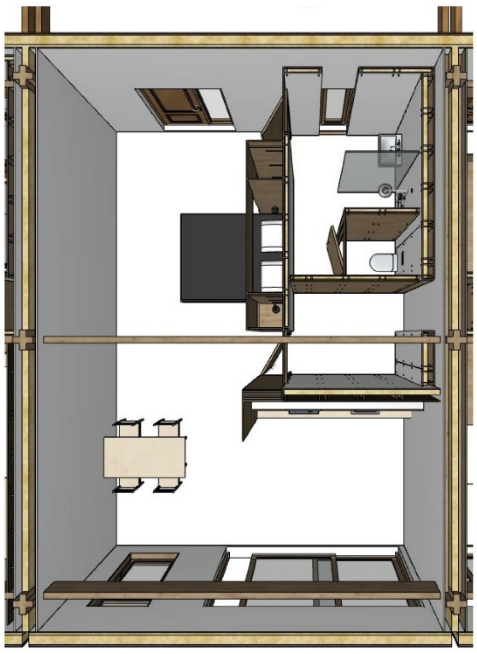
Heel erg bedankt alvast!

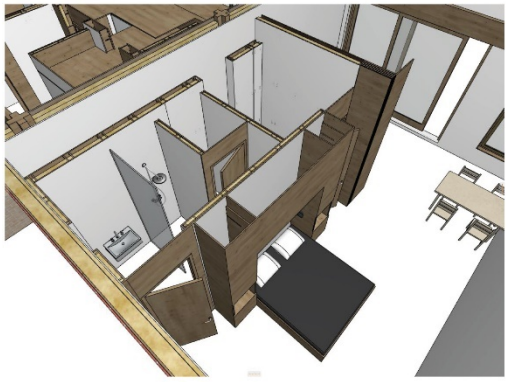
Melanie
m.berends@student.tudelft.nl

Belang van richtlijnen
(Eigen ervaring met het monteren/demonteren van bijvoorbeeld Ikea meubels)

1.
2.
3.
4.
5.

Als voorbeeld een impressie van een van de ontwerpen.
Onder: bovenaanzicht.
Rechts: 3d views.





Voorgeboorde gaten

Verbindingselementen (denk aan schroeven, houten deuvels) die al in een onderdeel zijn vastgezet.

Het aantal verbindingselementen is minimaal.*

Het aantal onderdelen is minmaal.*

Het aantal verschillende verbindingselementen is minimaal.*

Het aantal verschillende onderdelen is minimaal.*

De onderdelen zijn verplaatsbaar met de hand (geen gebruik van een steekkarretje etc. nodig).

De onderdelen zijn te hanteren door 1 persoon.

Een minimaal aantal handelingen is vereist om het product te monteren/ demonteren.

Bij het plaatsen van een verbindingselement (bijvoorbeeld een schroef) is tolerantie meegenomen (dat wil zeggen, er is meer ruimte aanwezig dan dat de schroef nodig heeft voor bijvoorbeeld de boor of om schade te voorkomen).

Er is ruimte rondom de verbinding om met twee handen het verbindingselement te monteren (ruimte rondom bijvoorbeeld een schroef).

Elektrisch gereedschap en speciaal gereedschap is niet nodig: Het product kan gemonteerd worden met behulp van de eigen handen of simpel handgereedschap zoals een schroevendraaier of hamer.

De onderdelen worden geplaatst op een frame zodat deze niet om kunnen vallen tijdens het monteren.

Er is een video beschikbaar waarin het monteren en demonteren wordt voor gedaan.

* Kies je een van de richtlijnen waar 'minimaal' bij staat en je hebt hiervoor al een getal/aantal in je hoofd, dan kun je 'minimaal' vervangen door 'maximaal ... elementen of verbindingen'.

Appendix B

Results questionnaire

1) Male, 20-25
1. The product comprises of a minimum number of types of components.*
2. Connectors are integrated into the product.
3. Components have pre-fabricated holes of insertion points.
4. A minimum number of motions is required for assembly and disassembly.
5. An assembly and disassembly video is available.

2) Male, 35-40
1. Tools are not required: task can be accomplished by hand / common hand tools are required.
2. The product comprises of a minimum number of types of connectors.*
3. Components have pre-fabricated holes of insertion points.
4. The product is manageable with two hands (<30kg).

3) Female, 60-65
1. Connectors are integrated into the product.
2. The product consists of a minimum amount of connectors*
3. The product consists of a minimum amount of components.*
4. An assembly and disassembly video is available.
5. The product is manageable with two hands (<7,5kg).

4) Male, 60-65
1. Components have pre-fabricated holes of insertion points.
2. The product consists of a minimum amount of connectors*
3. The product consists of a minimum amount of components.*
4. The product is manageable by one person (<23kg).
5. Tools are not required: task can be accomplished by hand / common hand tools are required.
6. Components are hold by a frame, the components cannot tip over during assembly.
7. An assembly and disassembly video is available.

5) Male, 35-40 (handy-man in his own home)
1 The product is manageable by one person (<23kg).
2: The product comprises of a minimum number of types of components.*
3: The product comprises of a minimum number of types of connectors.*
4: The product consists of a minimum amount of components.*
5: The product consists of a minimum amount of connectors.*

6) Female, 20-25
1. An assembly and disassembly video is available.
2. The product is manageable by one person (<23kg).
3. A minimum number of motions is required for assembly and disassembly.*
4. The product consists of a minimum amount of components.*
5. Tools are not required: task can be accomplished by hand / common hand tools are required.

7) Male, 55-60
1. Components have pre-fabricated holes of insertion points.
2. Connectors are integrated into the product.
3. The product consists of a minimum amount of connectors.*
4. The product consists of a minimum amount of components.*
5. The product comprises of a minimum number of types of components.*
6. An assembly and disassembly video is available.
7. The product is manageable by one person (<23kg).

8) Female, 50-55
1. The product consists of a minimum amount of components.*
2. A minimum number of motions is required for assembly and disassembly.*
3. Components have pre-fabricated holes of insertion points.
4. Tools are not required: task can be accomplished by hand / common hand tools are required.
5. The product is manageable by one person (<23kg).

9) Female, 35-40
1. Tools are not required: task can be accomplished by hand / common hand tools are required.
2. Components have pre-fabricated holes of insertion points.
3. Connectors are integrated into the product.
4. A minimum number of motions is required for assembly and disassembly.*

10) Male, 35-40
1. An assembly and disassembly video is available.
2. Tools are not required: task can be accomplished by hand / common hand tools are required.
3. The product is manageable by one person (<23kg).
4. The product consists of a minimum amount of components.*
5. A minimum number of motions is required for assembly and disassembly.*

**The guidelines; 'the product consists of 1-4 connectors', 'the product consists of 1-4 connectors', 'The product comprises of 1-2 types of connectors' and 'The product comprises of 1-2 types of components', was changed in the questionnaire in; 'the product consists of a minimum amount of connectors', 'the product consists of a minimum amount of components', 'the product comprises of a minimum number of types of connectors' and 'The product comprises of a minimum number of types of components'. The same was done for the number of motions required for assembly and disassemby. This was done, because it already appeared in the design process that just 1-4 components was not feasible. A new number for the minimum is dependent on the size of the infill. Because I was curious about the thoughts on this minimum number of the respondents, I asked them if they could fill it in when they had a number in mind.*