DESIGN FOR DISASSEMBLY WITH STRUCTURAL TIMBER CONNECTIONS

Analysis and assessment of different connection systems used in engineered timber building structures to maximise demountability and reuse of the elements

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Abstract

This paper illustrates how a decision-making process can be applied in the architecture field in order to find the most suitable solutions to design a modular and temporary mid-rise timber building structure that allows for disassembly and reuse of the elements. The paper explains the decision-making process adopted and different related weighting system to evaluate the importance of the criteria. It also illustrates and assesses the different connection systems, both carpentry (only wood) and mechanical (wood and steel), used in engineered timber structure, providing general information about the main characteristics of each connection system and giving sources to deepen the research. At the end conclusions are drawn, both in terms of validity of the different weighting systems adopted and in terms of which connection systems better fulfil the requirements of an engineered timber building structure that allows for disassembly and reuse of the elements, the main principles to consider when designing for disassembly in the building industry are also illustrated.

Keywords: *Structural timber connections, Engineered timber structures, Design for disassembly, Design for reuse, Assessment method, Decision-making process, Weighting system.*

I. Introduction

The increasing importance of the environmental impact of the building industry and the depletion of raw materials and non-renewable energy sources has been forcing architects, constructors and clients to start designing and constructing considering the end of life of buildings (Durmisevic, 2006).

Studies have shown that demolition processes account largely for the negative environmental impact of buildings. The main problem is the fact that the assembled materials have, nowadays, very low or no potential for reuse or recycle. During the last decades, while architects have been mainly dealing with reducing the energy consumption of buildings, the use life cycles of buildings has gradually shortened due to the fact that the use requirements and the needs of people and society have been changing at a faster pace. Conversely, the technical life cycle has increased and building structures have been designed to last for 50 to 100 years. This led to an unbalanced system where buildings are designed to last longer than their actual need (Durmisevic, 2006). Furthermore, the extensive use of non-renewable material in the building industry is leading to a faster depletion of the available resources and to an increase in C02 emissions and energy consumption due to manufacturing processes.

Therefore, it is time for a new design approach which takes into account the possibility of reusing components and elements or entire products and buildings extending their use life cycles. It is also important to maximise the use of natural and renewable materials in order to slow down the depletion process and minimise the environmental footprint of materials in the built environment.

Wood, with its engineered applications, has been recently rediscovered by architects and its use has been currently spreading around the world. Nowadays, it is possible to see many buildings that utilise engineered timber as the main structural material. Along with that, circular buildings are slowly taking hold. Pilot projects, designed accordingly with the design for disassembly principle, are revolutionising the architectural practice with a completely new concept and related new business models. For this reason, designing for disassembly using structural timber can be considered a new frontier in architecture.

The act of disassembly implies the separation of the elements and components of a building as a strategic part of the life cycle that can help to achieve improved economic and environmental performance (Crowther, 1999). Therefore, it is immediately clear that connectors play a key role in determining the demountability of a product. The type of connectors used dictates the possibility to disassemble using destructive or non-destructive disassembly approach and, if the goal is to extend the end of life of elements and components, non-destructive disassembly has to be preferred (Güngör, 2006).

Since there are many different types of connections for engineered timber structures that allow for non-destructive disassembly, it is important to define which one better fulfil the requirements of the specific application in which the connection system has to be employed. For this reason, a systematic decision-making approach and assessment method are needed. These allow the designer to scientifically address the decision problem in a logic and structured way, leading to reliable and consistent outcomes, strongly related to the requirements of the project and their specific importance.

The aim of this paper is to analyse and scientifically assess different connection systems used in engineered timber structures in order to find the most suitable solutions to design a modular and temporary mid-rise timber structure that allows for disassembly and reuse of the elements. The paper provides information regarding the decision-making approach, the assessment method and the connection systems analysed, it shows how the selected process has been applied in this specific situation and what are the consequent results of the study.

II. Methodology

This paper is written as support of the graduation project within the Architectural Engineering Studio at the Architecture faculty of the TU Delft under the supervision of Ir. Pieter Stoutjesdijk. The literature research was conducted using the TU Delft library database linked to the WorldCat database, the dedicated repository database of TU Delft and Google Scholar. The research was performed in parallel on two fronts; the analysis of the connection system for structural timber building construction and the analysis of the methods to assess these connection systems in a scientific way.

The different mechanical connection systems for engineered timber structures were found mainly on catalogues of the major industries of the sector, such as Rothoblaas (EU) and KNAPP (US), while regarding the carpentry joints an extensive internet research was conducted and the main reference books used were; Wood Joints in Classical Japanese Architecture by Sumiyoshi & Matsui and Woodwork joints by Fairham.

Regarding the decision-making process, the main author was Thomas L. Saaty who set the foundation for most of the decision-making procedures that are still applied and developed by researchers in the sector. Information about specific assessment of fasteners in relation to the design for disassembly principles was found on scientific papers, mainly coming from the industrial engineering field. The aim of this research was to translate this already built knowledge in the field of architecture and engineered timber structures. Additionally, the works of Nick van der Knaap and Jeroen van Veen, both graduated at TU Delft within the PD Lab project, were taken as additional references both for the decision-making and the assessment method employed.

III. Decision-making process

In order to define which connection systems used for engineered timber structures better fulfil the requirement of a modular and temporary timber mid-rise building structure that allows for disassembly and reuse of the elements different methods can be applied. During the 1980s and the 1990s, Thomas L. Staaty developed two of the most important decision-making approaches; the Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP).

The main difference between the two processes (Figure 1) is that the AHP is based on a hierarchical system with a linear top-down structure, where elements on a higher level are independent form elements on the lower levels, while the ANP is based on a network of relations. In the ANP, the network of relations involves cycles between clusters (groups of elements) and loops within the same cluster (Saaty & Vargas, 2013). This second process is used when the problem involves the interaction and dependence of higher-level elements with lower-level elements (Güngör, 2006). In case the decision problem has a large number of criteria and alternatives, the model can become very complex. For this reason, software programs such as Expert Choice (AHP) or Super Decisions (AHP and ANP) were developed to assist the decision maker in solving complex decision problems. Due to the complexity of the problem and the lack of knowledge in the software available, this paper proposes a simplified version of the AHP which will be discussed in the next paragraphs. For a detailed explanation of the ANP please refer to Saaty & Vargas (2013).

The AHP is a decision-making system that aims at finding the best solution between alternatives to fulfil a specific decision problem. Hierarchy is used to structure the decision problem; the main goal of the decision is at the top level, the different criteria which are important to obtain the goal are placed on a second level and the alternatives between which the decision maker have to choose are on a third level (Figure 2). Once the general scheme of the problem is clear, the criteria, which can be both qualitative and quantitative, are plotted in a matrix and weighted using a pairwise comparison (Saaty & Vargas, 2012). For this comparison, Saaty proposed a fundamental scale to represent the intensities of the judgments. This numerical scale goes from 1 to 9, each pair of criteria is evaluated in terms of importance; the value 1 is given to both the criteria if they have equal importance, whether a criterion is more important than the other a value from 2 to 9 is given to the more important criteria and its reciprocal, form 1/2 to 1/9, is given to the less important criteria. The sum of the values scored by each criterion is then converted in percentage, which represents its relative weighted importance (Saaty & Vargas, 2012). Consequently, the alternatives are compared and for each criterion a matrix with the alternatives is generated. Here, with the same scale used for the criteria, it is made clear on what extent the alternatives better fulfil the specific criterion with respect to the others. After all the matrices are completed, the decision maker has a clear view of which alternative suits better the defined problem. Since in many cases the decision problem can become very complex due to the high number of criteria and especially the high number of alternatives which lead to a large number of iterations in the last step of the process, different simplified versions of the AHP have been developed.

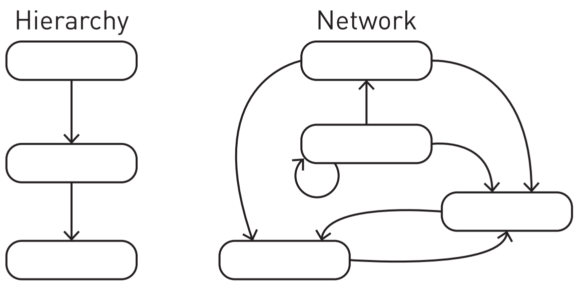

Figure 1. Difference between hierarchy and network relation systems (by author).

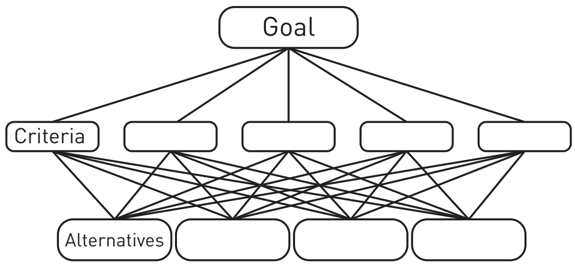

Figure 2. Structure of the hierarchical system proposed by Saaty (by author).

In this paper, three simplified versions of the AHP are presented and compared in order to understand what the implications of the different simplifications are. In all the versions the process is the same; after defining the main goal of the decision problem different criteria, concerning the main aspects of the decision problem, are identified. The criteria are weighted for importance in relation to the main goal of the decision problem using a matrix of pairwise comparisons. Based on the results of the matrices the criteria are divided into three categories of weight; very important (3), important (2) and relevant (1). Then every criterion is assessed on a numeric scale that goes from 1, when the criterion is not fulfilled, to 4, when the criterion is perfectly fulfilled. The score of each criterion is multiplied by the weight and all the specific scores are summed resulting in the final score of the connection system. The connection system with the highest score is the one that better fulfils the main goal of the decision problem. What changes between the three versions is the numerical scale, used for the pairwise comparison to weight the criteria, which is gradually simplified. By doing so, the entire process can be significantly speeded up since with large numerical scales the assessment process requires much more effort and time to be performed. The different weighting systems analysed are presented in section V.

IV. Criteria

Having clear the main goal of the decision problem; that is to find the best connection systems used in engineered timber building structures in order to design a modular and temporary mid-rise timber structure that allows for disassembly and reuse of the elements, different evaluation criteria, concerning the main aspects of the decision problem, are identified. These are defined by the decision maker in relation to the goal and the context of the decision problem.

In this case, the criteria are strongly related to the application of the connection system in engineered timber mid-rise building structures. For this reason, even though the objective of the research is to find the best connection systems which allow for disassembly and reuse of the elements, it is important to consider also the assembly operation and the in-use period of the building structure while defining the criteria that have to be assessed. Even if it is true that the aim is to find demountable connections, it is also important to keep in mind the fact that this connection should be, in the first place, suitable to be used in the design of a wooden mid-rise building structure where variables such as structural performances, element complexity, costs and finishing cannot be excluded from the decision-making process. Therefore, by considering the entire life cycle of the building and all the related aspects, the evaluation is seen from a wider perspective without losing the focus on the disassembly concerns (Güngör, 2006).

In Appendix 11.1. the different criteria adopted to evaluate the connection systems are listed and their importance for the selected goal and the related desirable performance are explained.

V. Weighting criteria

Weighting the criteria is an important step of the process. Different criteria are used to assess the alternatives but by assigning different weights the decision-making process can be focused on the more important criteria that the alternatives should fulfil. The weighting of the criteria is highly influenced by the main goal, application and context in which the alternatives perform. This part is crucial for the outcomes of the decision-making process; for this reason, great attention has to be given to the accuracy of its results.

The most used method to determine the importance of different criteria is the one proposed by Saaty & Vargas (2012) which uses a matrix where pairwise comparisons between the criteria are performed. As explained in section III, these comparisons are based on a numerical scale with values from 1 to 9. When the decision problem increases in complexity, the use of this scale become onerous in terms of time and effort. To speed up and simplify the process and focusing more on the design phase variation of this scale can be adopted. In this paper, three different scales for the pairwise comparisons are analysed and compared in order to understand the differences and the implications of the simplifications.

The first scale, used as reference, is the fundamental scale proposed by Saaty in his AHP while the other two are simplified versions which reduce the number of values that represents each comparison. The first simplified version takes the cue from the work of Nick van der Knaap and Jeroen van Veen in their projects for the PD Lab. In this case, only two values are used for the pairwise comparisons; 0 and 1. A value of 1 is assigned to the criterion which is considered more important and a value of 0 is assigned to the less important one. This extremely simple comparison can be seen as a ranking method for the criteria since it is not possible that two criteria score the same result. The main benefits are the simplicity and the velocity of the process, which is based on extremely quick comparisons suitable to handle a relatively high number of criteria and alternatives in a short amount of time (Van der Knaap, 2016). The second simplified version is a middle ground between the two. In this case, the pairwise comparisons are based on a scale from 1 to 3. If the criteria are equally important a value of 1 is assigned to both, if one criterion is relatively more important a value of 2 is assigned and a value of 1/2 is assigned to the less important, if one criterion is significantly more important a value of 3 is assigned and a value of 1/3 is assigned to the less important. In this case, the comparison process is not as straight forward as in the first simplified version because the decision maker has to think more about the relative importance of each criterion.

In Appendix 11.2. the three matrices using the three different systems are compared. The weight of the criteria is expressed both in terms of percentage over the overall score and in values from 1 to 3 where 3 is considered very important, 2 important and 1 relevant. These second weighting scores are defined by dividing the highest score by 3 and grouping the criteria within the same numerical range.

By comparing the three systems, it is possible to see how, when using the weighting scores even with the most simplified variation, the resulting weights are almost identical. In this case, it is possible to say that by simplifying the scale the obtained results are still reliable. On the other hand, when looking at the more accurate weighting percentage, more differences can be seen between the variations. Considering the fundamental scale by Saaty the most accurate one, because it involves the most detailed differences in the importance degree, the other two scales produce results which deviate in different ways. The most simplified one shows sharper and constant distinctions between the weighting percentages of every criterion since no criterion can be equally important to another. For this reason, in this case, the distance between the values cannot be considered relevant because of the absence of differentiation in the degree of importance. Conversely, the less simplified version shows more uniform results with smaller differences between the weighting percentages. In this case, the differentiation in the degree of importance is minimum and, therefore, the distances between the scores is less pronounced. By looking at the percentage it is possible to notice how the results of the second variation are more similar to the scale proposed by Saaty or at least deviate from it following a constant scheme. Instead, the percentages of the most simplified variation cannot be considered reliable due to their relatively random deviation caused by the too simplified comparison system.

VI. Connection systems

The defined weighted criteria are used to evaluate the different connection systems for engineered timber building structures which allow disassembly and reuse of the elements. The analysed connections are divided into four main groups, namely, column to column connections, beam to beam connections, beam to column connections and panel connections. These groups differentiate for the purpose and the field of application of the connection system. Another distinction is made between three categories that coexist within the main groups; carpentry connections, mechanical connections and fasteners. The carpentry connections are integrated systems that exploit the potentials of woodworking to create interlocking joints that minimise the use of additional fasteners. On the other hand, the mechanical connections are standardised systems developed by industries working in the sector which aim at minimizing the complexity of the structural elements by employing independent connections that can be added or removed from the element if necessary. Lastly, fasteners include the connection systems which focuses on the only use of bolts or screws to connect multiple elements together. Please note that also some of the carpentry connections and mechanical connections employ fasteners in their systems but they do not rely only on those.

In this section, a general explanation regarding the connection systems analysed is given. They are divided between the three main categories for a better understanding of the difference. For each connection it is also indicated in which applications it can be applied; column to column (CC), beam to beam (BB), beam to column (BC), panel (P). For additional information, drawings and evaluations refer to Appendix 11.3..

6.1. Carpentry connections

A. Mortise and tenon joint (BB, BC)

The mortise and tenon connection system is based on the principle that, in one of the two connecting elements, a mortise (hole) is cut and, on the other, a tenon (projection) is shaped to fit exactly into the mortise. When the two elements are connected the joint is locked by using pins, dowels, wedges or metallic fasteners (less common). This system is mostly used to connect perpendicular elements. It is one of the most widely used typical examples of interlocking joints and it has been developed in many different alternatives which vary from the very simple to the very complicated and self-locking ones (Fairham, 2007).

B. Box joint (P)

The box joint is created by cutting a set of complementary, interlocking profiles in the two connecting wooden panels, which are then joined usually at right angles. Box joints are mainly used for corners of box-like constructions. Even though in its simplest form the box joint is usually glued to prevent the separation of the two elements, some of the more complex alternatives are able to lock the connection in all the directions except the only one in which the two panels are pulled together.

C. Halved joint (BB)

The halved joint is created by removing material from both of the members so that the resulting joint is the thickness of the thickest member. Each piece is halved and shouldered at opposite sides forming a perfect fit one with the other and giving a strong joint with a minimum amount of labour (Fairham, 2007). The connection is generally screwed or bolted together. Also in this case, different variations have been created, from the simplest, which consist in a simple rectangular cut, to the more complex and self-locking cut geometries.

D. Tongue and groove joint (P)

The tongue and groove joint is used to join two or more panels together, usually on the same plane, even though variations of this connection system are used also to connect panels at an angle. Each piece has a slot (groove) cut all along one edge, and a thin, deep ridge (tongue) on the opposite edge. Usually, the tongue projects a little less than the depth of the groove so that the two or more pieces fit together closely. The tongue and groove is mostly seen in its rectangular variation but different shapes of tongue and groove are can be designed so that more directions of movement are locked.

E. Column splice joint (CC)

The column splice joint is used to connect two elements to increase the final length. Mainly used in the Japanese woodworking tradition, this joint is created by cutting two complementary interlocking ends on each element so that one or more directions of movement are locked. As for the other carpentry connections, different variations of the joint are available each locking the connection in different and multiple directions (Sumiyoshi & Matsui, 1991).

6.2. Mechanical connections

F. Metallic hanger (BB, BC)

The metallic hanger is probably the most used connection in engineered timber frame structures. The metallic connector is generally composed of a back plate, fastened with screws to one of the two elements, and a bearing seat or bracket to which the other element is connected, generally using metallic dowels, screws or bolts. Different variations of the connection have been developed by the industries in the sector, but the main difference can be considered whether or not the connectors are concealed by the wooden elements or visible. This not only influences the appearance of the connection but also its fire safety since metallic material experience drastic deterioration of their mechanical properties when exposed to fire. On the other hand, when exposed to fire, wood has proven to create a carbonised outer layer that protects the inner part of the element which maintains its mechanical properties unaltered.

G. Hook connector (BB, BC)

The hook connector is a mechanical connections system with a high degree of prefabrication. It is composed of two distinct parts that are already connected to the two elements. These parts are designed such as they can be easily interlocked creating a strong connection which is then generally secured using a single fastener which locks the direction opposite to the insertion. The main advantage of this connection system is related to the fast installation and the possibility of easy disassembly which made this system especially suitable for temporary structures.

H. Metallic brackets (P)

The metallic brackets are the most used connection system in engineered timber panel structures. The brackets are L-shaped with holes on the two wings to accommodate the fasteners which secure the connection to the elements. Since the panel elements of these structures have to bear both shear and tensile forces different brackets are designed for these two purposes; long vertical ones for tensile forces and low horizontal ones for shear forces. These brackets are usually connected through nails, but screws are also used if there is the need of having a reversible connection.

I. X-RAD (P)

The X-RAD is a connection system for engineered timber panel structures patented by Rothoblaas. This system replaced the conventional shear and tensile brackets with a sole corner connection that allows to transfer high tensile and shear stresses through the corners of the wall and floor panels. The X-RAD system is factory prefabricated and already connected to the panel elements. Each panel is connected to a corner core using bolts, this allows fast installation on site and the possibility of easy disassembly.

J. Post connector (CC)

The post connector is a connection system that allows to transfer the forces between two vertical engineered timber elements. These connectors are used to break the timber vertical elements in multiple parts reducing the overall effect of shrinkage of the wood. The metal connectors are usually fastened to the wooden elements using screws or bolts. There are different post connectors, some are made of a singular metal component which is then connected to the top and bottom of the vertical elements, others are made of two interlocking parts which are previously connected to the elements and then assembled together on site.

6.3. Fastener

K. Butt joint (BB, BC, P)

The butt joint is the simplest joint in terms of woodworking since it merely involves cutting the elements to the appropriate length and pulling them together. The butt joint only relies on the fasteners that connect the elements together, usually screws or bolts. For this reason, the design of the position, dimension and length of the fasteners is crucial. The fasteners are usually inserted into an edge on side of one member and extend through the joint into the adjacent member. This connection system is widely used in modern timber construction since it requires almost no element preparation or workers' qualifications and it represents a simple and cheap way of connecting two or more wooden elements.

VII. Assessment method

As explained in the previous chapter, for every connection system a lot of different variations have been developed, from the simpler to the more complex ones. The impossibility of addressing every different variation of every connection system lead to the choice of addressing only the two extreme cases of each family. By doing so, the advantages and disadvantages of creating more complicated solutions are made clear and a general overview of the different systems and the principles behind are illustrated. Nevertheless, a lot of intermediate solutions are available or can be designed in order to find the best compromise for the specific situation.

Each connection system is evaluated regarding every criterion using this numerical scale, with values from 1 to 4. These values are then multiplied by the weight of the criterion, explained in chapter V, and then summed to calculate the final score (Appendix 11.4.). Whenever it is possible, the individual scores are based on data available or peculiar characteristics regarding the specific connection that can determine a valid score. Due to the fact that some criteria aim to assess qualitative values, the scores are assigned directly by the decision maker and that represent more a subjective judgment than an objective evaluation. For this reason, the knowledge of the decision maker regarding the analysed subject is crucial to produce reliable outcomes.

In this specific case, it is clear how criteria such as Element complexity, Reusability or End of cycle waste can be considered more subjective, while others such as Structural strength, Degree of freedom or Number of elements more objective since they can be based on actual data.

For this reason, whenever specific data regarding the objective criteria are not available or depend on many different variables, it is not possible to assign an objective score. An example of this situation is found with the structural strength criterion. Even though this is a very important criterion to consider when choosing connections for building structures this criterion depends, in this case, on many factors, such as the type of wood or steel used in the connection, the dimensions of the fasteners and also the different types of loads applied. For this reason, this criterion is assessed in a more empirical way mostly related to the geometry of the connection and not on its material, trying to estimate whether or not the specific connection geometry can be considered stronger or weaker than the others.

Since the aim of the paper is focused on the possibility of reusing the connection system multiple times to extend the use life cycle of the structure, particular attention has been given to assess the criteria related to this aspect, which are also the ones that have the highest weight; Ease of assembly, Ease of disassembly and Reusability. The assessment of these criteria is based on the research done by Das, Yedlarajiah and Narendra (2000), with respect to the assembly and disassembly procedure for which they have developed the DEI (Disassembly Effort Index) that can be also applied to the assembly process; and on the research done by Hradil et al. (2017), with respect to the reusability of building systems and components for which they have developed a system that evaluates the difficulties of different operations within the process of reuse. Both these assessment methods include the different aspects related to the whole process of assembly, disassembly and reuse. The different aspects have different weights on the overall score. Firstly, they are evaluated individually and then added up to obtain the final score. This score is then translated to the 1 to 4 numerical scale used to assess the different connection systems.

For the criteria Number of elements and Degree of freedom, the evaluation is based on the data obtained from the study of the geometry and characteristics of the connection system. The other criteria; Element complexity, Prefabrication degree, Finishing, End of cycle waste and Costs are evaluated in a more empirical way based on the acquired knowledge of the author and general assumptions, therefore, they cannot be considered extremely reliable since they are more open to individual interpretation.

The assessment process can be considered finished once all the connection systems are assessed in all the different criteria and the final scores are calculated. The connections are then divided into the four main groups (CC, BB, BC, P) that are used to perform the final comparison. In each group, the best connection system for the defined goal is then identified (Appendix 11.4.).

VIII. Conclusion

The paper illustrates how decision-making processes and the relative assessment methods can be used to determine the most suitable connection systems to design a modular and temporary mid-rise timber building structure that allows for disassembly and reuse of the elements in a scientific method. From this research, conclusions can be drawn both related to the decision-making process itself and to the engineered timber connection systems to be used for demountable timber structures.

Exploring in depth different weighting approaches used to evaluate the importance of the criteria in a decision problem, it has been found that the fundamental scale proposed by Saaty & Vargas (2012) is not the only valid option, especially if the weights are not expressed in percentage but in numbers, as in this case from 1 to 3. In this situations, simplified versions of the scale can be used causing very small to no deviation from the reference scale. This reduces the time and the effort of the decision-making process leaving more time to the design phase and the development of the selected alternatives. On the other hand, if the percentage (more accurate) is chosen as the representative value for the weights, the fundamental scale represents the most reliable weighting system. If there is a strong need for simplification the middle scale can be used being aware that it does not allow for pronounced differences between the importances of the criteria.

By scientifically assessing the different connection system used in timber structure, it is possible to understand what the main benefits and drawbacks of each connection are in relation to the aim of designing a modular and temporary mid-rise timber building structure that allows for disassembly and reuse of the elements. It was immediately clear how the ease of assembly and disassembly were fundamental aspects to be considered. These are related not only to the amount of time and actions needed but also to the complexity of the tools, the required workers' skills and the accessibility of the connection. For the purpose of reusing connection system, it was also clear that the most important aspect is not whether or not the connection system can be detached from the elements but, conversely, if the connection can be dismounted without being separated from the singular elements. For this reason, plug-in connections systems scored the highest in terms of reusability; they reduce the action and the time needed to separate the elements and they are also the ones with the lowest possibility of failure after reuse, exactly because they remain fixed to the separated elements.

The last important aspect to consider when focusing on designing a modular and temporary mid-rise timber building structure that allows for disassembly and reuse of the elements was found to be the structural strength. This, along with other criteria, is not closely related to the possibility of disassembly or reuse of the structural elements, but it reminds the importance of avoiding losing the wider perspective when addressing a decision problem from a specific point of view. Especially in this case, it was fundamental to consider all the criteria related to the construction and the in-use period of a building because, by focusing only on the disassembly related aspects, the result might be, on the one hand, more suitable for the reuse purpose but, on the other hand, less to no suitable for designing a structure of a building.

To conclude, the results in appendix 11.3. and 11.4. show that the best connection systems to design a modular and temporary mid-rise timber building structure that allows for disassembly and reuse of the elements are; for the column to column connection the alternative J.2., for the beam to column and beam to beam connection the alternative G.2. and for the panel system the alternative I.. All these connection systems represent the best compromise between maximising the disassembly and reuse potentials and maximising the structural performances and in-use quality of the engineered wooden structure.

IX. Limits and recommendation for further research

This entire decision-making process is more inclined to qualitative instead of quantitative. It very much involves the decision maker to actively assess the different alternatives based on criteria that cannot always be assessed in an objective way. Therefore, the result of the study is strongly influenced by the decision maker and his knowledge in the field. Therefore, his objectivity in approaching the decision problem is crucial for the reliability of the result. To improve the validity of the process, multiple decision makers, with different qualifications, can be involved in the assessment, as proposed also by Saaty & Vargas (2012). The criteria can also be assessed in a more quantitative way by collecting specific criteria-related data on all the possible alternatives. By doing so the decision-making outcomes will be improved but the time and resources needed would also increase. In order to define the feasibility of a designed for disassembly engineered timber structure, further research about the structural performances of the connections and the different types of wood is needed. Also, the conclusions related to the simplified version of the fundamental scale, used for the weighting of the criteria, are drawn from this specific case only and might not be exactly true for other situation with other criteria and different decision makers. Further tests on other situation are needed to validate this result.

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XI. Appendix

11.1. Explanation of the different evaluation criteria

11.1.1. Number of elements

The number of elements evaluates how many elements the connection is made of. It affects the assembly and disassembly process in various ways since the more elements have to be moved or fastened, the more complex and long the assembly time would be. Even if the connection system is already assembled in the factory the number of elements is still relevant because it extends the prefabrication time. Therefore, it influences costs, time and complexity of the connection. For these reasons, a connection system, which minimises the number of elements, is desired.

11.1.2. Elements complexity

The design complexity evaluates the complexity of the shape of the elements caused by the chosen connection. The design of the product can be more complex and parts more open to failures. The elements complexity also influences the prefabrication time and cost since more complex elements requires specific machinery and different prefabrication steps. Additionally, the simpler are the elements the higher is the possibility of reusing them at the end of the life cycle of the building. For these reasons, a connection system, which minimises the design complexity, is desired.

11.1.3. Prefabrication degree

The prefabrication degree evaluates the degree in which the connection system is prefabricated in the factory environment. Therefore, the prefabrication degree influences the number of assembly steps that have to be made on site to fix the connection system and the construction time and costs related. The prefabrication degree also affects the accuracy of the positioning of the connectors and the damage chances that can occur on-site slowing down the entire construction process. For these reasons, a connection system, which maximises the prefabrication degree, is desired.

11.1.4. Ease of assembly

The ease of assembly evaluates all the procedures needed to assemble the pieces together. It is a global parameter based on the DEI method developed by Das, Yedlarajiah and Narendra (2000), it includes the assembly time, the ease of access of the connection, the operator's qualification, the specificity of the required tools and eventual protective equipment needed. It has an influence on construction time and costs. For these reasons, a connection system, which maximises the ease of assembly, is desired.

11.1.5. Degree of freedom

The degree of freedom evaluates the number of directions in which the connection system is free to move and therefore needs to be locked on site with additional fasteners. This influences the time of assembly and disassembly since multiple additional operations have to be done on site. On the other hand, connections systems with a higher degree of freedom are usually simpler. For the main goal defined, a connection system, which minimises the degree of freedom, is desired.

11.1.6. Structural strength

The structural strength evaluates the strength of the connection. This is strongly related to the materials implied in the connection system but also to the fastener selected to connect the different elements of the connection and of the structure. The required strength is highly dependent on the specific situation in which the connection is used. In general, it is possible to say that connection systems which maximise the structural strength are preferred.

11.1.7. Finishing

The finishing evaluates the final visibility of the connection system in terms of whether the connection is visible, partially visible or hidden. This not only influences the aesthetic qualities of the connection in the in-use period, but it can also influence fire safety, for example in case metallic connections are used. Therefore, a hidden connection system is desired both for aesthetic and for safety reasons.

11.1.8. Ease of disassembly

The ease of disassembly evaluates all the procedures needed to disassemble the elements. It is a global parameter based on the DEI model developed by Das, Yedlarajiah and Narendra (2000), it includes the disassembly time, the ease of access of the connection, the operator's qualification, the specificity of the required tools and eventual protective equipment needed. It has an influence on deconstruction time and costs. For these reasons, a connection system, which maximises the ease of disassembly, is desired.

11.1.9. End of cycle waste

The end of cycle waste evaluates the amount of waste that is likely to be produced when the connection system is disassembled and reassembled. It considers all the part of the connection that will not be reused for the future life-cycles of the structure. It affects the environmental impact of the reuse and it has influence also on costs. For these reasons, a connection system, which minimises or eliminates the end of cycle waste, is desired.

11.1.10. Reusability

The reusability evaluates the number of times in which the elements and the connection system can hypothetically be reused after it has been demounted. It is a global parameter based on the model developed by Hradil et al. (2017), it includes the steps from disassembly to reassembly, the handling manipulation difficulties, the possibility of redesigning and modifications and also the difficulties of performing quality checks before the reuse. It considers the system as a whole and it influences the cost and the feasibility of the potential reuse in terms of the economic investment and also the environmental impact in relation to the eventual production of waste. For these reasons, a connection system, which maximises the reusability, is desired.

11.1.11. Costs

The cost of a connection system evaluates the production and/or purchase of the connection system composed both by the connecting and connected elements. The costs are influenced mainly by the complexity of the design, its uniqueness, the materials involved and the number of elements of the connection. The cost of a connection system is also highly influenced by the geographical area since there are parts of the world where industrial products are cheaper than man labour and vice versa. In general, a connection system, which minimises the cost, is desired.

11.2. Comparison of weighting using the fundamental scale and the simplified scales

FUNDAMENTAL SCALE (1 to 9) -reference-

	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	tot	weight	weight (%)
number of elements		2,00	0,20	0,14	2,00	0,17	7,00	0,14	4,00	0,14	8,00	23,80	oo	0,0783
elements complexity	0,50		0,17	0,14	1,00	0,17	6,00	0,14	6,00	0,17	7,00	21,29	oo	0,0700
prefabrication degree	5,00	6,00		0,25	4,00	0,50	6,00	0,25	5,00	0,25	6,00	33,25	oo	0,1094
ease of assembly	7,00	7,00	4,00		6,00	3,00	8,00	1,00	7,00	2,00	8,00	53,00	ooo	0,1743
degree of freedom	0,50	1,00	0,25	0,17		0,17	6,00	0,17	5,00	0,20	6,00	19,45	oo	0,0640
structural strenght	6,00	6,00	2,00	0,33	6,00		7,00	0,33	6,00	0,33	7,00	41,00	ooo	0,1349
finishing	0,14	0,17	0,17	0,13	0,17	0,14		0,13	0,50	0,13	0,50	2,16	o	0,0071
ease of disassembly	7,00	7,00	4,00	1,00	6,00	3,00	8,00		7,00	2,00	8,00	53,00	ooo	0,1743
end of cycle waste	0,25	0,17	0,20	0,14	0,20	0,17	2,00	0,14		0,14	2,00	5,41	o	0,0178
reusability	7,00	6,00	4,00	0,50	5,00	3,00	8,00	0,50	7,00		7,00	48,00	ooo	0,1579
costs	0,13	0,14	0,17	0,13	0,17	0,14	2,00	0,13	0,50	0,14		3,64	o	0,0120
												303,99	tot	1,00

COMPARATIVE SYMBOLS

- √ Equal
- ↓ Slightly lower (<1%)
- ↑ Slightly higher (<1%)
- ↓ Much lower (>1%)
- ↑ Much higher (>1%)

SIMPLIFIED SCALE (1 to 3)

	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	tot	weight	weight (%)	
number of elements		1,00	0,50	0,33	1,00	0,33	3,00	0,33	2,00	0,33	3,00	11,82	oo √	0,0743	↓
elements complexity	1,00		0,50	0,33	1,00	0,33	3,00	0,33	2,00	0,33	3,00	11,82	oo √	0,0743	↓
prefabrication degree	2,00	2,00		0,50	2,00	1,00	3,00	0,50	2,00	0,50	3,00	16,50	oo √	0,1037	↓
ease of assembly	3,00	3,00	2,00		3,00	2,00	3,00	1,00	3,00	2,00	3,00	25,00	ooo √	0,1572	↓
degree of freedom	1,00	1,00	0,50	0,00		0,33	2,00	0,33	2,00	0,33	2,00	9,49	oo √	0,0597	↓
structural strenght	3,00	3,00	1,00	0,50	3,00		3,00	0,50	3,00	0,50	3,00	20,50	ooo √	0,1289	↓
finishing	0,33	0,33	0,33	0,33	0,50	0,33		0,33	0,50	0,33	0,50	3,81	o √	0,0240	↑
ease of disassembly	3,00	3,00	2,00	1,00	3,00	2,00	3,00		3,00	2,00	3,00	25,00	ooo √	0,1572	↓
end of cycle waste	0,50	0,50	0,50	0,33	0,50	0,33	2,00	0,33		0,33	1,00	6,32	o √	0,0397	↑
reusability	3,00	3,00	2,00	0,50	3,00	2,00	3,00	0,50	3,00		3,00	23,00	ooo √	0,1446	↓
costs	0,33	0,33	0,33	0,33	0,50	0,33	2,00	0,33	1,00	0,33		5,81	o √	0,0365	↑
												159,07	tot	1,00	

A deviation pattern can be found. Since less distinction of the level of importance is possible, the lowest scores result much higher and the highest scores much lower while the intermediate scores are just slightly deviated.

MOST SIMPLIFIED SCALE (1 or 0)

	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	tot	weight	weight (%)	
number of elements		1	0	0	1	0	1	0	1	0	1	5	oo √	0,0909	↑
elements complexity	0		0	0	1	0	1	0	1	0	1	4	oo √	0,0727	↑
prefabrication degree	1	1		0	1	0	1	0	1	0	1	6	oo √	0,1091	↓
ease of assembly	1	1	1		1	1	1	1	1	1	1	10	ooo √	0,1818	↑
degree of freedom	0	0	0	0		0	1	0	1	0	1	3	o ↓	0,0545	↓
structural strenght	1	1	1	0	1		1	0	1	0	1	7	ooo √	0,1273	↓
finishing	0	0	0	0	0	0		0	0	0	0	0	o √	0,0000	↓
ease of disassembly	1	1	1	0	1	1	1		1	1	1	9	ooo √	0,1636	↓
end of cycle waste	0	0	0	0	0	0	1	0		0	1	2	o √	0,0364	↑
reusability	1	1	1	0	1	1	1	0	1		1	8	ooo √	0,1455	↓
costs	0	0	0	0	0	0	1	0	0	0		1	o √	0,0182	↑
												55	tot	1,00	

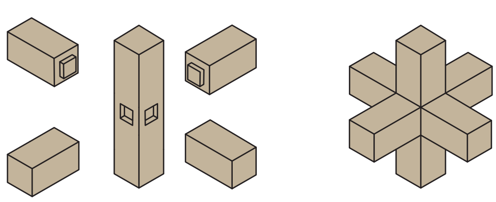
A deviation pattern cannot be found. No distinction of the level of importance is possible, therefore, the deviation is random.

11.3. Evaluation of the connection systems

A. Mortise and tenon (BB, BC)

Score reliability:
- reliable
- empiric
- assumed

A.1. SIMPLE (additional fasteners needed)



Additional information about this connection can be found in: Fairham (2007).

NUMBER OF ELEMENTS (2)

A LOT — A FEW; 1 2 3 4

SCORE = 6

Additional fasteners are needed to secure the elements, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN; 1 2 3 4

SCORE = 2

The additional fasteners are exposed undermining the appearance and the safety of the connection.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE; 1 2 3 4

SCORE = 6

The shapes of the elements are relatively simple. Basic woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY; 1 2 3 4

SCORE = 9

The connection is easy to disassemble. It requires short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

PREFABRICATION DEGREE (2)

LOW — HIGH; 1 2 3 4

SCORE = 4

The shape of the elements can be prefabricated but a lot of actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING; 1 2 3 4

SCORE = 2

This connection system might cause significant waste at the end of use since both the fasteners and the elements can be easily damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY; 1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

REUSABILITY (3)

LOW — HIGH; 1 2 3 4

SCORE = 6

The reusability of the connection system is relatively low due to the fact that the fasteners have to be removed every time the connection is disassembled and reassembled.

DEGREE OF FREEDOM (2)

6 — 0; 1 2 3 4

SCORE = 6

The connection is free to move only in the direction of insertion.

COSTS* (1)

HIGH — LOW; 1 2 3 4

SCORE = 4

The costs of the connection are considered low due to the fact that basic woodworking and fasteners are needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

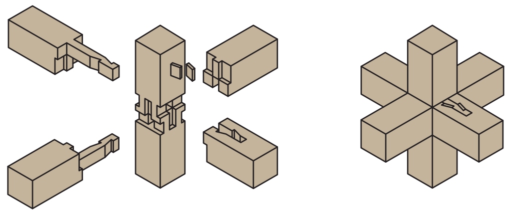
LOW — HIGH; 1 2 3 4

SCORE = 6

The relatively short tenon makes this connection weaker and it has to rely a lot on the additional fasteners.

FINAL SCORE
60

A.2. COMPLEX (self locking)



Additional information about this connection can be found in: Sumiyoshi & Matsui (1991).

NUMBER OF ELEMENTS (2)

A LOT — A FEW; 1 2 3 4

SCORE = 8

No additional elements are needed except from the two looking wood pieces.

FINISHING (1)

EXPOSED — HIDDEN; 1 2 3 4

SCORE = 3

The looking wood pieces are exposed influencing the safety of the connection.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE; 1 2 3 4

SCORE = 2

The shapes of the elements are complex. Complicated woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY; 1 2 3 4

SCORE = 6

The connection is relatively difficult to disassemble. Even if almost no tools are needed, it requires time and worker instruction and it is only accessible from one direction.

PREFABRICATION DEGREE (2)

LOW — HIGH; 1 2 3 4

SCORE = 8

Every piece of the connection can be prefabricated and then assembled on-site where almost no additional actions are needed.

END OF CYCLE WASTE (1)

A LOT — NOTHING; 1 2 3 4

SCORE = 3

This connection system might cause waste at the end of use since the wood locking elements and the geometry of the elements can be damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY; 1 2 3 4

SCORE = 6

The connection is relatively difficult to assemble. Even if almost no tools are needed, it requires time and worker instruction due to the high geometry complexity.

REUSABILITY (3)

LOW — HIGH; 1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged but the quality check might result difficult to perform.

DEGREE OF FREEDOM (2)

6 — 0; 1 2 3 4

SCORE = 8

The connection is self locking so the connection leaves no degree of freedom.

COSTS (1)

HIGH — LOW; 1 2 3 4

SCORE = 3

The costs are considered relatively low since only complex woodworking is needed which can be also done with CNC milling machines.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH; 1 2 3 4

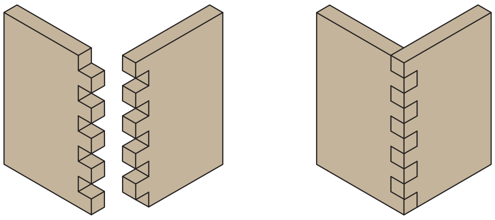
SCORE = 9

The interlocking elements act together against tensile stresses and the passing tenon provide high shear strength.

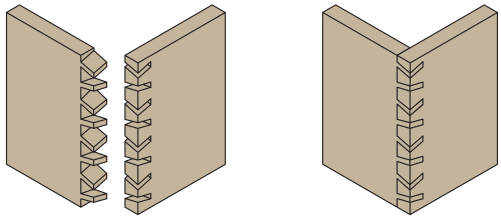
FINAL SCORE
65

B. Box joint (P)

B.1. SIMPLE (2x90° intersections)



B.2. COMPLEX (single 45° intersection)



Score reliability: reliable / empiric / assumed

B.1. SIMPLE

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 6

Additional fasteners are needed to secure the elements, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 3

The additional fasteners are exposed undermining the appearance and the safety of the connection.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 6

The shapes of the elements are relatively simple. Basic woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to disassemble. It requires short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The shape of the elements can be prefabricated and just a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause significant waste at the end of use since both the fasteners and the elements can be damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 6

The reusability of the connection system is relatively low due to the fact that the fasteners have to be removed every time the connection is disassembled and reassembled causing permanent damage.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 4

The connection is free to move in two perpendicular directions which frees also the torsional movement.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 4

The costs of the connection are considered low due to the fact that basic woodworking and fasteners are needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 6

The connection has to rely mainly on the additional fastener to secure most of the movements.

FINAL SCORE
64

B.2. COMPLEX

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 8

No additional elements are needed except possible fasteners to lock the sole direction of insertion.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 4

The wood connection express its uniqueness in its carved appearance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 2

The shapes of the elements are complex. Complicated woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to disassemble. Even if almost no tools are needed, it requires time and worker instruction and it is only accessible from one direction.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

Every piece of the connection can be prefabricated and then assembled on-site where almost no additional actions are needed.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause waste at the end of use since the geometry of the elements can be easily damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to assemble. Even if almost no tools are needed, it requires time and worker instruction due to the high geometry complexity.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged but the quality check might result difficult to perform.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection is locked in almost all the directions leaving only one degree of freedom which can be additionally fastened.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 3

The costs are considered relatively low since only complex woodworking is needed which can be also done with CNC milling machines.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

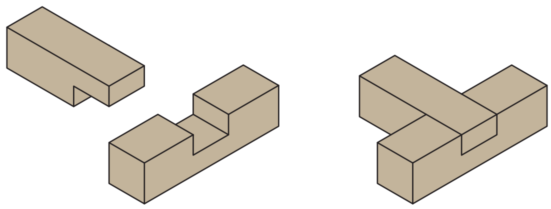
SCORE = 9

The interlocking shapes act together against all the stresses but their minuteness might lead to fragility of the connection.

FINAL SCORE
66

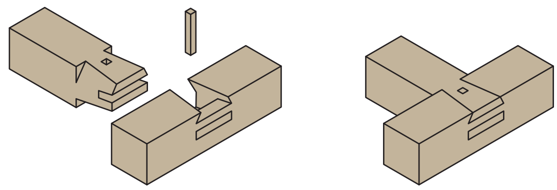
C. Halved joint (BB)

C.1. SIMPLE (simple lap)



Additional information about this connection can be found in: Fairham (2007).

C.2. COMPLEX (self locking)



Additional information about this connection can be found in: Sumiyoshi & Matsui (1991).

Score reliability:
- reliable
- empiric
- assumed

C.1. SIMPLE

NUMBER OF ELEMENTS (2)

A LOT — A FEW
1 2 3 4

SCORE = 4

Additional fasteners are needed to secure the elements, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN
1 2 3 4

SCORE = 2

The additional fasteners are exposed undermining the appearance and the safety of the connection.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE
1 2 3 4

SCORE = 6

The shapes of the elements are relatively simple. Basic woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY
1 2 3 4

SCORE = 12

The connection is very easy to disassemble. It requires short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

PREFABRICATION DEGREE (2)

LOW — HIGH
1 2 3 4

SCORE = 6

The shapes of the elements can be prefabricated but a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING
1 2 3 4

SCORE = 2

This connection system might cause significant waste at the end of use since both the fasteners and the elements can be easily damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY
1 2 3 4

SCORE = 12

The connection is very easy to assemble. It requires short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

REUSABILITY (3)

LOW — HIGH
1 2 3 4

SCORE = 6

The reusability of the connection system is relatively low due to the fact that the fasteners have to be removed every time the connection is disassembled and reassembled.

DEGREE OF FREEDOM (2)

6 — 0
1 2 3 4

SCORE = 4

The connection is free to move in two perpendicular directions which frees also the torsional movement.

COSTS* (1)

HIGH — LOW
1 2 3 4

SCORE = 4

The costs of the connection are considered low due to the fact that basic woodworking and fasteners are needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH
1 2 3 4

SCORE = 6

The connection has to rely mainly on the additional fastener to secure most of the movements.

FINAL SCORE
64

C.2. COMPLEX

NUMBER OF ELEMENTS (2)

A LOT — A FEW
1 2 3 4

SCORE = 8

No additional elements are needed except from the looking wood piece inserted at the end to secure the connection.

FINISHING (1)

EXPOSED — HIDDEN
1 2 3 4

SCORE = 3

The looking wood pieces are exposed influencing the safety of the connection which on the other hand express its uniqueness in the appearance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE
1 2 3 4

SCORE = 4

The shapes of the elements are relatively complex. Complicated woodworking is needed on both the two elements.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY
1 2 3 4

SCORE = 9

The connection is relatively easy to disassemble. Almost no tools are needed, but it requires a particular angle and some worker instruction to be dismounted.

PREFABRICATION DEGREE (2)

LOW — HIGH
1 2 3 4

SCORE = 8

Every piece of the connection can be prefabricated and then assembled on-site where almost no additional actions are needed.

END OF CYCLE WASTE (1)

A LOT — NOTHING
1 2 3 4

SCORE = 4

This connection system might cause very low waste at the end of use since the wood locking element is the only element that is likely to be damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY
1 2 3 4

SCORE = 9

The connection is relatively easy to assemble. Almost no tools are needed, but it requires a particular angle of insertion and some worker instruction to be secured.

REUSABILITY (3)

LOW — HIGH
1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged but the quality check might result difficult to perform.

DEGREE OF FREEDOM (2)

6 — 0
1 2 3 4

SCORE = 8

The connection is self locking so the connection leaves no degree of freedom.

COSTS (1)

HIGH — LOW
1 2 3 4

SCORE = 3

The costs are considered relatively low since only complex woodworking is needed which can be also done with CNC milling machines.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH
1 2 3 4

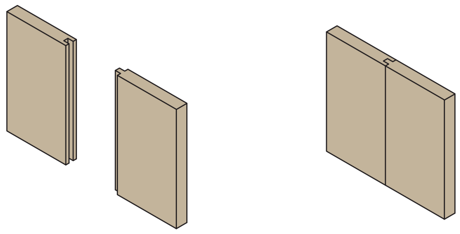
SCORE = 9

The interlocking elements act together against all the stresses generating a solid connection.

FINAL SCORE
74

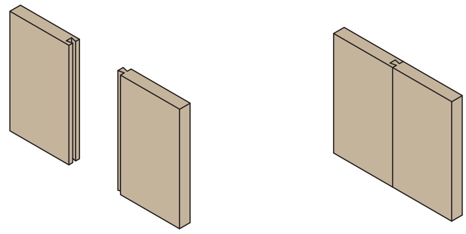
D. Tongue and groove (P)

D.1. SIMPLE (rectangular tongue and groove)



Additional information about this connection can be found in: Fairham (2007).

D.2. COMPLEX (dovetail tongue and groove)



Additional information about this connection can be found in: Fairham (2007).

Score reliability: reliable / empiric / assumed

D.1. SIMPLE

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 6

Additional fasteners are needed to secure the elements in position, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 4

The connections is completely hidden conferring a smooth appearance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 6

The shapes of the elements are relatively simple. Basic woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 12

The connection is very easy to disassemble. It requires short time, simple tools, low worker instruction and low force.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The shape of the elements can be prefabricated and just a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause significant waste at the end of use since both the fasteners and the elements can be easily damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 12

The connection is very easy to assemble. It requires short time, simple tools, low worker instruction and low force.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 4

The connection is free to move in the direction of insertion and it is also free to slide.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 4

The costs of the connection are considered low due to the fact that basic woodworking and fasteners are needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 6

The relatively small interlocking parts make this connection relatively weak if no rely additional fasteners are used.

FINAL SCORE
74

D.2. COMPLEX

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 8

No additional elements are needed except if sliding have to be prevented.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 4

The connections is completely hidden conferring a smooth appearance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 6

The shapes of the elements are relatively simple. Basic woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is relatively easy to disassemble. It requires short time, simple tools, low worker instruction but the connection can only be dismounted along one direction.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The shape of the elements can be prefabricated and just a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 4

This connection system might cause waste only in the eventuality that the elements are damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is very easy to assemble. It requires short time, simple tools, low worker instruction but the accessibility is limited because the connection has only one direction of insertion.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be easily separated and reused multiple times if not damaged.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 6

The connection is only free to slide while in all the other directions the movements are locked.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 4

The costs of the connection are considered low due to the fact that only basic woodworking is needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

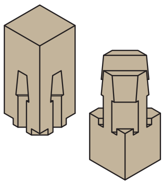
SCORE = 9

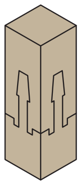
The interlocking elements act together against tensile stresses but the relatively small interlocking parts can be considered the weak parts.

FINAL SCORE
76

E. Column splice joint (CC)

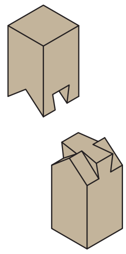
E.1. HORIZONTAL (interlock by planar sliding)

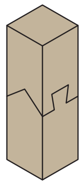




Additional information about this connection can be found in: Sumiyoshi & Matsui (1991).

E.2. 45 DEGREE (interlock by 45° sliding)





Additional information about this connection can be found in: Sumiyoshi & Matsui (1991).

Score reliability:
- reliable
- empiric
- assumed

E.1. HORIZONTAL

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 8

No additional elements are needed except if sliding have to be prevented.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 4

The wood connection express its uniqueness in its carved appearance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 2

The shapes of the interlocking elements are complex. Complicated woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to disassemble. Even if almost no tools are needed, it requires time, worker instruction and due to the geometry complexity it is only detachable along one direction.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The shape of the elements can be prefabricated and just a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause waste at the end of use since the woodwork geometry can be damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to assemble. Even if almost no tools are needed, it requires time, precision and worker instruction due to the geometry complexity.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged but quality checks result difficult.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 4

The connection is only free to slide while in all the other directions the movements are locked.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 3

The costs are considered relatively low since only complex woodworking is needed which can be also done with CNC milling machines.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The interlocking elements act together against most of the possible stresses. Shear forces in the direction of insertion represent the only weakness of this joint.

FINAL SCORE
62

E.2. 45 DEGREE

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 8

No additional elements are needed except if the movement along the angled direction of insertion has to be prevented.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 4

The wood connection express its uniqueness in its carved appearance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 4

The shapes of the interlocking elements are relatively complex. Complicated woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to disassemble. Even if almost no tools are needed, it requires time, worker instruction and due to the geometry complexity it is only detachable along one direction.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The shape of the elements can be prefabricated and just a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause waste at the end of use since the woodwork geometry can be damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to assemble. Even if almost no tools are needed, it requires time, precision and worker instruction due to the geometry complexity.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged but quality checks result difficult.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 6

The connection is free only in the opposite direction of insertion.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 3

The costs are considered relatively low since only complex woodworking is needed which can be also done with CNC milling machines.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

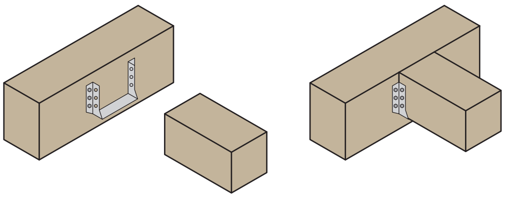
SCORE = 6

The interlocking elements act together against most of the possible stresses locking the elements along all the principle directions.

FINAL SCORE
66

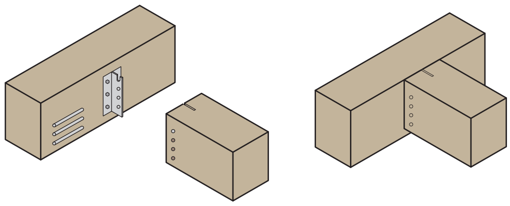
F. Metallic hanger (BB,BC)

F.1. VISIBLE (external exposed support)



Additional information about this connection can be found in: https://www.rothoblaas.com/products/fastening/brackets-and-plates/metal-hangers/bsa

F.2. CONCEALED (internal hidden support)



Additional information about this connection can be found in: https://www.rothoblaas.com/products/fastening/brackets-and-plates/concealed-junctions/alumaxi

Score reliability: reliable · empiric · assumed

F.1. VISIBLE

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 6

A few additional fasteners are needed to secure the elements, these relatively increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 1

The steel connection is exposed, this influences both the appearance and the fire safety since exposed metals have low fire resistance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 8

The shapes of the elements are very simple since they only need to be cut in length.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to disassemble. It requires relatively short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 6

The shape of the elements can be prefabricated and a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause waste at the end of use since the fasteners and the wings can be damaged due to high loads.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires relatively short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 6

The reusability of the connection system is relatively low due to the fact that the fasteners have to be removed every time the connection is disassembled and reassembled causing permanent damage to the connection.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection system locks the movement along every direction.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 3

The costs of the connection are considered relatively low since it is one of the most basic mechanical connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The connection system is very stiff and the stability of the elements is also helped by the external supporting wing.

FINAL SCORE 71

F.2. CONCEALED

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 6

A few additional fasteners are needed to secure the elements, these relatively increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 3

The steel connection is almost completely hidden, only very small parts are exposed.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 6

The shapes of the elements are relatively simple. Only a vertical cut has to be done at the ends of the element to host the wing of the hanger.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 6

The connection is relatively difficult to disassemble. The dowels are usually hidden inside and not very accessible, therefore, it requires additional time to be dismounted.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 6

The shape of the elements can be prefabricated and a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 4

This connection system potentially causes no waste since all the elements can be reused during a second life cycle.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires relatively short time, simple tools, some worker instruction and it is easily accessible from multiple directions.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The reusability of the connection system is high due to the fact that all the parts can be reused multiple times if not damaged.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection system locks the movement along every direction.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 2

The costs are considered relatively low since it can be considered a simple mechanical connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

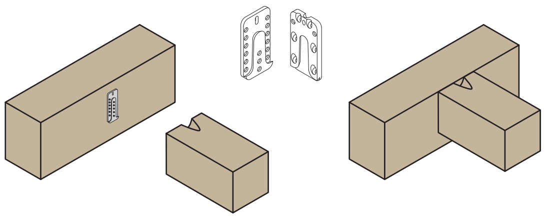
SCORE = 9

The connection system is stiff (up to 320 kN, Rothoblaas) but the internal dowels along the whole hight of the element might cause splits at the end of the elements.

FINAL SCORE 72

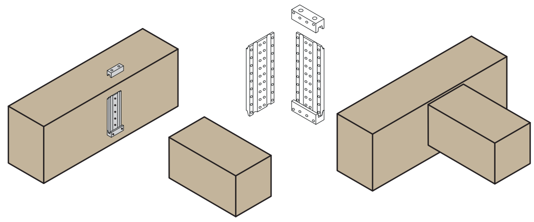
G. Hook connector (BB,BC)

G.1. UV-T (Rothoblaas®)



Additional information about this connection can be found in: https://www.rothoblaas.com/products/fastening/brackets-and-plates/concealed-junctions/uv-t

G.2. MEGANT (KNAAP®)



Additional information about this connection can be found in: https://www.knapp-verbinder.com/en/produkt/megant-heavy-duty-system/

Score reliability: reliable / empiric / assumed

G.1. UV-T

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 2

Lots of fasteners are needed to secure the connection system to the elements, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 4

The steel connection is almost completely hidden, only very small parts are exposed. If the elements are properly carved the connection system can be fully hidden.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 6

The shapes of the elements are simple since they only need to be cut in length and a carving on the top is needed to secure the connection.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 12

The connection is very easy to disassemble. It requires very short time (only one fastener need to be removed), simple tools, simple movement and low worker instruction.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The elements can arrive on-site already with the connection system completely installed, they just need to be mounted and secured with a single fastener.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 4

This connection system potentially causes no waste since all the elements can be reused during a second life cycle.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 12

The connection is very easy to assemble. It requires very short time, simple tools, simple movement and low worker instruction.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The reusability of the connection system is very high due to the fact that all the parts can be reused multiple times and do not have to be separated from the connected elements.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 6

The connection system locks the movement along every direction even if the direction of insertion remain weaker than the others.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 2

The costs are considered relatively high since it can be considered an advanced mechanical connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 6

The connection system is relatively stiff (up to 65 kN shear forces) but it is mostly intended for relatively small temporary structures.

FINAL SCORE
74

G.2. MEGANT

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 2

Lots of fasteners are needed to secure the connection system to the elements, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 3

The steel connection is almost completely hidden, only very small parts are exposed.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 8

The shapes of the elements are very simple since they only need to be cut in length.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is relatively easy to disassemble. It requires short time, simple tools, and some worker instruction to be dismounted, the accessibility might cause difficulties.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The elements can arrive on-site already with the connection system completely installed, they just need to be mounted and secured with simple actions.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 4

This connection system potentially causes no waste since all the elements can be reused during a second life cycle.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is relatively easy to assemble. It requires short time, simple tools and some worker instruction to be properly secured.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The reusability of the connection system is very high due to the fact that all the parts can be reused multiple times and do not have to be separated from the connected elements.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection system locks the movement along every direction.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 2

The costs are considered relatively high since it can be considered an advanced mechanical connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

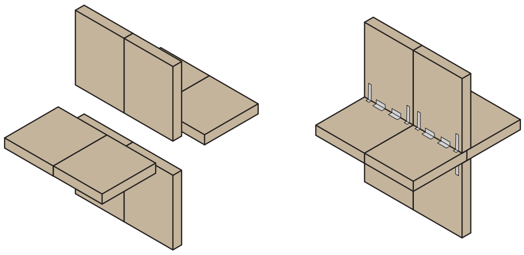
SCORE = 12

The connection system is very stiff (up to 400 kN shear forces if the biggest connectors are used).

FINAL SCORE
77

H. & I. Brachets & X-RAD (P)

H. METALLIC SHEAR AND TENSILE BRACHETS (conventional)



Additional information about this connection can be found in: https://www.rothoblaas.com/products/fastening/brackets-and-plates

Score reliability: reliable, empiric, assumed

NUMBER OF ELEMENTS (2)

A LOT — A FEW (1 2 3 4)

SCORE = 2

Lots of fasteners are needed to secure the brackets to the elements, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN (1 2 3 4)

SCORE = 1

The steel brackets are completely exposed and need fire protection measures,

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE (1 2 3 4)

SCORE = 8

The shapes of the elements are very simple since they only need to be cut in length and hight.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY (1 2 3 4)

SCORE = 9

The connection is relatively easy to disassemble. It only requires time to remove all the fasteners, but simple tools, basic actions and low worker instruction.

PREFABRICATION DEGREE (2)

LOW — HIGH (1 2 3 4)

SCORE = 4

The shape of the elements can be prefabricated but a lot of actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING (1 2 3 4)

SCORE = 2

This connection system might cause waste at the end of use since the high number of fasteners and the elements can be damaged during the disassembly.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY (1 2 3 4)

SCORE = 9

The connection is relatively easy to assemble. It only requires some time, but simple tools, basic actions and low worker instruction.

REUSABILITY (3)

LOW — HIGH (1 2 3 4)

SCORE = 3

The reusability of the connection system is very low due to the fact that all the fasteners have to be removed every time the connection is disassembled and reassembled.

DEGREE OF FREEDOM (2)

6 — 0 (1 2 3 4)

SCORE = 8

The connection system locks the movement along every direction.

COSTS* (1)

HIGH — LOW (1 2 3 4)

SCORE = 3

The costs are considered relatively low since it can be considered a conventional and simple mechanical connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

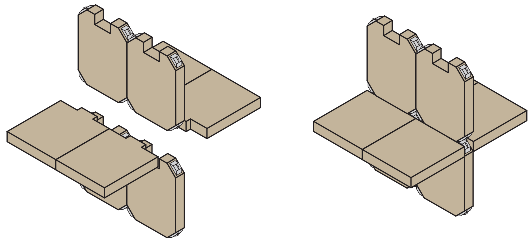
LOW — HIGH (1 2 3 4)

SCORE = 6

The connection system is relatively stiff since specific brackets are designed to bear both shear and tensile loads.

FINAL SCORE 58

I. X-RAD BY ROTHOBLAAS® (innovative corner connection)



Additional information about this connection can be found in: https://www.rothoblaas.com/products/fastening/x-rad

NUMBER OF ELEMENTS (2)

A LOT — A FEW (1 2 3 4)

SCORE = 6

A few fasteners are needed to secure the elements, these relatively increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN (1 2 3 4)

SCORE = 3

The steel connection is visible in the corners but specific covering is available to hide and seal the corners.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE (1 2 3 4)

SCORE = 6

The shapes of the elements are relatively simple. Basic woodworking is needed.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY (1 2 3 4)

SCORE = 9

The connection is relatively easy to disassemble. It requires short time, simple tools but some worker instruction to be properly dismounted.

PREFABRICATION DEGREE (2)

LOW — HIGH (1 2 3 4)

SCORE = 8

The elements can arrive on-site already with the connection system completely installed, they just need to be mounted and secured with simple actions.

END OF CYCLE WASTE (1)

A LOT — NOTHING (1 2 3 4)

SCORE = 4

This connection system potentially causes no waste since all the elements can be reused during a second life cycle.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY (1 2 3 4)

SCORE = 9

The connection is relatively easy to assemble. It requires short time, simple tools but some worker instruction to be properly secured.

REUSABILITY (3)

LOW — HIGH (1 2 3 4)

SCORE = 12

The reusability of the connection system is very high due to the fact that all the parts can be reused multiple times and do not have to be separated from the connected elements.

DEGREE OF FREEDOM (2)

6 — 0 (1 2 3 4)

SCORE = 8

The connection system locks the movement along every direction.

COSTS (1)

HIGH — LOW (1 2 3 4)

SCORE = 1

The costs are considered very high since it is an innovative and advanced mechanical connection system patented by Rothoblaas.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH (1 2 3 4)

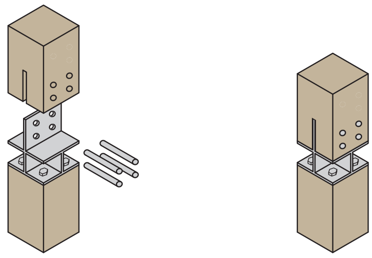
SCORE = 12

The connection system is very stiff (up to 20 kN/m of distributed vertical load).

FINAL SCORE 78

J. Post connector (CC)

J.1. CROSS (normal connection attached to one element)



Additional information about this connection can be found in: http://dylanbrowndesigns.com/resources/parametric-timber-connections-for-revit

Score reliability:

- reliable
- empiric
- assumed

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 6

A few additional fasteners are needed to secure the elements, these relatively increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 1

The steel connection is exposed, this influences both the appearance and the fire safety since exposed metals have low fire resistance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 8

The shapes of the elements are relatively simple. Only a vertical cut has to be done at the end of the element to host the wing of the post connector.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to disassemble. It requires relatively short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 6

The shape of the elements can be prefabricated and a few actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 3

This connection system might cause waste at the end of use since the fasteners are likely be damaged due to perpendicular high loads.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires relatively short time, simple tools, low worker instruction and it is easily accessible from multiple directions.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 6

The reusability of the connection system is relatively low due to the fact that the fasteners have to be removed every time the connection is disassembled and reassembled causing permanent damage to the connection.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection system locks the movement along every direction.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 3

The costs of the connection are considered relatively low since it is one of the conventional post connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

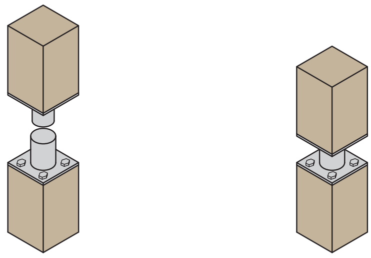
1 2 3 4

SCORE = 12

The connection system can be considered relatively stiff even if the fasteners placed perpendicular to the load might cause splits.

FINAL SCORE
64

J.2. CIRCULAR (plug connection attached to both elements)



Additional information about this connection can be found in: Kaufmann et al. (2018), p 169.

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 4

A few additional fasteners are needed to secure the elements, these relatively increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 1

The steel connection is exposed, this influences both the appearance and the fire safety since exposed metals have low fire resistance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 8

The shapes of the elements are very simple since they only need to be cut in length.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 12

The connection is very easy to disassemble. It requires short time, simple tools and low worker instruction to be properly dismounted.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 8

The elements can arrive on-site already with the connection system completely installed, they just need to be mounted and secured with simple actions.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 4

This connection system potentially causes no waste since all the elements can be reused during a second life cycle.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 12

The connection is very easy to assemble. It requires short time, simple tools and low worker instruction to be properly mounted and secured.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The reusability of the connection system is very high due to the fact that all the parts can be reused multiple times and do not have to be separated from the connected elements.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 6

The connection system locks the movement along every direction even if the direction opposite to the insertion is weaker.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 3

The costs of the connection are considered relatively low since it is one of the conventional post connection system.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

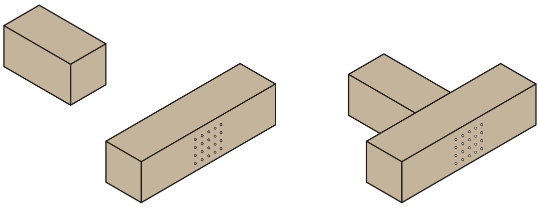
SCORE = 9

The connection system can be considered relatively stiff but attention has to be given to the design of the interlocking steel elements.

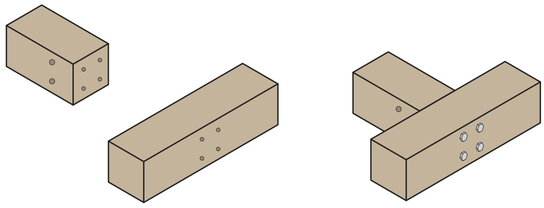
FINAL SCORE
79

K. Butt joint (BB,BC,P)

K.1. SCREW (one side access)



K.2. BOLT & NUT (two side access)



Score reliability: reliable / empiric / assumed

K.1. SCREW (one side access)

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 2

Lots of fasteners are needed to secure the elements in place, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 1

The steel fasteners are exposed, this influences both the appearance and the fire safety since exposed metals have low fire resistance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 8

The shapes of the elements are very simple since they only need to be cut in shape.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to disassemble. It requires time, but only simple tools and low worker instruction are needed to be properly dismount the fasteners.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 4

The shape of the elements can be prefabricated but multiple actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 1

This connection system might cause significant waste at the end of use since both the fasteners and the elements can be easily damaged.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires time, but only simple tools and low worker instruction are needed to be properly mount and secure the fasteners.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 3

The reusability of the connection system is very low due to the fact that a lots of fasteners have to be removed every time the connection is disassembled and reassembled potentially damaging the elements.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection system locks the movement along every direction.

COSTS* (1)

HIGH — LOW

1 2 3 4

SCORE = 4

The costs of the connection are considered very low due to the fact that only basic fasteners are needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The connection system is very stiff due to the high number of fasteners connecting the elements together.

FINAL SCORE
61

K.2. BOLT & NUT (two side access)

NUMBER OF ELEMENTS (2)

A LOT — A FEW

1 2 3 4

SCORE = 4

A significant number of fasteners are needed to secure the elements in place, these increase the total number of elements.

FINISHING (1)

EXPOSED — HIDDEN

1 2 3 4

SCORE = 1

The steel fasteners are exposed, this influences both the appearance and the fire safety since exposed metals have low fire resistance.

ELEMENT COMPLEXITY (2)

COMPLEX — SIMPLE

1 2 3 4

SCORE = 8

The shapes of the elements are very simple since they only need to be cut in shape.

EASE OF DISASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to disassemble. It requires time, but only simple tools and low worker instruction are needed to be properly dismount the fasteners.

PREFABRICATION DEGREE (2)

LOW — HIGH

1 2 3 4

SCORE = 4

The shape of the elements can be prefabricated but multiple actions have to be done on-site to secure the connection.

END OF CYCLE WASTE (1)

A LOT — NOTHING

1 2 3 4

SCORE = 2

This connection system might cause waste at the end of use since fasteners and the elements can be damaged due to loads perpendicular to the fasteners.

EASE OF ASSEMBLY (3)

DIFFICULT — EASY

1 2 3 4

SCORE = 9

The connection is easy to assemble. It requires time, but only simple tools and low worker instruction are needed to be properly mount and secure the fasteners.

REUSABILITY (3)

LOW — HIGH

1 2 3 4

SCORE = 9

The reusability of the connection system is relatively high due to the fact that all the parts can be reused multiple times if not damaged.

DEGREE OF FREEDOM (2)

6 — 0

1 2 3 4

SCORE = 8

The connection system locks the movement along every direction.

COSTS (1)

HIGH — LOW

1 2 3 4

SCORE = 4

The costs of the connection are considered very low due to the fact that only basic fasteners are needed.

*costs are evaluated based on the western Europe prices and economy.

STRUCTURAL STRENGTH (3)

LOW — HIGH

1 2 3 4

SCORE = 12

The connection system is very stiff due to the high number of fasteners connecting the elements together.

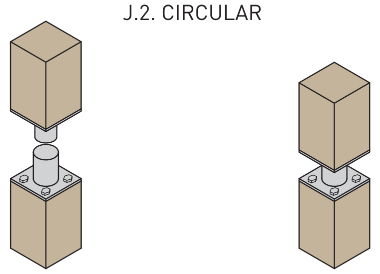
FINAL SCORE
70

11.4. Final comparison of the connection systems

CC	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	weighted score
weight	2	2	2	3	2	3	1	3	1	3	1	
E.1.	4	1	4	2	2	3	4	2	3	3	3	62
E.2.	4	2	4	2	3	3	4	2	3	3	3	66
J.1.	2	3	3	3	4	3	1	3	3	2	3	64
J.2.	2	4	4	4	3	3	1	4	4	4	3	79

COLUMN TO COLUMN CONNECTION (CC)

J.2. CIRCULAR

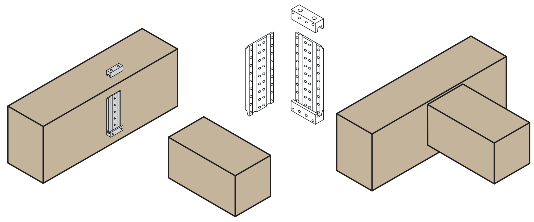


Additional information about this connection can be found in: Kaufmann et al. (2018), p 169.

BC	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	weighted score
weight	2	2	2	3	2	3	1	3	1	3	1	
A.1.	3	3	2	3	3	2	2	3	2	2	4	60
A.2.	4	1	4	2	4	3	3	2	3	3	3	65
F.1.	3	4	3	3	4	4	1	3	3	2	3	71
F.2.	3	3	3	3	4	3	3	2	4	4	3	72
G.1.	1	3	4	4	3	2	4	4	4	4	2	74
G.2.	1	4	4	3	4	4	3	3	4	4	2	77
K.1.	1	4	2	3	4	4	1	3	1	1	4	61
K.2.	2	4	2	3	4	4	1	3	2	3	4	70

BEAM TO COLUMN CONNECTION (BC)

G.2. MEGANT (KNAAP®)

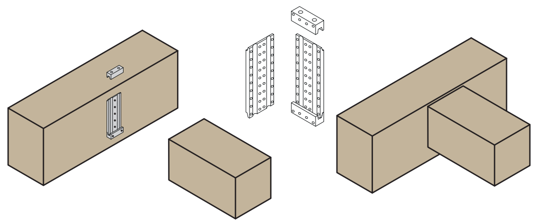


Additional information about this connection can be found in: https://www.knapp-verbinder.com/en/produkt/megant-heavy-duty-system/

BB	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	weighted score
weight	2	2	2	3	2	3	1	3	1	3	1	
A.1.	3	3	2	3	3	2	2	3	2	2	4	60
A.2.	4	1	4	2	4	3	3	2	3	3	3	65
C.1.	2	3	3	4	2	2	2	4	2	2	4	64
C.2.	4	2	4	3	4	3	3	3	4	3	3	74
F.1.	3	4	3	3	4	4	1	3	3	2	3	71
F.2.	3	3	3	3	4	3	3	2	4	4	3	72
G.1.	1	3	4	4	3	2	4	4	4	4	2	74
G.2.	1	4	4	3	4	4	3	3	4	4	2	77
K.1.	1	4	2	3	4	4	1	3	1	1	4	61
K.2.	2	4	2	3	4	4	1	3	2	3	4	70

BEAM TO BEAM CONNECTION (BB)

G.2. MEGANT (KNAAP®)

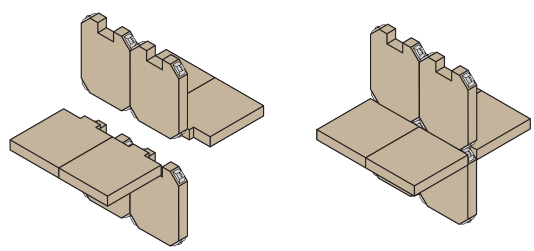


Additional information about this connection can be found in: https://www.knapp-verbinder.com/en/produkt/megant-heavy-duty-system/

P	number of elements	elements complexity	prefabrication degree	ease of assembly	degree of freedom	structural strenght	finishing	ease of disassembly	end of cycle waste	reusability	costs	weighted score
weight	2	2	2	3	2	3	1	3	1	3	1	
B.1.	3	3	4	3	2	2	3	3	3	2	4	64
B.2.	4	1	4	2	4	3	4	2	3	3	3	66
D.1.	3	3	4	4	2	2	4	4	3	3	4	74
D.2.	4	3	4	3	3	3	4	3	4	3	4	76
H.	1	4	2	3	4	3	1	3	2	1	3	58
I.	3	3	4	3	4	4	3	3	4	4	1	78
K.1.	1	4	2	3	4	4	1	3	1	1	4	61
K.2.	2	4	2	3	4	4	1	3	2	3	4	70

PANEL CONNECTION (P)

I. X-RAD (ROTHOBLAAS®)



Additional information about this connection can be found in: https://www.rothoblaas.com/products/fastening/x-rad