ASSESSMENT OF COMPONENT CONNECTIONS BASED ON THE DESIGN OF DISASSEMBLY STRATEGY

Qi Gao
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft
gaoqi1994@126.com

ABSTRACT

This paper uses different classification methods to make an overview of different demountable connections in current architecture practices. Then based on the typologies and literature research, it built an assessment system to evaluate the connections in a circular building economy.

KEYWORDS: *Design for disassembly, demountable, tightness*

I. INTRODUCTION

1.1. Problem statement

Design for disassembly is often discussed primarily as a strategy to meet environmental goals, at the same time meet social and economic goals as well. It suggests careful thought about how material, assemblies, and building systems interconnect but in all, it requires building components to have high adaptivity. However, a building also needs high tightness to keep interior climate and save energy. Therefore, how to find a balance between detachability and tightness becomes the question for connection design.

On the other hands, there are already many practices on prefabricated building elements in recent years. In the perspective of assembly, the prefabricated elements are separated parts, but when it comes to disassembly, there are more problems to consider because there are many differences between the two processes (see the table below). Therefore, this paper tried to find a method of assessment for the current connection types.

Table 1. Difference between assembly and disassembly

Contents	**Assembly**	**Disassembly**
Building state	Known	Unknown
Precision requirements	High	Medium
Working method	Mainly machinery	Mainly manual
Life cycle stage	Construction	Reuse, recycle or maintain

1.2. Thematic research question

How to assess current connection types for enclosure components based on the design for disassembly strategy and tightness requirement of construction?

II. METHOD

Basic on the positivism, this paper adopts review of literatures, case study design, prototype database and making assessment as research methods. It will also be a part of research by design process in the graduation design project.

The purpose of literature study in this paper is to summarize the cause of leakage, which is the basement of followed assessments of connection tightness. The literature also helps to find the characteristics of different materials in design for disassembly. Literatures discussed that reinforced concrete structures are not suitable for deconstruction because the structures are difficult to take apart without any damage (Tingley, 2012). This makes reuse of concrete structures generally difficult and inflexible (Davison and Tingley, 2011) but readily recyclable. In this way, recycling concrete elements should be prioritized over reuse. On the other hand, the design project will be a building transformation mainly using lightweight materials such as steel and wood, so the main focus of case study and research is on connections for steel, wood, and composite materials.
For case study I chose six projects among many practices related to design for disassembly in recent years based on the representative and the main materials (2 of steel structure, 2 of wood structure and 2 of composite materials). Some of them are not fully demountable but has many interesting designs of demountable connection. They are:
1. Cellophane house, New York, Kieran Timberlake;
2. THEKRANE, Copenhagen, Arcgency;
3. Social house, Lisbjerg, Vandkunsten Architects;
4. Sailing club, Zeebrugge, Wim Goee Architects;
5. IKEA better shelter, IKEA;
6. NewBud Eco-School, ZHU Jingxiang Architects.

The analysis of these cases is in the appendix. These cases can represent part of demountable component practice in the building industry but not the whole. Therefore, the next step was to classicize them into a general prototype database according to two dimensions of looking at connections: the relationship between two components, and the relationship between connections and connected components. Nine types are sorted, still, in practice, they are all used in different situations and sometimes combined to achieve a better result. In order to evaluate them properly and choose which connection type should be applied to a certain component of a certain material in a certain circumstance, the latter part of this paper built up assessment standards in different perspectives to score the former types. As a result, the characteristics of different connection types for enclosure components are showed and it will be easier to choose appropriate connections when designing for disassembly.

III. RESULTS

3.1. Causes of leakage in connections

Generally, an unfilled joint approximately 1 mm – 5 mm in height at the floor or wall joints brings water in. There are different physical reasons of water leakage (table 2, Appendix) and targeted solutions. Traditionally, engineers have tried to solve the problem by various means. These include using PVC Waterstops, applying epoxy adhesive to the joint, grouting into the joint using cement grout etc. However, each of these methods has its own problems and may not be hundred percent effective. Hence engineers are highly divided on the effectiveness of each method.

3.2. Connection types and watertight performance

The selection of appropriate connections for building depends on the design of spatial separation of the building, the material and the wanted durability and appearance of the joints. But first, we need to sort the basic connection type between enclosure components.

There can be two ways of sorting different types of connections between enclosure components. The first simple and effective way of sorting is according to the relationship between the ends to elements: butt, open and overlapping connections (Maarten, 2009).

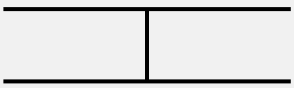
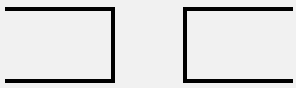
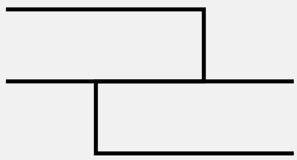
3.2.1. Connection types according to the relationship between two components

Butt joints mean that the two parts connected fit very closely together. As it was discussed in the former chapter, through the capillary effect water can be sucked into the connection but then hard to evaporate. In other words, it is suitable for interior situations where there is less moisture.

The second type is an open connection. This type is special because the two connected parts do not touch each other in fact. This method can save the expensive cost of applying expensive sealer or joints between the two components. However, components still need to be fixed into the underlying layer or structure. This type can provide the first line of rainwater resistance and protect thermal insulation against force and UV radiation as well as offer an aesthetic purpose. Therefore, it is usually applied to composite enclosure most in the exterior.

Overlapping connections remain open for certain functions such as air but closed for others like rain. The two parts can either touch each other or not depending on the needs and the flatness of component surfaces.

Table 3. Different types of connections (first classification)

Butt connections	**Open connections**	**Overlapping connections**
		

3.2.2. Connection types according to the relationship between connection and components

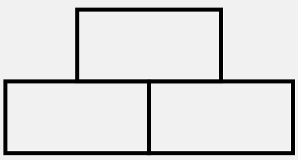
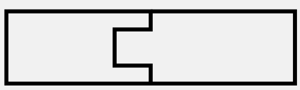
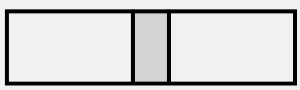
The second way of sorting connections is by looking at the relationship between it and the connected object. The three types are: position, form and material. Not like the former classification method, these three types can often be combined with each other for a stronger or multi-functional connection.

In a connection through position, the binding force is usually provided by gravity or structure of near elements. If the frictional resistance is strong enough a stack structure can hold the wind for collision force.

Form-locking connections have the similar principles with Lego blocks: two objects have certain shapes which can lock into each other such as zips, nuts with bolts and plug with socket.

Connection through the material is provided by a physical or chemical bond between the connected components. This method can also be either directly or indirectly, depending on whether using a third material that activates the bond between the two components.

Table 4. Different types of connections (second classification)

Position connections	**Form-locking connections**	**Material connections**
		

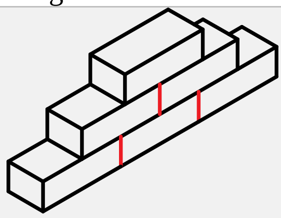
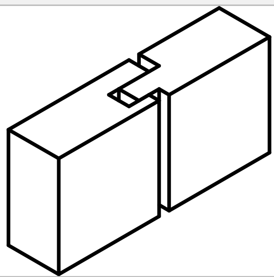
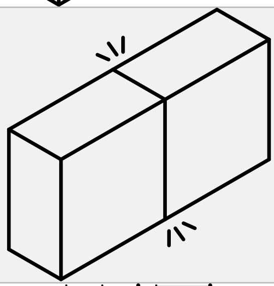
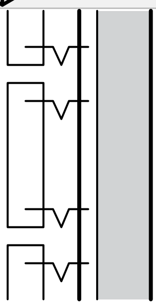
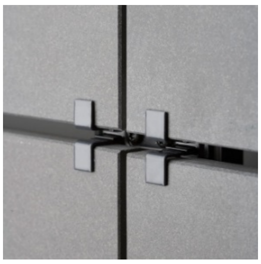
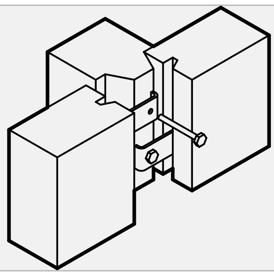
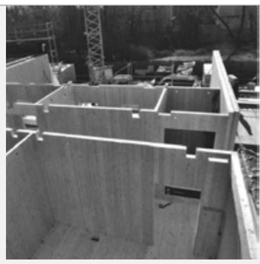
3.2.3. Case study and type classification

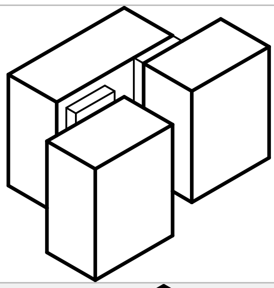
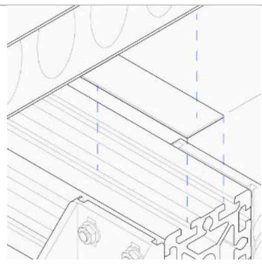
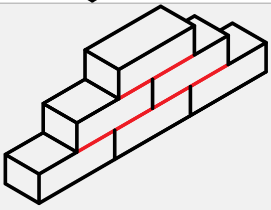
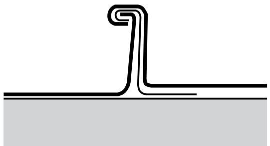
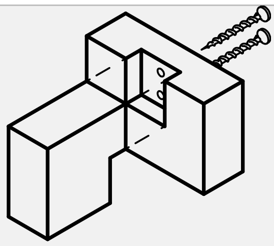
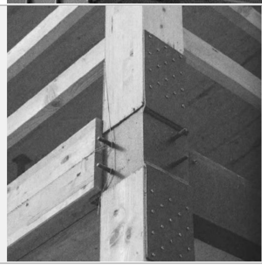
Combining the above two classification methods, I summarized nine basic types of component connections in the cases and listed the applicable materials of connected components.

Table 5. Different types of connections (combining two methods)

	Butt	Open	Overlapping
Position	Stacking (short ends)	Anchored cladding	Stacking (long ends)
Form-locking	Interlock panel	Bolts	Single lock standing
Material	Magnetic	Tape	Screws

Table 6. Characteristics of different connection types

Type	Diagram	After assembly	Applicable materials
Stacking (short ends)			Wood Composite
Interlock panel			Metal Wood Composite
Magnetic			Metal
Anchored cladding			Metal Composite
Bolts			Metal Wood Composite

Tape			Metal Wood Composite
Stacking (long ends)			Wood Composite
Single lock standing			Metal Composite
Screws			Wood Composite

3.3.Assessment standards

3.4.1 detachability

This assessment standard tries to evaluate whether the connection is easy to be demounted qualitatively and quantitatively. There are many researches on this topic in the mechanical field.
Early method is based on disassembly time through analysis of relevant influencing factors (Kroll, 1998). The integration of product structure type, accessibility and other parameters is expressed by the disassembly time data. The long disassembly time indicates that the product has poor detachability. This quantitative approach allows designers to consider the detachability of the product at the design stage and then optimize the design. The detachability of the drill was tested and analyzed in the study.
Furthermore, based on a study on the disassembly time of products and the reversibility of fasteners (Kondo, 2003). The experiment was only on metal elements but showed that the connection type, product state, structural form and some other factors will have different impact on the disassembly time, among those factors the connection type have the greatest impact on the disassembly time. Obviously, permanent joints such as welding and bonding require longer disassembly time and poor reversibility, while screws and bolts require less time.
Disassembling cost can also be an evaluation index to measure the detachability of a prototype. A lower cost usually means a better detachability (Banda, 2006).
For the whole building we can build up an evaluation model to score its detachability with some tools like BIM (Olugbenga, 2015). However, when it comes to single connection type and design

stage, we need to set some principles and compare the cases with them. In this research the detachability of connection is evaluated by these five aspects:
1. Use of prefabricated elements;
2. Size of demountable element;
3. The visibility of connection or joints;
3. Joint amounts in the connection;
4. Average construction time.

3.4.2 tightness and permeability
Building tightness refers to the ability to block rain or air through the enclosure when the doors and windows are closed. Because the building envelope is often composed of multiple layers of perforated materials, there is a possibility of water or air infiltration between the layers. Because of this, the energy lost through the gap between the building openings and the enclosure is the main part of the building energy consumption.
Cause one of the purposes of design for disassembly is also to save materials and energy which benefit to circular economy and the environment, we should find the balance between making building components demountable and keeping the tightness. To really determine the optimal combination, sequence and size of materials and connections for us as architects, we should use the knowledge of building physics, material science and applied mechanics as tools. But for starting, this paper will evaluate the tightness of connections by comparing their watertight performance. Score 0 means the connection is total open and can let water easily through, score 3 means that this connection can avoid normal rainwater but need extra layers to be totally watertight, and score 5 means the connection can satisfy the waterproof requirement in its application position.

3.4.3 environment impact
Demountable connections ensure that building components can be disassembled appropriately and reused in other constructions. Therefore, they already saved the embodied energy of produce new components and demolish cost, which has a very positive environment impact. Thought the material volume percentage of connection in a building is very low, we should consider the environment impact of connections themselves for a more comprehensive goal. This assessment will evaluate the types of connection by these principles:
Whether the connection can keep integrity of components;
Whether the connection uses additional material except the connected components;
Whether the connection may contain or produce toxic material in production and use;
Whether the connection can minimize the use of composite materials;
The lifespan of connections (long lifespan means that it can save the cost of maintenance).

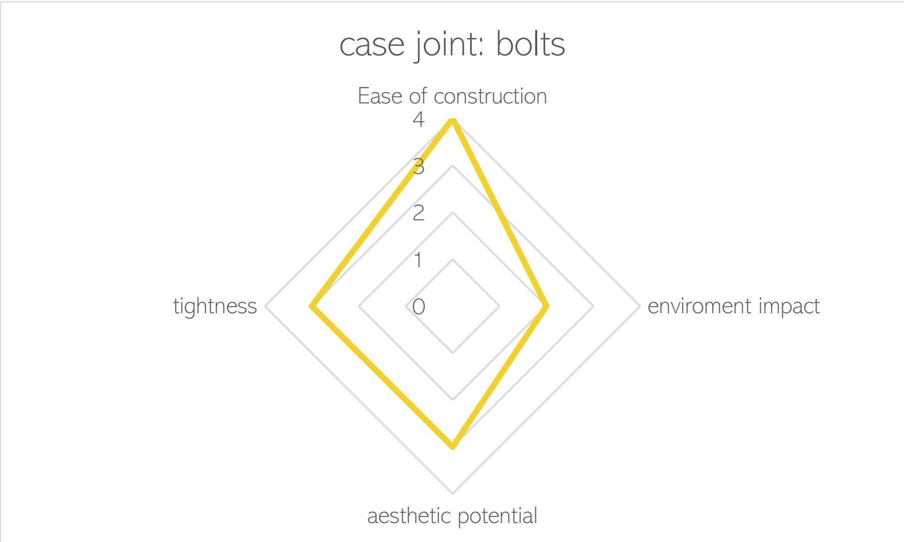
3.4.4 aesthetic potential
In the second chapter we discussed about the two basic connection type of building: internal and external connections. As Louis Kahn has said, design is not making beauty, beauty emerges from selection, affinities, integration, love. In the current practice of flexible house or demountable structures, because of cost and technical reasons, aesthetic performance is usually not the most important factor. However, if we want to promote this type of building and construction methods, we should at least provide the customers results equally beautiful as usual houses. Further, the good influence on environment and circular economy will be the extra attractive points.
The aesthetic performance of a connection is difficult to evaluate because it depends on many factors beyond the connection itself like the position of it in the building, the building context and so on. However, we can evaluate the aesthetic potential for design and it will be helpful to adjust the design details in different context according to these assessment principles.
Looking back at the history of component connections, it first appeared to satisfy practicality with simple outlooking. Later, functions of connections have been refined and people ask for higher aesthetic requirements. After industrialization of building elements, new practical requirements were placed on the design of the connections to accommodate the assembling buildings. From the

architectural point of view, most connections are designed both on form and technology, and the final form design result can be said to strike a balance between "emphasis" and "hiding". Therefore, connections meet function and structure requirements beautifully and delicately, which fully shows the pass of force in building. So, here I listed three languages of connection related to aesthetic potential of emphasis or hiding: 1. Potential to be scaled up or down (2 points); 2. Ability to imply function (2 points); 3. Potential to be as a decoration at the same time (1 point).

IV. Conclusions

By the assessment standards discussed in the last chapter and the comparison between the types of connections, we got the evaluation results. Here is the result for bolts in the case. The results for other types of connections are in the appendix (table 2). According to the four assessment before, we can sort the types by a certain standard and find a type we want in the category (chart 1).

In general, stacking (by long ends) won by the total score (17), which mean it performs very well in design for disassembly. However, it has a low score in the aspect of tightness (3), which means we still need to balance and make innovation when apply it into design and construction.



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Appendix

Table 2. Main causes of water leakage in connections

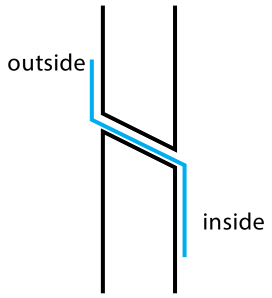
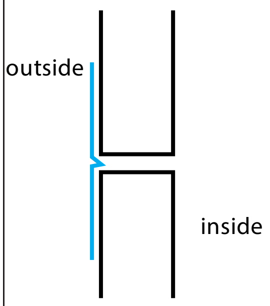
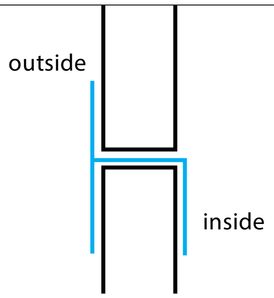
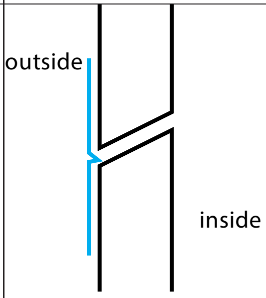
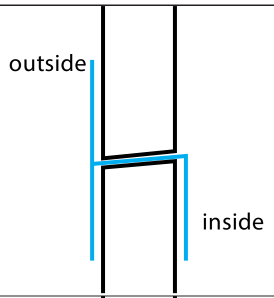
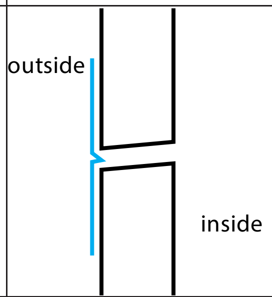
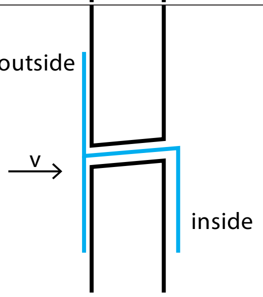
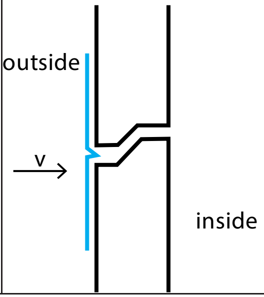
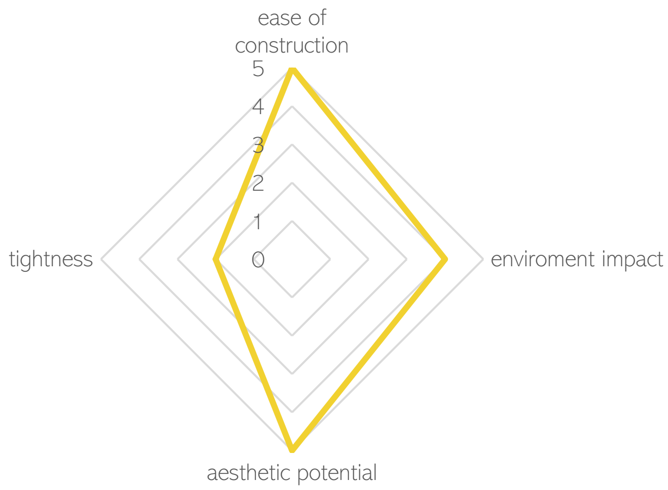
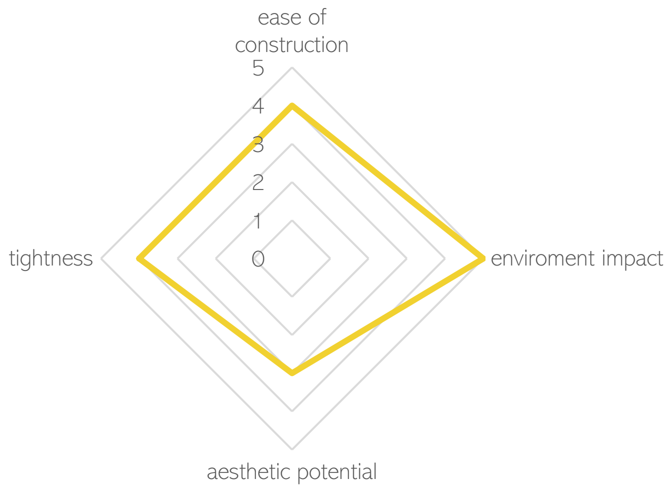
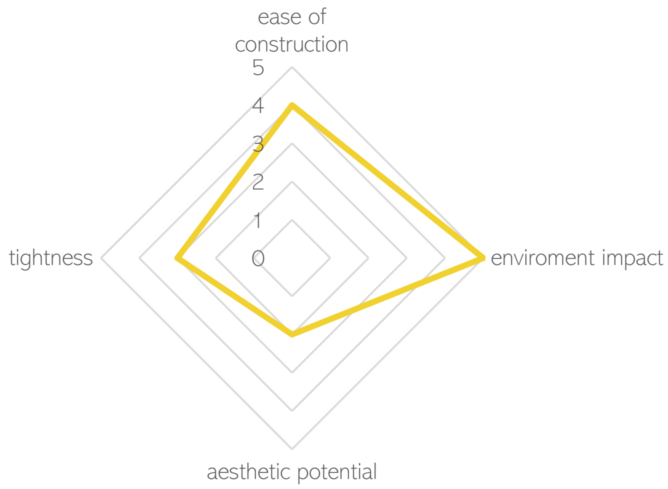
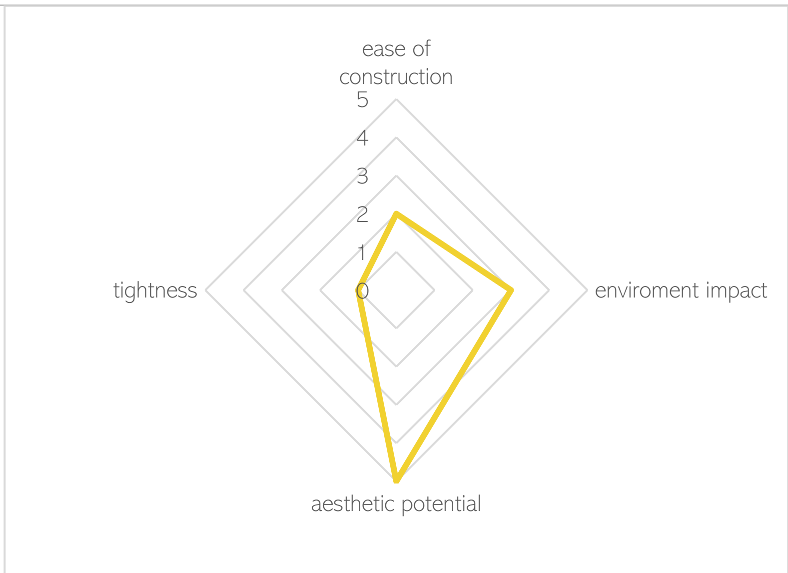
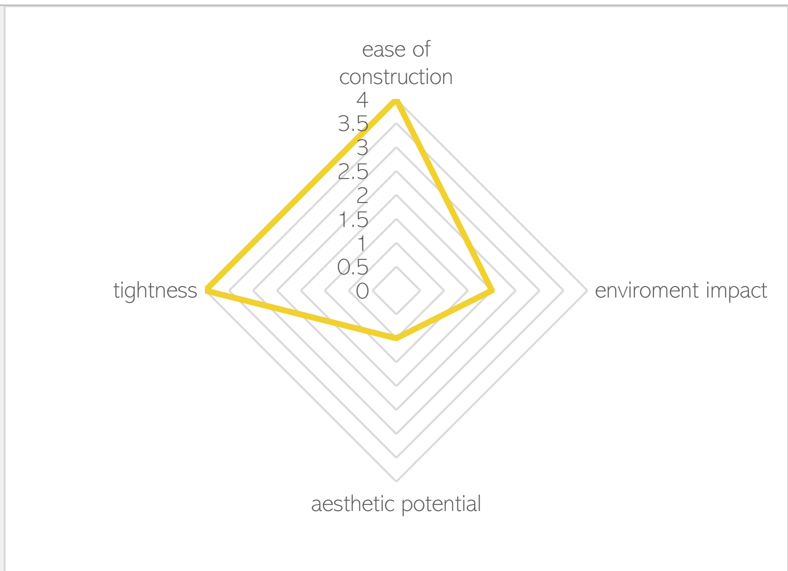
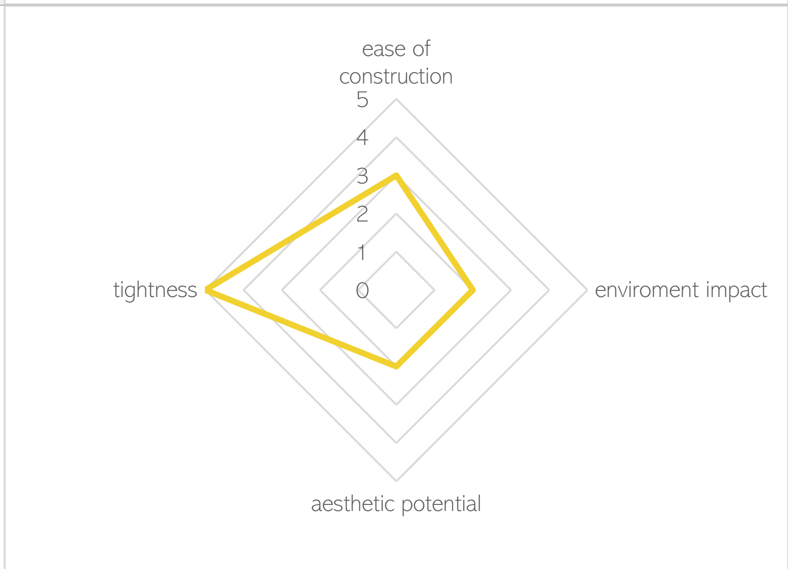
Factors	Solution	Causes of water seepage	Correct design method
gravity	Make the seam at least horizontal		
surface tension	Make height difference		
capillary action	Increase seam width		
kinetic energy	increase slope and reduce kinetic energy		

Table 3. Assessment results for different types of connections

Type	Assessment results
Stacking (short ends)	
Interlock panel	
Magnetic	

Anchored cladding	
Bolts	
Tape	

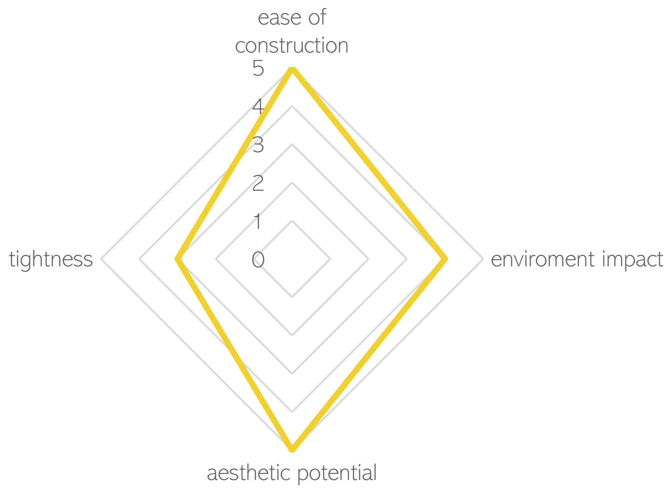
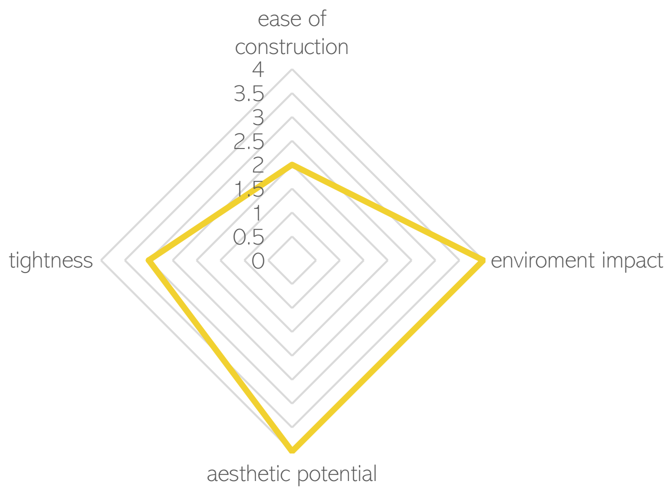
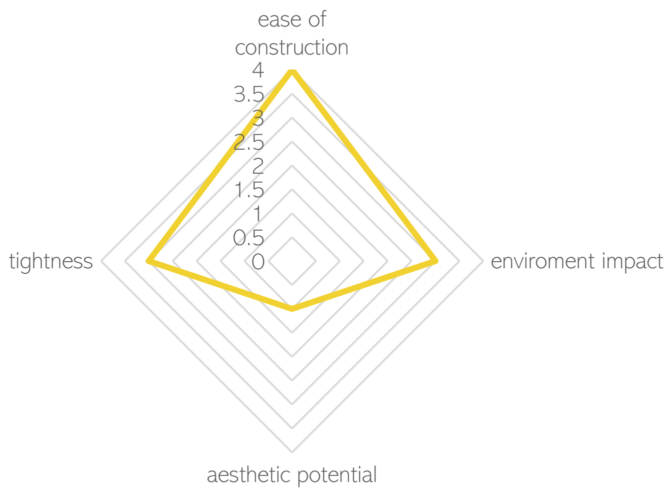
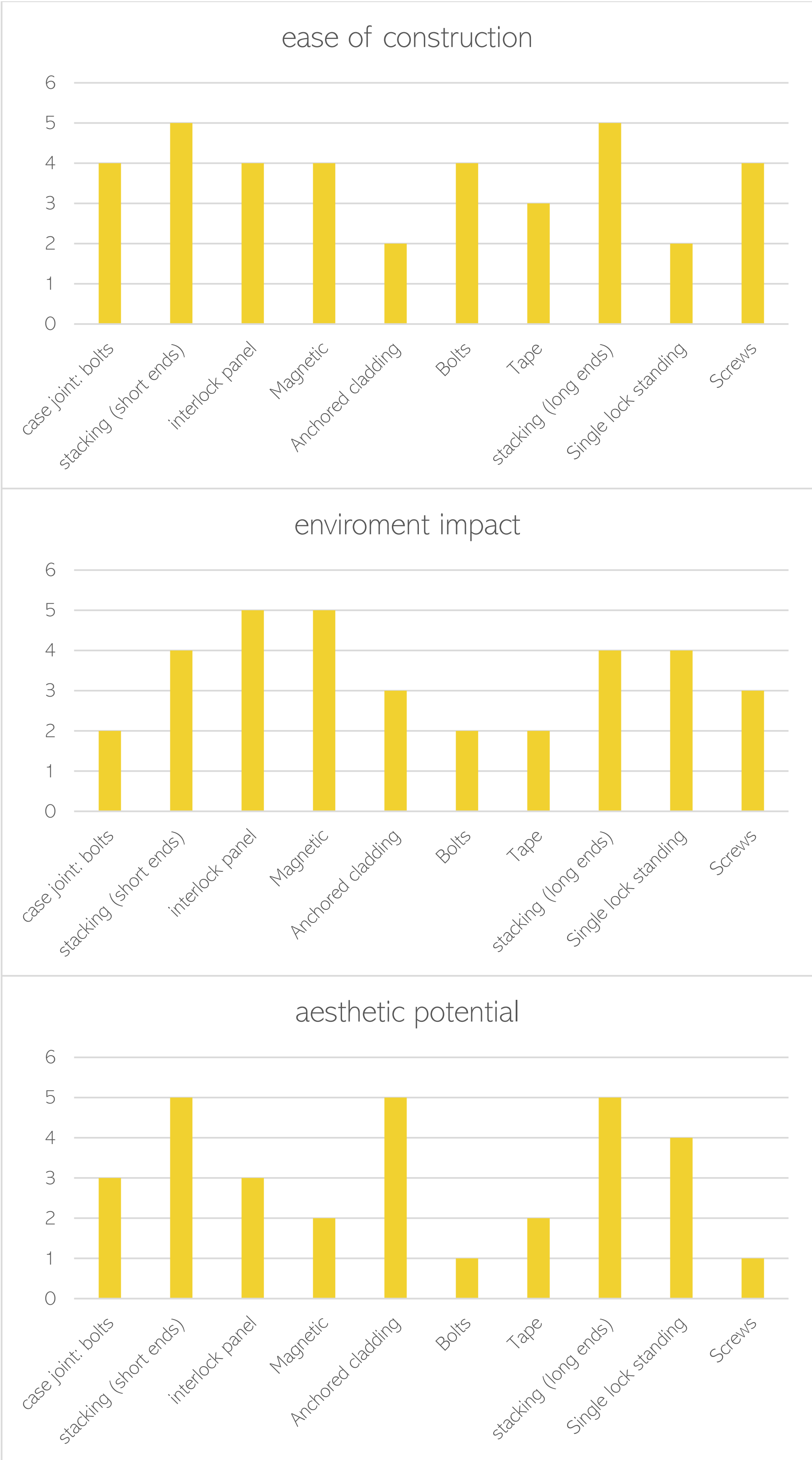
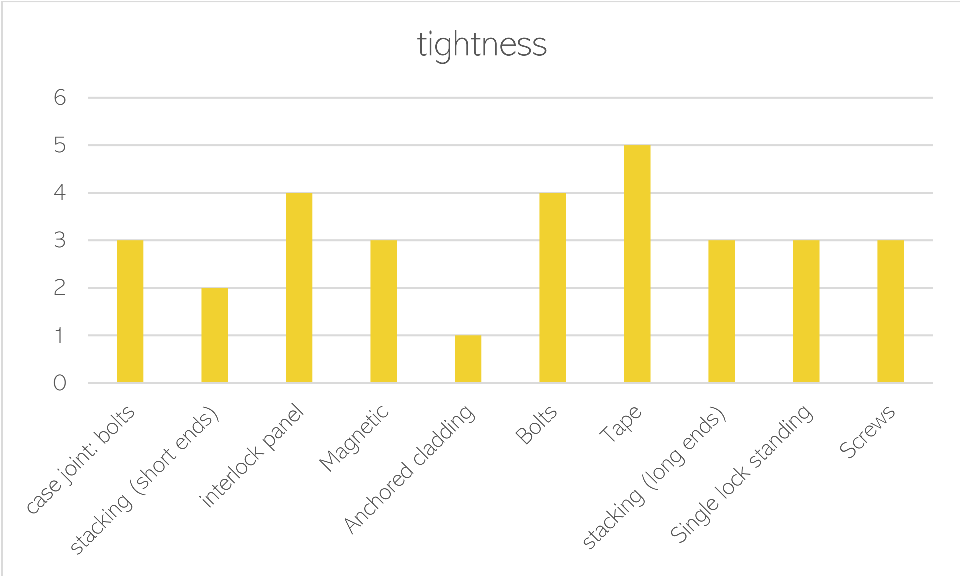
Stacking (long ends)	
Single lock standing	
Screws	

Chart 1-1, 1-2, 1-3, 1-4: Sub-indicator Assessments




tightness
6
5
4
3
2
1
0
case joint: bolts
stacking (short ends)
interlock panel
Magnetic
Anchored cladding
Bolts
Tape
stacking (long ends)
Single lock standing
Screws