SEAM SEALS FOR REMOUNTABLE BUILDINGS

An evaluation of remountable seam sealing products

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ABSTRACT

Remountability is a design strategy, which focus on reducing material consumption by minimizing waste and maximizing the reuse potential. One of the important issues of remountability is that there is no standardized evaluation method that can be used within the field of the built environment to compare design solutions. This paper shows how remountable seam seal solutions within the field of the built environment can be evaluated and what products are suitable for specific applications. The proposed evaluation method is developed by using multi-criteria decision making methods and is based on descriptive ratings. The application of the method is focused on comparing remountable solutions to find the most suitable seam sealing products to realize a portable building that can be rebuilt at least twenty times during the expected lifespan of fifty years.

KEYWORDS: *Remountability, AHP, Multi-Criteria Decision making, Evaluation method, Seam seals.*

1. Introduction

Within the field of the built environment, biological and technical materials are often being mixed by the use of concrete, sealants or adhesives. After their lifetime neither of the bonded materials can be reused or re-cycled without the use of labour intensive activities or chemical processes. This leads to a faster depletion of resources next to the pollution that sealants and adhesives brings. In addition, most assembled materials, elements and components in buildings have low or no potential for reuse, remanufacture or recycling, because they are not standardized.

Remountability is a design strategy that can be used to tackle this problem, but the research work that has been done is limited and mostly focussed on product design. The strategy focuses on the reduction of new material consumption by making material, elements or components detachable. Therefore waste can be minimized and reuse (and remanufacture) can be maximized, which can contribute to realise a circular economy.

1.1. Problem statement

Some research have been done on the implementation of remountability, but there is no standardised or universal method to evaluate remountability within in field of the built environment, which can be used to compare different design approaches regarding remountability (Vanegas, et al., 2018). This would help to give insight in what factors are most important to realizing a remountable component or building in a specific context and with a specific goal or vision.

Where Design for Disassembly (DfD) is mainly focussed on separating parts, energy efficiency and indoor climate are related to the tightness of seams. This contradiction have hardly been researched, while this is fairly important to realise a circular economy. Airtightness, watertightness and insulation, but also soundproofing and fire resistance are important criteria to achieve a lowered energy demand and a better indoor climate. Furthermore seams are the places where most adhesives, sealants and other sticky filling materials can be found. These problems led to the following research questions:

“Which types of seam seals are suitable to realize a remountable and portable housing system that can be rebuilt at least twenty times?”

This question resulted in the following subquestions:

- “How can the term remountability be defined?”
- “How can remountability be evaluated within the field of the built environment?”
- “Which types of seam seals are available and what purpose do they fulfil?”

1.2. Methods

This thematic research paper is written in the context of the Architectural Engineering (AE) Intecture graduation studio, which is part of the Master of Science (MSc) Architecture, Urbanism and Building Sciences graduation program. The topic of this paper is based on a technical fascination which has a strong relation with the overall design question. The goal of the graduation is to design portable dwellings for temporary unused areas, with the keyword ‘remountability’ as the technical fascination and challenge.

To give answers to the research question, there will first be searched for useable and relevant evaluation methods by using literature, whereby the focus is aimed on the application within the built environment. The findings from this research will then be used to optimize a evaluation method for remountability by selecting relevant criteria and evaluating them. This optimized method will be based on findings within existing evaluation methods by using literature and will be made in collaboration with the students Axel Beem, Léon Veldhuis and Steven Lammersen, which can be found in chapter 3.

To test this method, several different seam applications with different performance requirements will be used to compare a number of available seam sealing products. The goal of remountability is strongly depending on the vision of the designer. This is why an explanation of this vision is made, which can be found in chapter four.

1.3. Theoretical framework

In literature Design for Deconstruction related work is limited (Güngör, 2006) and most work is related to product design. Furthermore evaluation methods of disassembly are often based on time and most research work is focused on mathematical algorithms which optimizes the sequence of disassembly (Mital, 2008).

Research that is more related to evaluation methods of remountability within the built environment is often focussed on the joints (nodes) whereby seams (lines) are left out, while this is highly important for the airtightness and watertightness of the building. Research on the remountability of seam seals is therefore relevant and could contribute to an economy with less waste and a higher potential for reuse.

2. Disassembly & Remountability

Design for Disassembly (DfD) is a design strategy within the field of the built environment that focuses on reducing new material consumption by minimizing waste and maximizing the reuse potential of materials, elements and components (Guy & Ciarimboli, 2008). This strategy is also intended to make elements more maintenance friendly and remanufacturing friendly. Disassembly is a method for separating components into parts, elements or other groupings without destructing it (Güngör, 2006).

Remountability goes one step further then this strategy and is more focused on reusing and reassembling materials, elements and components instead of remanufacturing or recycling. Reusing is the second highest tier next to refuse (of rethink) in the scale of the 7 R's of the circular economy, which is higher than the ambitions of Design for Disassembly. It is important to mention that remountability is a term that have hardly been used in literature and is often seen as disassembly.

3. Evaluating remountability

To select the most suitable design solution for remountability an evaluation method has been developed. The goal of the evaluation method is to create a tool that can be used for decision making in the design process and is intended for the comparison of elements or products in the field of the built environment.

The remountability evaluation method is inspired by a design tool developed by Devdas Shetty. This tool is based on rating factors and consist out of six criteria that can be evaluated using lists with several options (Shetty & Ali, 2015). The method can be improved and altered by prioritizing certain criteria and need to be made more suitable for the field of the built environment. This optimisation will be explained in the next paragraphs.

3.1 Structure of the evaluation method

These types of evaluation methods are often based on a system called Analytical Hierarchy Process (AHP), which is invented by Thomas L. Saaty. This multi-criteria decision making (MCDM) method uses a hierarchy which compares the relation between all criteria and alternatives.

Another widely used MCDM method is the Analytic Network Process (ANP) which is also invented by Saaty. This method is focused on a network of relations and can be used when alternatives can influence the weighting of criteria this method can be used. Special calculation software and programming knowledge is required for using this method. This is why the remountability evaluation method is based on the AHP method. Different profiles can be made by using a pair comparison to translate a specific vision or goal into a set of weighted criteria, which can be used to calculate a score for every alternative.

3.1. Criteria

There are many criteria related to remountability with different levels of priority. Several criteria from existing evaluation tools were selected by eliminating irrelevant criteria. Criteria like motion complexity and internal dirt traps were eliminated because they are specifically used in the product industry. Some of the terms found in literature show many similarities and are therefore combined to reduce the amount of criteria.

Tool complexity, accessibility, the number of fasteners and the connector types are criteria which are widely used in design for disassembly related work (see table 1). The number of parts and the amount of fasteners have a huge impact on the efficiency of disassembly processes, whereby the fastener type is crucial according to Askiner Güngör (Güngör, 2006). Other researchers like Fernanda Cruz Rios claim that the accessibility of connections and the separation of systems is highly important for disassembly. Simple structures and forms which allow standardisation are therefore desirable (Rios, et al., 2015).

Table 1. Design for Disassembly criteria mentioned in literature

Criteria	Times mentioned
Functional damage	3
Tool complexity	8
Accessibility	9
Labour intensiveness	5
Number of elements	9
Number of fastener types	4
Fastener type	7
Replacement factor	2
Standardization	6
Durability	3
End of life potential	4
Recycling factor	5

3.2. Descriptive rating (rating scale)

The rating scale uses descriptions of varied options (with a score from 1 to 9) that have influence on the grade of remountability. Score 9 can be seen as the best case scenario to stimulate remountability, where score 1 is the worst possible scenario (see figure 1). The range is therefore depending on its context and can be changed.

The use of numbers in the options have been avoided because a sentence (which is familiar) is more sufficient than a numerical judgement according to researchers (Ishizaka & Labib, 2011). The method is moreover more user-friendly because the options are recognizable for people involved in the field of the built environment and no additional time calculations are needed.

Tool complexity	**Rating**
Tools are not required; task is accomplished by hand	9
Common hand tools are required	7
Powered tools are needed	5
Special tools are required	3
Significant time delay	-2
Special care/techniques are needed	-1

Figure 1. Descriptive rating scale from the end of cycle potential criteria

3.3. Evaluation method

A clear vision or goal and some construction knowledge is needed to use the evaluation method. Specific properties like lifespan, connector type and end of cycle potential of materials or products are also necessary.

The first step of using the remountability evaluation method is to determine the priority of certain criteria by using a Pair Comparison Chart (PCC). All criteria are compared in pairs and rated from a scale 1-9, which result in *profile factors*. The scale, which is invented by Thomas L. Saaty ranges between equal importance (1) to extreme importance (9). The alternatives which will be compared are rated using lists with several options with a scale from 1 to 9. The scores for each criteria are then multiplied by the *profile factors* generated with the pair comparison to form a final score for every alternative. The final scores can then be compared and a decision can be made.

This method will be further explained in an application example, where different seam seals for a portable and remountable dwelling are compared.

4. Evaluation of seam seal products

Several seal sealing products have been tested on the basis of a vision for a remountable design. This has been done, because the weight of the criteria are partly dependent on the vision or goal and this will also explain why certain criteria are favoured over others. The focus in this vision is on re-building or moving a building to a new location within its lifespan with the least amount of hassle. A remountable and portable system with an intended lifespan of fifty years, which will be rebuild at least ten times forms the scenario for the evaluation. The vision is translated into factors for the criteria by using pair comparison, which can be found in appendix A. The result of this pair comparison is shown in table 2.

Table 2. Design for Disassembly criteria mentioned in literature

Group	Criteria	Weight factor
Assembly & Disassembly (39,3%)	Number of connectors	6,1 %
	Tool complexity	2,5 %
	Connector type	**12,5 %**
	Required accessibility	7,8 %
	Labour intensiveness	0,7 %
	Ease of disassembly	9,7 %
Re-use potential (56,1%)	End of cycle potential	**13,2 %**
	Durability	**14,0 %**
	Degree of standardization	6,2 %
	Replaceability	8,3 %
	Functional damage	**14,4 %**
Process & Costs (4,8%)	Transport optimisation	3,5 %
	Costs	1,3 %

4.1. Application types

Several application types that are crucial for remountable buildings are used in the set up to test a variety of seam sealing product types. These applications have been divided into four group types (see figure 2). Structural seams is the first group and is intended to transfer forces between elements. The second group is focussed on the expansion of seams due to temperature differences and other influences. The application type 'movement' can be used on moving parts in a building envelope. The last group seals elements to form planes, such as claddings and water vapour barriers (Knaack, et al., 2012; Allen & Rand, 2016).

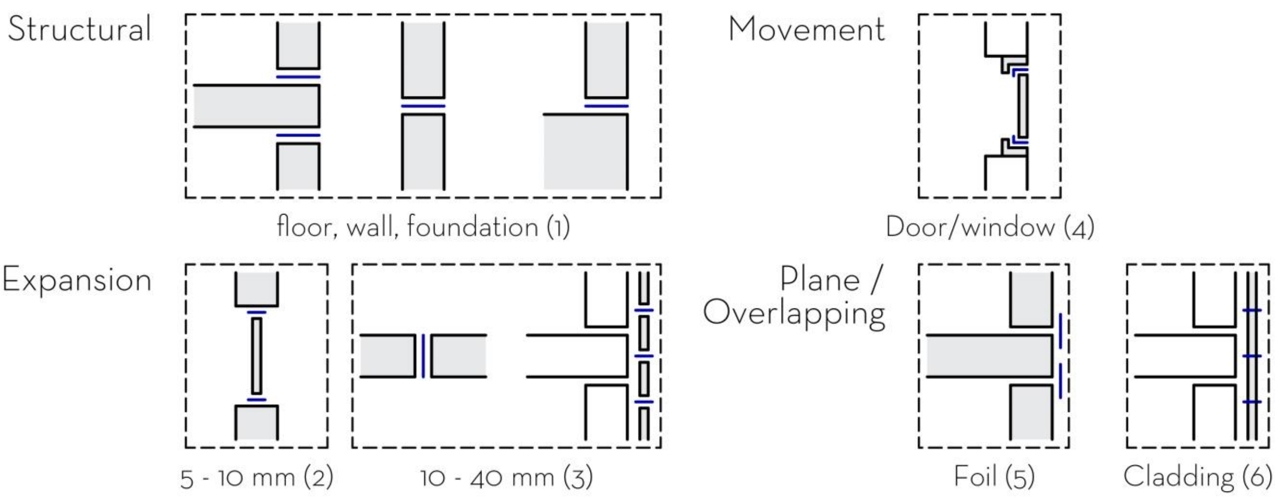

Figure 2. Six application types in the four defined group types

4.2. Products

To understand the purpose of sealing types and products an overview is made from the largest seam seal suppliers, which can be seen in table 3 (Rothoblaas, sd; Tremco illbruck, sd; Celdex, sd). A complete overview of the sealing products and there purpose can be found in appendix B.

Table 3. An overview of products, product groups and application types

Overall type	Sub type	Products	Application type			
			Stuc-tural	Ex-pansion	Move-ment	Over-lapping
Extruded mastics	- Weatherstrip	Tubular gasket, sponge gasket		x	x	
	- Structural	EPDM strips (multiple shapes), felt, cork	x			
	- Compression	Compriband		x		
Adhesive membranes	- Tape					x
	- Sealant			x		x
Expanding foams	- Elastic foam			x		
	- Rigid foam			x		
Specific sealing products	- Weatherstrip	Sweep (or brush)		x	x	
	- Form locking	Tongue and groove, interlocking panels		x		
	- Alternatives	Velcro, zipper, buttons, magnetic seals				x

4.3. Comparison & Selection

Several products have been compared in six applications. The score is calculated by multiplying the criteria weight with the descriptive rating. Then the scores from each criteria is summed to form a total score for each product, where a maximum score of 100 can be acquired. This chapter forms a critical analysis and substantiation of the results, followed by recommendations for the application of certain products. The complete calculation and the descriptive ratings can be found in appendix C and D.

Each scheme shows separate scores for the three groups and a total score. As mentioned earlier, does the re-use potential group have the most influence on the total score with 56,1%. All the weight factors of the assembly and disassembly group combined also have a severe influence on the total score with 39,3% and process and costs have the least amount of impact with 4,8%.

After a test run of the remountability evaluation tool, some adjustments were made after founding some small clashes. The accessibility rating has changed from space available to space required and the criteria 'ease of disassembly' was added, because disassembly showed important contradictions in comparison with assembly.

The results of the comparison of seam sealing products show that the alternatives differ the most in the potential of re-using the product. This is especially important when a building will be dismantled often. It is just as important to prevent damage to the product and its adjacent elements when dismantling. These criteria are accompanied with the durability of the product and this is why EPDM (ethylene propylene diene monomer) rubber seems to be the most appropriate material for remountable seams. This material can be widely used for different applications and it has a high wear resistance and it should ultimately be used without adhesives and even without connectors if possible, to contribute to the remountability of the building. Alternative solutions originating from the clothing and car industry also show loads of potential to increase remountability, but research and technical development is needed.

The vision, which is translated into weight factors for the criteria, has some impact on the amount of difference in the score of the products, but no rank reversal took place when the vision was altered various times.

Table 4. The results of the comparison of load bearing seam seals

Application 1	**Alternatives**					
1. Structural	EPDM strip	Tie-beam strip	Xylofon	Felt	Cork	Granulo
(Dis)assembly	81%	79%	81%	81%	81%	81%
Re-use potential	84%	62%	62%	93%	71%	75%
Process & Costs	83%	61%	67%	94%	89%	83%
Total score	83,6	66,8	68,2	88,9	74,1	77,2

All the compared products have the same connector type in the first application. This is why the assembly and disassembly rating is nearly the same. Felt and EPDM strips are both very good options for a remountable seam seals which can transfer loads, because they can be re-used multiple times effortlessly without taking damage and leaving damage to adjacent elements after several years in contrast to the other alternatives.

There is a slight difference in the performance of the products. Xylofon by Rothoblaas performs best to reduce contact noise for example and Tie-beam strip by Rothoblaas is the most appropriate solution when it comes to airtightness.

Table 5. The results of the comparison of expanding seals

Application 2	**Alternatives**			
Expansion (5-10 mm)	Tape (flexiband)	Sealant	Expanding foam	PE band
(Dis)assembly	76%	61%	61%	87%
Re-use potential	49%	42%	49%	49%
Process & Costs	89%	78%	97%	83%
Total score	50,1	39,5	44,6	60,6

Application 3	**Alternatives**			
Expansion (10-30 mm)	Gasket (flexiwing)	Compriband	Expanding foam	PE band
(Dis)assembly	70%	74%	61%	87%
Re-use potential	82%	51%	51%	51%
Process & Costs	67%	83%	89%	83%
Score	73,8	56,2	46,0	60,6

The comparison of seam sealing products that can be used in seams which expand reveals that products which can be disassembled the easiest score the highest, such as gaskets that are being mechanically fixed and products which aren't glued. Compriband is a good alternative when gaskets can't be used because the seam have to be sealed after an element have been placed.

Table 6. The results of the comparison of door and window seals

Application 4	**Alternatives**		
Doors/windows	Gasket (flexiwing)	Gasket (adhesive)	PE band (adhesive)
(Dis)assembly	70%	57%	57%
Re-use potential	82%	40%	40%
Process & Costs	83%	89%	83%
Score	74,3	39,2	35,8

Gasket that are being mechanically fixed are the most appropriate remountable solution for operable doors and windows, because they can be detached effortlessly in contrast to the other alternatives. There are no differences in the performance of the products.

Table 7. The results of the comparison of sealing vapour barriers

Application 5	**Alternatives**					
Plane (foil)	Tape (flexiband)	Velcro	Zipper	Buttons	Spring	Washers
(Dis)assembly	76%	89%	89%	89%	89%	74%
Re-use potential	49%	87%	89%	87%	78%	84%
Process & Costs	89%	61%	56%	61%	56%	97%
Score	50,1	86,2	86,9	86,2	80,4	80,0

The only standardized solution to seal sealing vapour barriers is tape, but several alternative solutions like Velcro and zippers, show loads of potential to improve the remountability.

Table 8. The results of the comparison of cladding products

Application 6	**Alternatives**					
Cladding	Interlocking panel	Zinc cladding	Swedish rabat	Tongue and groove	Ceramic facade	Timber alternative
(Dis)assembly	59%	64%	70%	68%	61%	67%
Re-use potential	89%	89%	84%	69%	84%	84%
Process & Costs	78%	78%	83%	89%	78%	78%
Score	75,0	77,0	75,8	65,9	73,6	75,3

The investigated cladding products show many similarities on the connector type and ease of disassembly. This is why almost every system has roughly the same score. Most systems require a specific order of removal, which lowers the ease of replaceability. This feature can be improved, but this can also lead to vandalism, because everyone have access to the connector this way.

5. Discussion

A wide variety of products from the largest seam seal suppliers are used, but it is possible that there are other alternatives, which are more suitable for a specific situation. It is important to be aware of the fact that this depends on the application and vision of the designer.

When selecting a seam sealing product is important to be aware of the fact that choosing for remountability could be at the expense of the airtightness or watertightness. This is why it is highly important to critically review the results to make a well-considered decision. Furthermore, the placement has a huge impact on the performance and should therefore be done by following the instructions given by the manufacturer. Another remark on the proposed evaluation methods is that the hierarchy of the criteria can have impact on the results and should be further explored to increase the reliability of the comparison next to the development of the method to make it also suitable for a larger scale.

6. Conclusion

There is no universal definition of the term remountability, but it is clear that this strategy goes one step further than Design for Disassembly (DfD). Remountability is besides dismantling focused on reusing and reassembling materials, elements and components, but both strategies focus on minimizing waste and maximizing the reuse potential.

The developed remountable evaluation method shows that remountability can be evaluated by using a Multi-Criteria Decision Making (MCDM) method called Analytic Hierarchy Process (AHP). The method uses a pair wise comparison to define the weight of all criteria and the descriptive rating lists are thereafter used to rate each alternative. The addition of these lists contribute to the user-friendliness and increase the reliability of the results.

The vision of the development of a remountable and portable system that can be rebuild at least twenty time, led to the conclusion that the connector type, the end of life potential and the functional damage when disassembled are crucial criteria to accomplish this goal. Seam seal products which don't take damage or cause damage to adjacent elements during disassembly and can be re-used multiple times are therefore the most suitable for remountable, portable and reconfigurable housing systems that can be rebuilt several times.

There are many seal sealing products available, but it important to be aware that they fulfil different purposes. Most product types focus on expanding seams where other products are meant for structural seams, door- or window seals or seams that connect materials to create a plane. This is why different applications were used to test the products, which resulted in the conclusion that EPDM rubber seems to be the most appropriate material in most cases. This material can be widely used due to its versatility and it had a high wear resistance.

The product should be applied without the use of adhesives and without causing damage to the adjacent elements when dismantled to contribute to the remountability of a building. Alternative solutions originating from the clothing and car industry like zippers and Velcro also show loads of potential to increase remountability, but the application within the built environment should be further investigated.

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Appendix A

Pairwise Comparison Chart (PCC)

The vision of the development of a remountable and portable system was used as input for the PCC that is based on Saaty's rating scale and led to the following overview.

	Number of connectors	Tool complexity	Connector type	Transport optimisation	Required accessibility	Labour intensiveness	Ease of disassembly	End of cycle potential	Durability	Degree of standardization	Replaceability	Functional damage	Costs	Total	
Number of connectors		5	1/2	4	1/2	6	1/4	1/6	1/7	1/4	1/4	1/7	5	22,2	6,1%
Tool complexity	1/5		1/3	1/4	1/5	4	1/5	1/6	1/7	1/5	1/5	1/7	3	9,0	2,5%
Connector type	2	3		6	3	7	2	1/3	3	5	3	5	6	45,3	12,5%
Transport optimisation	1/4	4	1/6		1/5	4	1/6	1/6	1/6	1/5	1/5	1/6	3	12,7	3,5%
Required accessibility	2	5	1/3	5		6	1/3	1/4	1/4	2	3	1/4	4	28,4	7,8%
Labour intensiveness	1/6	1/4	1/7	1/4	1/6		1/7	1/6	1/7	1/4	1/7	1/7	1/2	2,5	0,7%
Ease of disassembly	4	5	1/2	6	3	7		1/4	1/5	2	2	1/3	5	35,3	9,7%
End of cycle potential	6	6	3	6	4	6	4		1/2	3	3	1/3	6	47,8	13,2%
Durability	7	7	1/3	6	4	7	5	2		3	3	1/2	6	50,8	14,0%
Degree of standardization	4	5	1/5	5	1/2	4	1/2	1/3	1/3		1/3	1/4	2	22,5	6,2%
Replaceability	4	5	1/3	5	1/3	7	1/2	1/3	1/3	3		1/3	4	30,2	8,3%
Functional damage	7	7	1/5	6	4	7	3	3	2	4	3		6	52,2	14,4%
Costs	1/5	1/3	1/6	1/3	1/4	2	1/5	1/6	1/6	1/2	1/4	1/6		4,7	1,3%

Table A1. Saaty's rating scale

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

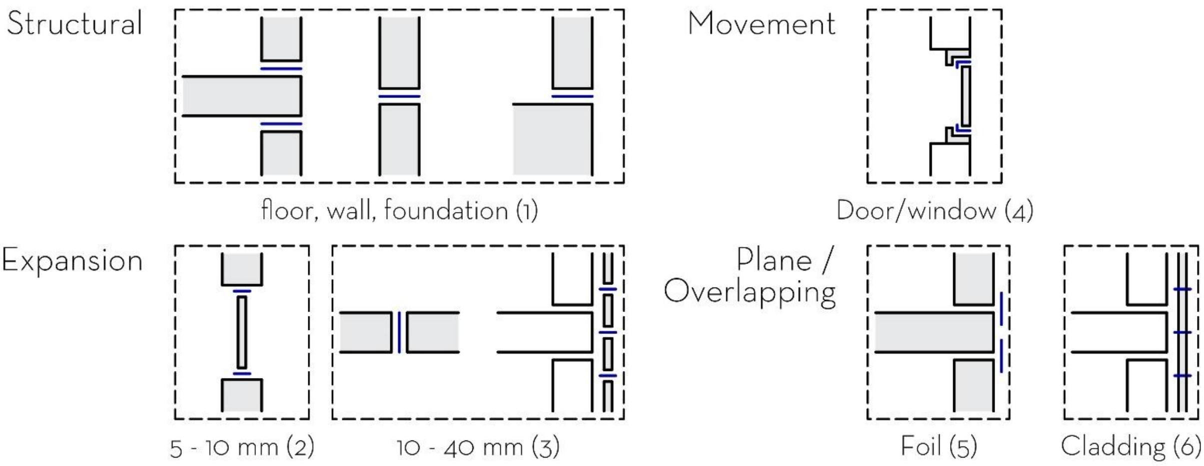
APPENDIX B

Overview seam sealing products

					Characteristics												Application				
Overall types	**Subtype**	**Product**	**Manufacturer**	**Material**	Moving element	Expansion	Structural seams	Airtight	UV resistant	Watertight	Sound	Fire resistant	Insulating	Surface irregulations			Structural	Expansion 10-40 mm	Expansion 5-10 mm	Door /window	Foil
Extruded mastics	Weatherstrip	Tubular gasket (bulb)	Several	Rubber	+			+		+	+/-									+	
		Sponge gasket	Several	Rubber	+			+		+	+/-									+	
		Flexi-Wing	Kilargo	Rubber	+			+		+	+/-							+		+	
	Structural mastic	EPDM strip	Rothoblaas	EPDM			+	+/-		+/-	+						+				
		Sill seal(er)	Reflectix	Polyethylene (closed cell)			+/-	+		+	+/-		+	+/-							
		Tie-beam stripe	Rothoblaas	EPDM (high density)		+/-	+	+		+	+			+			+				
		Xylofon	Rothoblaas	Polyurethane			+			+/-	++			+			+				
		Aladin stripe	Rothoblaas	EPDM		+/-	+				x			+			+				
		Level band	Rothoblaas	PE & EPDM			+	+		+							+				
		Felt (Kenaf band)	Rothoblaas	Felt natural fibre			+				+		+				+				
		Cork	Rothoblaas	Cork			+				+						+				
		Granulo	Rothoblaas	Rubber granules			+				+						+				
	Tape	Flange seal tape	Illbruck	PE		+/-		+		+										+	
		Rubber foam tape	Illbruck	EPDM		+/-	+/-	+		+		+								+	
	Com-pression	Gapseal FR	Illbruck	Graphite-based		+		+		+		+		+				+			
		Compriband jointspan	Tremco	CP201		+		+				+						+			
		Flexible Intumescent	Nullifire	Graphite-based		+		+			+	+	+					+			
		Kompri (Compri)band	Rothoblaas	Polyurethane foam		+		+		+	+/-	+		++				+			
Adhesive membranes	Tape	Flexi band	Rothoblaas	PE		+/-				+									+		+
		Multi band	Rothoblaas	PL					+	+									+		+
		Facade Band UV	Rothoblaas	PE		++			+	+									+		+
	Sea-lant	Superb Glue	Rothoblaas	Water-based polumeric		+/-		+		+	+			+					+		
		Intumescent sealant	Nullifire	Graphite-based				+		+		+		+					+		
Expanding foams	Expanding foam	Mermetic foam	Rothoblaas	Polyethylene (closed cell)		+		+		+	+		+	+					+		
		Perfect Elastic Foam	Illbruck	Polyurethane foam		+		+		+			+	+				+	+		
		Perfect Foam	Illbruck	Polyurethane foam				+		+			+	+					+		
		PU Foam	Nullifire	Polyurethane foam				+		+		+	+	+					+		
Specific sealing products	Strip	Sweep/brush/fin	Several		+			+/-		+/-										+/-	
		Spring metal/vinyl	Several	Metal/vinyl	+			+/--		+										+/-	
	Alternatives	Velcro	Several																		+
		Zipper	Several					+		+											+
		Magnetic seal strip	Kilargo					+													+
		Buttons	Several																		+
		Nut screwing	Several																		+
		Spring loaded seal	Several																		+

APPENDIX C

Calculations of the comparison



Application 1 Structural, watertight & airtight

		Factor	EPDM strip R	EPDM strip S	Tie-beam strip R	Tie-beam strip S	Xylofon R	Xylofon S	Felt R	Felt S	Cork R	Cork S	Granulo R	Granulo S
Assembly & Disassembly	Number of connectors	22,2	7	155	7	155	7	155	7	155	7	155	7	155
	Tool complexity	9,0	7	63	7	63	7	63	7	63	7	63	7	63
	Connector type	45,3	7	317	7	317	7	317	7	317	7	317	7	317
	Required accessibility	28,4	7	199	7	199	7	199	7	199	7	199	7	199
	Labour intensiveness	2,5	8	20	8	20	8	20	8	20	8	20	8	20
	Ease of disassembly	35,3	8	282	7	247	8	282	8	282	8	282	8	282
	Subtotal		31,7		30,6		31,7		31,7		31,7		31,7	
Re-use potential	End of cycle potential	47,8	9	431	1	48	1	48	9	431	4	191	4	191
	Durability*	50,8	8	407	8	407	8	407	8	407	8	407	8	407
	Degree of standardization	22,5	9	202	9	202	9	202	9	202	9	202	9	202
	Replaceability	30,2	5	151	5	151	5	151	7	211	6	181	6	181
	Functional damage	52,2	7	365	5	261	5	261	9	470	5	261	7	365
	Subtotal		47,5		32,6		32,6		52,6		38,0		41,1	
Process & Costs	Transport optimisation	12,7	9	114	8	101	9	114	9	114	9	114	9	114
	Costs*	4,7	6	28	3	14	3	14	8	38	7	33	6	28
* assumed	Subtotal		4,4		3,5		3,9		4,6		4,5		4,4	
	Total score		83,6		66,8		68,2		88,9		74,1		77,2	

			App. 2 Expansion (5-10 mm)						App. 3 Expansion (10-30 mm)					
			Tape (flexiband)		Sealant (superb glue)		Epanding foam		Gasket (flexi wing)		Compriband (gapseal)		Expanding foam	
		Factor	R	S	R	S	R	S	R	S	R	S	R	S
Assembly & Disassembly	Number of connectors	22,2	7	155	7	155	7	155	7	155	7	155	7	155
	Tool complexity	9,0	9	81	7	63	7	63	7	63	7	63	7	63
	Connector type	45,3	2	91	1	45	1	45	5	227	7	317	1	45
	Required accessibility	28,4	7	199	8	227	8	227	4	114	5	142	8	227
	Labour intensiveness	2,5	9	22	9	22	9	22	8	20	8	20	9	22
	Ease of disassembly	35,3	7	247	1	35	1	35	7	247	6	212	1	35
	Subtotal		24,3		16,8		16,8		25,2		27,8		16,8	
Re-use potential	End of cycle potential	47,8	1	48	1	48	1	48	9	431	1	48	1	48
	Durability*	50,8	3	153	3	153	6	305	6	305	6	305	7	356
	Degree of standardization	22,5	9	202	9	202	9	202	9	202	9	202	9	202
	Replaceability	30,2	8	241	5	151	5	151	7	211	6	181	5	151
	Functional damage	52,2	1	52	1	52	1	52	6	313	1	52	1	52
	Subtotal		21,3		18,5		23,2		44,7		24,1		24,7	
Process & Costs	Transport optimisation	12,7	9	114	9	114	9	114	9	114	9	114	9	114
	Costs*	4,7	7	33	5	24	8	38	3	14	6	28	7	33
	Subtotal		4,5		4,2		4,6		3,9		4,4		4,5	
	Total score		50,1		39,5		44,6		73,8		56,2		46,0	

* assumed

App. 4 Weatherstrip

		Factor	Gasket (flexi wing) R	Gasket (flexi wing) S	Gasket (adhesive) R	Gasket (adhesive) S	PE band (adhesive) R	PE band (adhesive) S
Assembly & Disassembly	Number of connectors	22,2	7	155	7	155	2	44
	Tool complexity	9,0	7	63	8	72	8	72
	Connector type	45,3	5	227	1	45	1	45
	Required accessibility	28,4	4	114	6	171	6	171
	Labour intensiveness	2,5	8	20	8	20	8	20
	Ease of disassembly	35,3	7	247	1	35	1	35
	Subtotal		25,2		15,2		11,8	
Re-use potential	End of cycle potential	47,8	9	431	1	48	1	48
	Durability*	50,8	6	305	6	305	6	305
	Degree of standardization	22,5	9	202	9	202	9	202
	Replaceability	30,2	7	211	1	30	1	30
	Functional damage	52,2	6	313	1	52	1	52
	Subtotal		44,7		19,5		19,5	
Process & Costs	Transport optimisation	12,7	9	114	9	114	9	114
	Costs*	4,7	6	28	7	33	7	33
	Subtotal		4,4		4,5		4,5	
	Total score		74,3		39,2		35,8	

* assumed

App. 5 Plane (foil)

		Factor	Tape (flexiband) R	Tape (flexiband) S	Velcro R	Velcro S	Zipper R	Zipper S	Buttons R	Buttons S	Spring R	Spring S	Washers R	Washers S
Assembly & Disassembly	Number of connectors	22,2	7	155	7	155	7	155	7	155	7	155	7	155
	Tool complexity	9,0	9	81	9	81	9	81	9	81	9	81	5	45
	Connector type	45,3	2	91	7	317	7	317	7	317	7	317	5	227
	Required accessibility	28,4	7	199	7	199	7	199	7	199	7	199	7	199
	Labour intensiveness	2,5	9	22	9	22	9	22	9	22	9	22	9	22
	Ease of disassembly	35,3	7	247	9	318	9	318	9	318	9	318	7	247
	Subtotal		24,3		33,4		33,4		33,4		33,4		27,4	
Re-use potential	End of cycle potential	47,8	1	48	9	431	9	431	9	431	9	431	9	431
	Durability*	50,8	3	153	6	305	6	305	6	305	3	153	7	356
	Degree of standardization	22,5	9	202	7	157	7	157	7	157	7	157	7	157
	Replaceability	30,2	8	241	8	241	9	272	8	241	7	211	7	211
	Functional damage	52,2	1	52	9	470	9	470	9	470	9	470	8	418
	Subtotal		21,3		49,0		49,9		49,0		43,4		48,0	
Process & Costs	Transport optimisation	12,7	9	114	9	114	9	114	9	114	9	114	9	114
	Costs*	4,7	7	33	2	9	1	5	2	9	1	5	8	38
	Subtotal		4,5		3,8		3,6		3,8		3,6		4,6	
	Total score		50,1		86,2		86,9		86,2		80,4		80,0	

* assumed

App. 6 Cladding

		Factor	Interlocking panel R	Interlocking panel S	Zinc cladding R	Zinc cladding S	Swedish rabat R	Swedish rabat S	Tongue and groove R	Tongue and groove S	Ceramic facade R	Ceramic facade S	Timber alternative R	Timber alternative S
Assembly & Disassembly	Number of connectors	22,2	7	155	7	155	7	155	7	155	5	111	7	155
	Tool complexity	9,0	5	45	5	45	5	45	5	45	5	45	5	45
	Connector type	45,3	5	227	5	227	5	227	5	227	5	227	5	227
	Required accessibility	28,4	4	114	5	142	7	199	6	171	6	171	6	171
	Labour intensiveness	2,5	7	17	8	20	9	22	9	22	8	20	9	22
	Ease of disassembly	35,3	4	141	5	176	5	176	5	176	4	141	4	141
	Subtotal		21,4		23,4		25,2		24,3		21,8		23,3	
Re-use potential	End of cycle potential	47,8	9	431	9	431	9	431	4	191	9	431	9	431
	Durability*	50,8	6	305	7	356	6	305	6	305	7	356	6	305
	Degree of standardization	22,5	9	202	9	202	9	202	9	202	9	202	9	202
	Replaceability	30,2	7	211	7	211	7	211	5	151	5	151	7	211
	Functional damage	52,2	9	470	8	418	7	365	7	365	8	418	8	418
	Subtotal		49,5		49,4		46,3		37,1		47,6		47,9	
Process & Costs	Transport optimisation	12,7	9	114	9	114	9	114	9	114	9	114	9	114
	Costs*	4,7	5	24	5	24	6	28	7	33	5	24	5	24
* assumed	Subtotal		4,2		4,2		4,4		4,5		4,2		4,2	
	Total score		75,0		77,0		75,8		65,9		73,6		75,3	

APPENDIX D

Descriptive ratings and definitions of the criteria

Assembly & Disassembly

Theoretical best- and worst-case scenarios are used as extremes in the rating list, with practical intermediate steps. There are some reasons to lower the score with some points, when special care, special tools or techniques are needed to accomplish the task, but the score cannot be lower than one.

Definitions

Connector or fastener: A mechanical device for fastening together two or more pieces, members, or parts, including anchors, fasteners, or wall ties.

Component: Composition of elements that can be joined together, forming the subassembly of a total building.

Element: Composition of building materials that form together one functional and/or architectural unit, which is part of a component and/or total building.

Tool Complexity Rating

The complexity of mechanical tools required to mount or demount the element.

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

Ease of disassembly

The complexity regarding the disassembly task.

Ease of disassembly	**Rating**
Elements can be disassembled without tools (unclipping, lifting or similar)	9
Elements can be disassembled by removing nuts and bolts	8
Elements can be unscrewed	7
Hand tools are required	6
Powered tools are required	5
Special tools are required	3
The elements can’t be separated without severe damage (sawing, breaking etc.)	1
Significant time delay	-2
Special care/techniques are needed	-1

Workspace Accessibility Rating

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

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

Labour intensiveness

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

Labour intensiveness	**Rating**
The element is manageable with one hand (<7.5kg)	9
The element is manageable with two hands (7.5-15kg)	8
The element is liftable in accordance with working conditions (15-25kg)	7
The element requires two people to manage (25-50kg)	5
The element requires more than two people to manage (50-100kg)	3
The element is hard to grasp or manage (tool needed, flexible, slippery, long or similar)	-1
Placement above head, sitting or squatted while lifting	-1

Connectivity Rating: Connector type

The type of connector used to connect the elements.

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

Connectivity Rating: Number of fasteners

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

Number of fasteners	Rating
No fasteners are needed to connect two components	9
One fastener is needed to connect two component	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

Re-use potential

Replaceability within Host Building Lifecycle

The degree of complexity in replacing an element within the host building's functional life.

Replaceability within Host Building Lifecycle	Rating
Elements can be replaced without removing an adjacent element	9
Elements can be replaced by removing one adjacent obstructive element	7
Elements can be replaced by removing two adjacent obstructive elements	5
Elements can be replaced by removing several adjacent obstructive elements	3
Elements can't be replaced	1
Special care/tools/equipment/techniques are needed	-1
Significant time delay	-1
Damage to adjacent elements are probable	-2

Degree of standardization

The grade of conformity of measurements of the element compared to market standards.

Degree of standardization	Rating
Element has market standard dimensions and connection-system	9
Element can be easily altered to market standard dimensions and connection-system, or can be easily used along-side market-standard elements	7
The element can be further dismantled and individually altered to market standard dimensions and connection-system	4
Element cannot be standardized in dimensions and connections and cannot be easily used along-side market-standard elements.	1

Element Durability

The lifespan of an element in relation to the expected lifespan of a building of the intended type.

Durability of element	**Rating**
Lifespan of ≥ 300% in relation to the intended lifespan of the building	9
Lifespan of ≥ 200% in relation to the intended lifespan of the building	8
Lifespan of ≥ 100% in relation to the intended lifespan of the building	7
Lifespan of < 100% in relation to the intended lifespan of the building	6
Lifespan of > 50% in relation to the intended lifespan of the building	3
Lifespan of < 50% in relation to the intended lifespan of the building	1

End of cycle potential
The circularity potential of an element at the end of its total lifecycle. Definitions of the words used in the rating list (reuse, repair, etc.) are according to Vermeulen et al. (2018).

End of Cycle Potential Rating	**Rating**
Element can be directly re-used	9
Element can be repaired	8
Element can be refurbished	7
Element can be remanufactured	6
Element can be repurposed	5
Element can be recycled	4
Element can be recovered (combustion)	2
Element has no recovery potential	1

Damage Rating: Functional Damage

The amount of functional damage to the element during (dis)assembly. Constructional damage is defined as damage that reduces the structural integrity of the element.

Damage Rating: Functional Damage	**Rating**
No noticeable damage when assembled or disassembled multiple times	9
Small scratches or dents (or similar) which have hardly any impact on the performance	8
Deep scratches or dents (or similar) which have some small impact on the performance	7
Light damage such as screw holes or rust formation during (dis)assembly	6
Constructional performance is reduced when disassembled, repair is desirable	5
Repair is always necessary when after disassembly	3
Replacement is needed after disassembly (one time use)	1

Process & Costs Evaluation

Transport Optimisation Rating

The Transport Optimisation Rating evaluates how well the element is optimised for efficient transport of the building element to the building site.

Transport Optimisation: Volume Optimisation

The Volume Optimisation measures how much empty volume is left over when a relevant cargo transport (truck, freight train) is filled with the element.

Volume Optimisation	Rating
Can fill relevant cargo space with less than 15% empty volume	9
Can fill relevant cargo space with less than 20% empty volume	7
Can fill relevant cargo space with less than 30% empty volume	5
Can fill relevant cargo space with less than 40% empty volume	3
Cannot fill cargo space with less than 40% volume.	1

Transport Optimisation: Weight Classification

The Weight Classification determines the weight class of the element, according to market standards of its type and function. If such standards do not exist, figure 2 is used to determine the weight class.

Weight Classification	Rating
Elements are considered Heavy Weight	9
Elements are considered Mid Weight	5
Elements are considered Light Weight	1

Element Costs

The total costs to produce one element of its type, in relation to the generally accepted average costs for a functionally similar element.

Element Costs	Rating
Less than 50% of the generally accepted average for a functionally similar element	9
Between 50 - 75% of the generally accepted average for a functionally similar element	8
Between 75 - 100% of the generally accepted average for a functionally similar element	7
Roughly 100% of the generally accepted average for a functionally similar element	6
Between 100 - 125% of the generally accepted average for a functionally similar element	5
Between 125 - 150% of the generally accepted average for a functionally similar element	4
Between 150 - 175% of the generally accepted average for a functionally similar element	3
Between 175 - 200% of the generally accepted average for a functionally similar element	2
More than 200% of the generally accepted average for a functionally similar element	1