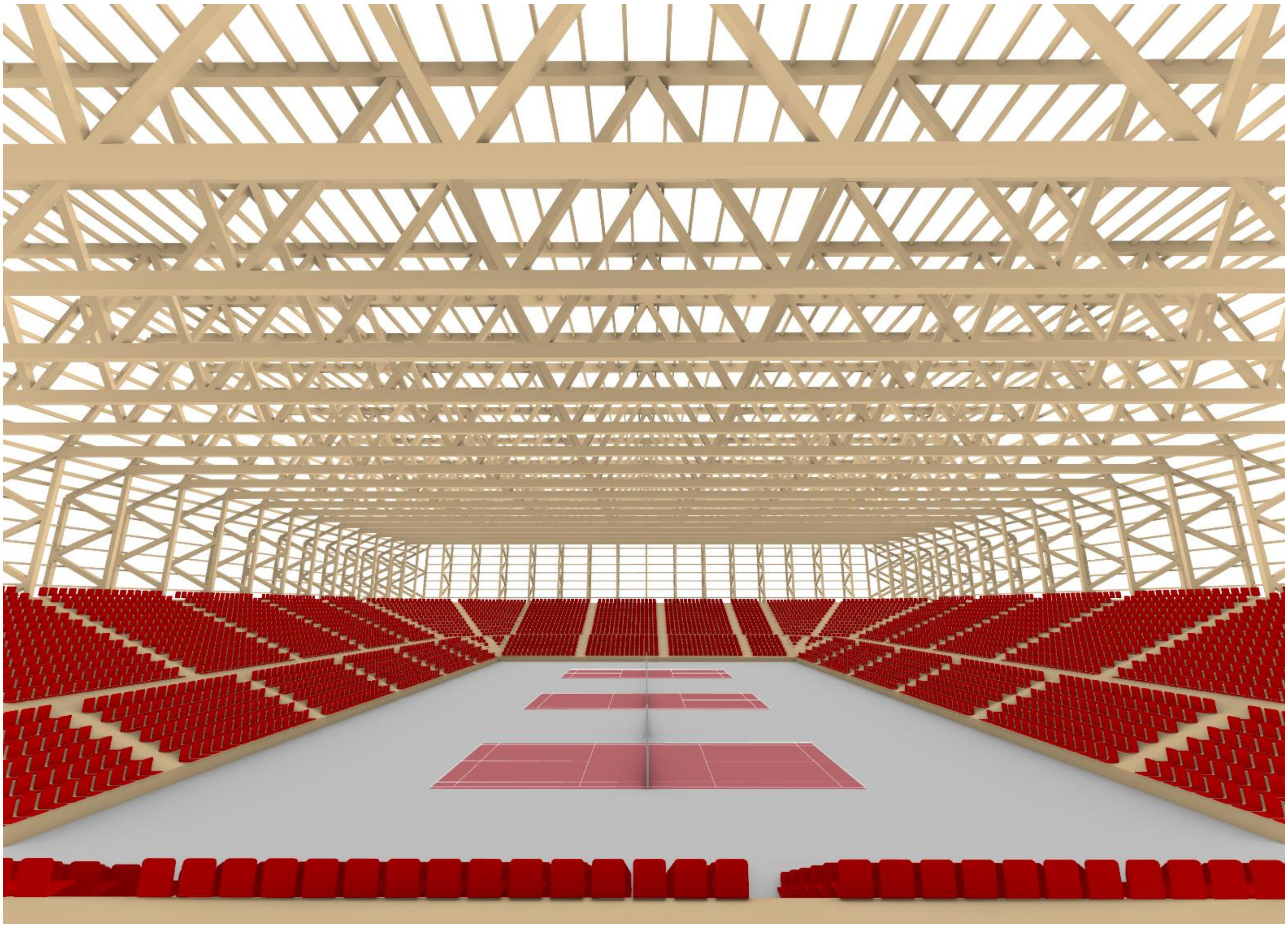


DESIGN OF A MULTI-USE, DEMOUNTABLE, TIMBER ARENA

A research in re-usable timber structures

Nicolas Mariller; TU Delft

PERSONAL AND COMMITTEE INFORMATION

Personal Information

Name Nicolas Mariller

Email n.l.d.mariller@tudelft.nl

Address Pletterijstraat 57
2515 AV, Den Haag NL

Committee Members Information

Name Ir. S. Pasterkamp

Email S.Pasterkamp@tudelft.nl

Address Delft University of Technology
Faculty of Civil Engineering and Geosciences
Stevinweg 1, room 6.46
2628 CN Delft

Name Dr.ir. G.J.P. Ravenshorst

Email G.J.P.Ravenshorst@tudelft.nl

Address Delft University of Technology
Faculty of Civil Engineering and Geosciences
Stevinweg 1, room S2 2.57
2628 CN Delft

Name Prof. ir. R. Nijsse

Email R.Nijsse@tudelft.nl

Address Delft University of Technology
Faculty of Civil Engineering and Geosciences
Stevinweg 1, room S2 1.36
2628 CN Delft

TABLE OF CONTENTS

Summary

The goal of this thesis is to research multi-purpose, re-usable timber structures as a step towards sustainable construction. To reach it, the work was divided into four parts.

The project starts with an introduction explaining the motivations behind this work. It continues by grounding the problem in the context of major sports events. Indeed, the temporary quality of such manifestations, as well as their promotion of innovative solutions made it ideal for this study. Moreover, reviewing Olympic legacies showed the need for a structure capable to be re-used in different contexts.

The second part of the research englobes a literature review on two subjects. Exploring sustainable construction highlighted the main principles in environmentally friendly structural design. Life cycles assessments are identified as the main tool for evaluating the ecological performances and their process is therefore described. Moreover, reviewing existing LCA on timber constructions showed hotspots in the manufacturing of timber such as the importance of local sourcing.

Additionally, the second part examines existing work on designing for re-use. Multiple factors should be incorporated to ensure the re-usability of a construction. The most essential one, demountability was explored in length and a table showing the related design criterion, such as minimizing the number of different connectors, was devised. A review of existing constructions designed for re-use concludes this second part.

The third part applies the findings of the second to the selection of timber solutions. To narrow the possible products, the roof structure of an indoor arena is preselected for the case study. Locally sourced glue-laminated timber is chosen for its dimensional stability, whereas assemblies using glued-in rods and steel connectors show great versatility and are therefore preferred. Considering the structural system adapted for multi-purpose re-use, a truss was selected for the origin structure because of its inherent standardization. The third part is concluded by the development of a structural solution for the case study.

The fourth part concerns the design of the roof and façade structures of a badminton arena. To maximize re-use options, the structural elements are designed to be applicable to different contexts such as the main structure of a high school. The designed solution was finally assessed using the developed guidelines and an LCA-based study.

The study shows that multi-purpose re-use is a structurally feasible alternative. Indeed, through careful planning, and by using the developed guidelines, it is possible to re-use the structural elements from a 60-meter span roof in a 6.3-meter span high school with relatively high efficiency. Moreover, the environmental study, although superficial, showed a reduction in global warming potential of 60-90% depending on the re-use scenario compared with a one-off design.

Keywords

Re-use; Timber; Sustainability; Modular; Demountable; Structural engineering; Construction; Arena; Olympics; Connections; LCA

PART I

INTRODUCTION

Figure 1 Davos ice rink

CHAPTER I: Introduction

Figure 2 Dutch fans at the women football WC

Being in a stadium filled with people chanting, cheering, and supporting the same team is an incredible feeling. Perhaps, what best exemplifies the desire to share this adventure is the Olympics.

Dating back to ancient Greece and the 8th century BC and renewed in 1894 by Pierre de Coubertin, the international competition brings together athletes and supporters from around the world.

Given the size of such events, their impact is not limited to sport. Indeed, they also have major political, social, and ecological repercussions in the host country. Stadiums, for example, are both icons of the games and major actors in resource consumption. When successful, they become a landmark in the city, a social hub, and a major actor in the local economy. However, such big scale constructions frequently struggle to find usage after the end of the event; putting all resources invested at the risk of being wasted. The Bird's nest, for example, required 45'000 tons of steel and cost 480 million USD to build for the 2008 Olympics. It has, since then, proved difficult to fill the 91'000-seat capacity of Beijing's national stadium and the associated 11 million dollars of annual maintenance costs (Lim, 2012).

These concerns over the financial and ecological implications of hosting a major sport event can be highlighted by the 2015 competition for hosting the 2024 summer Olympics. Indeed, during the selection process, Boston, Rome, and Hamburg all withdrew their candidature because of insufficient support from the population due to the financial burden and ecological impact of the games. ("2024 Olympics: Hamburg says 'No' to hosting Games," 2015; "Italy withdraws Rome 2024 Olympic Games bid," 2016; Seelye, 2015)

Olympic structures are just the tip of the iceberg. Indeed, the construction industry is responsible for almost a third of the global carbon emissions (International Energy Agency, 2017). Moreover, in Europe, forty percent of the total waste production is linked to the building industry (Crowther, 2009). It is therefore crucial, for civil engineers and architects, to minimize the environmental impact of their construction.

Designing for re-use is one of the most promising strategies to mitigate these effects. Indeed, constructions often reach their end-of-life prematurely because they fail to adapt to changing demands. In the current design philosophy, it is more profitable to destroy these constructions to make room for newer, more adapted, edifices. Everything is thus landfilled, or sometimes recycled, and new products, participating in the increase of pollution and resource depletion, are required. This includes many components, the structural elements in particular, which could still fulfill their function. Therefore, the core concept of re-use is to design in such a way that these components are easy to salvage and to apply to new constructions.

Major sports events, notably the London Olympics, have started implementing re-use in their designs. Although it is a step in the right direction, multiple limitations need to be overcome. First, it is mostly restricted to the construction of stands using scaffolding structures. Therefore, it can be difficult to find a market for such specific components. Additionally, the impact of stadia and arena are marginal in the global construction scale, and such scaffolding structures are difficult to implement in other fields. Finally, the use of steel as a material of choice for temporary stands can be problematic due to its high environmental impact.

For these reasons, the idea to develop a versatile timber system, designed for re-use arose. The Olympics, due to their important coverage and their demand for big scale, temporary structures are the perfect context for this study. Therefore, the goal is to develop a structural solution for sustainable constructions, applicable to both complex structures, such as the roof of a semi-temporary arena, and to more traditional constructions for instance schools or residential buildings. Such a solution, if feasible, would expend the possibilities of re-use and work towards a more sustainable future.

Figure 3 Roof of the Hamar Viking ship, the arena for speed skating in the Lillehammer Olympics

CHAPTER II: Research Design

In this chapter, the research objectives will be defined which will lead to a set of research questions. The problematic will then be compared to existing work to highlight the relevance of the research. Finally, the methodology needed to perform the analysis will be exposed.

Research objectives

The main goal of this research is to propose a re-usable timber solution for sustainable construction. By designing a demountable structure that can be re-arranged to fit multiple briefs, the objective is to enhance its re-use possibilities, thus reducing the resource consumption and waste generation associated with the construction industry.

To reach this objective, research is necessary for two closely related fields: sustainable construction and re-usable structures.

Additionally, a case study is required to test the structural feasibility of multi-use timber construction. The Olympics, or other major sports events, have been highlighted as environment stimulating innovation. Moreover, their disposition to waste due to their temporary nature makes them the perfect context for the first construction, hereafter referenced as the origin structure.

Research questions

To achieve the objectives of the research, questions must be answered. The main interrogation of this research is:

How to design a timber, multi-use, structural solution to maximize re-use possibilities?

To answer this question, it is necessary to break it into multiple sub-questions. They can be clustered into three groups:

The first group addresses the strategies that must be implemented in the design:

What are the important guidelines and constraints for a re-usable structure?
How to design more sustainable constructions?

The second cluster builds upon the first and applies its findings to timber constructions:

What structural systems are appropriate to multi-use?
What timber products should be selected for re-use?
What assembly should be used when designing for re-use?

Finally, the last groups aim at synthesizing the knowledge created by the mean of a case study:

Is it structurally feasible to re-use an Olympic construction in residential or office settings?

Relevance of the research

This thesis adds to the existing knowledge of re-usable structures. Extensive work is already available on re-usable stadiums using steel scaffolding types of construction. However, this research aims at developing a structural solution that could be used, similarly to a box of Lego, to serve different purposes. Developing such a system is of interest to simplify re-use logistics and to increase its applicability.

Moreover, while the re-use of steel structures is well documented, the same cannot be said for timber structures. However, there is a growing interest in this material, both for its ecological performances and the technological developments in its manufacture. Therefore, this thesis also aims at filling this knowledge gap by exploring the application of re-use to timber construction.

Methodology

The research will be structured into five parts. The introduction, the theoretical framework, the application and analysis, the case study, and a concluding part.

Introduction

The goal of this part is to contextualize the problem and to define the scope of the research. This includes research design as well as a review of the literature on MSE and their legacies.

Theoretical framework

The second part of the research consists of a literature review on two fields. The first is re-use and its constraints, while the second focuses on sustainability in the construction industry.

This part is concluded by a review of existing demountable structures and their design strategies.

Figure 4 Brummel city hall and Paleo's terrace

Application and analysis

This part researches how to apply the conclusions of the literature review to timber construction.

Case study

In this part, research by design is used. A case study is developed to investigate if applying the conclusions of the preliminary research allows for a structurally feasible, multi-purpose, re-use of timber structures.

Conclusions

This part concludes the research by answering the research questions and giving leads for further research.

Hypotheses

Some hypotheses are required to conduct this research in the given time. First, it focuses solely on timber structures, ignoring possible steel or concrete alternatives.

Secondly, given the variability of timber resources and, to a lesser extent, of the design codes, a geographical focus is needed. Because of the prior knowledge of the researcher, this document will focus on Europe and, more precisely, on Switzerland.

Additionally, the research is conducted from a structural point of view with an interest in its sustainability performance. For this reason, other important dimensions of construction projects, such as costs and building physics are left for further research.

CHAPTER III: Problem Context

Mega sports events (MSE) have been selected as context to this study for their high resource consumption, temporary nature, and promotion of innovation. First, a broad understanding of their challenges and opportunities is necessary to root the project. In addition, an overview of the legacies of previous Olympic Games and a review of the applied sustainability strategies is performed.

Mega sports events

MSE are a complex system with multiple aspects. The following definition by Byers (2012) is taken as a starting point for their understanding:

"Mega sporting events are defined as those one-time sporting events of an international scale organized by a special 'authority' and yielding extremely high levels of media coverage and impacts (economic, tourism, infrastructure, etc.) for the host community because of the event's significance and/or size." (Byers, 2012, p. 103)

This definition, contains four key elements highlighted by Müller (2015): Visitor attractiveness, mediatic reach, costs, and urban transformation. Each will be analyzed separately to understand their implications.

Figure 5 Flags of the represented nations in London

Visitor attractiveness

Hosting an MSE means attracting thousands of peoples such as athletes, supporters, officials, and press representatives. This major influx of visitors is believed to cause significant developments in the tourism industry (Teigland, 1999). However, as exemplified by the 1988 winter Olympics, the boost provided by the Olympics can fade away after the event. In Lillehammer, for example, developers made massive investments to develop roads and hotels. This decision was motivated by the expected economic turnout from developing the tourism industry. However, in the eleven years following the event, 40% of the full-service hotels of the city went bankrupt (Teigland, 1999). This example shows that there are important incertitudes related to the long term investments on MSE.

Mediatic reach

The development of the media industry means that millions of people can now watch the same event live. In MSE, the role of the media is not only to relay information but to create the atmosphere of the event as well (Müller, 2015). Indeed, one of the indirect benefits of the MSE is to bring people from all over the globe closer. Additionally, a direct benefit from the media coverage is the revenues it generates. The London Olympics, for instance, yielded over 2.5 billion USD in broadcasting rights (Müller, 2015).

Of interest to this research are the opportunities for branding the host city, region, or even country that the increased media coverage creates (Ferrari & Guala, 2017). Indeed, MSE can be a vitrine for the region in the hope of harvesting investments. An example of the positive impact of the Games is the city of Turin. The Olympics helped shift its image from an industrial Fordist city to a cultural tourism destination. As a result, tourist arrivals increased by 90% between 2002 and 2011 (Ferrari & Guala, 2017). Governments can also use the Olympics to demonstrate their strength, often ignoring standard solutions in favor of innovative or grandiose constructions. With sustainability becoming increasingly important politically, this is an opportunity for a re-usable structure as a statement of changing construction philosophy.

Costs

One of the major talking points of MSE is their cost. The total investment can be colossal, 14 billion USD in the case of Rio de Janeiro in 2014 (Müller, 2015). The money usually comes from a combination of public and private investments with the balance varying depending on the events. This raises the concern of the taxpayer's approval of such public expenditures.

Finally, due to the one-off nature of MSE and the related time pressure, cost overruns are common. Indeed, in the case of the Olympic Games (OG), the average cost overrun amounted to 179% between 1968 and 2012 (Müller, 2015).

Urban transformation

To host MSE, important infrastructures are required. First, stadium or arenas complying with the requirement of the event are necessary. Furthermore, transport systems need to take in the important flux of visitors. Finally, the city must provide possibilities for accommodation. In fact, the infrastructure is responsible for the major part of the costs of MSE. During the Asian Games in Guangzhou, for instance, 94% of the spending was dedicated to capital investments (Müller, 2015). Such a cost is also an opportunity. Indeed, hosts often use MSE as leverage for funds to help urban renewal. For example, Poland took advantage of Euro 2012 to modernize its highways (Müller, 2015).

Figure 6 World cup stadium under construction

Deconstructing MSE showed the opportunities present in this field for demountable timber constructions. Indeed, designing a demountable stadium ensures that the colossal investments made for the event are not wasted. Moreover, developing an innovative design will help to show a positive image of the host to the millions of people watching the event. However, further investigations into previous MSE are needed to show what strategies have been tried and their successes.

Legacies of Mega sporting events

To further understand the implications of MSE, it is of interest to look at what remains from past events. In the literature, the term *legacies* is used to refer to "*all planned and unplanned, positive and negative, tangible and intangible structures created for and by a sport event that remain longer than the event itself* " (Ferrari & Guala, 2017,p.3). When analyzing the legacies of past events, it becomes evident that not all cities benefited equally from hosting MSE. The legacies of the OG in Barcelona and Athens, for example, differ strongly. Indeed, in the case of Barcelona, the games have positively affected the urban renewal of the city (Essex & Chalkley, 2004). Athens, on the other hand, produced mixed outcomes. While the Olympics provided an opportunity for the city to modernize its infrastructure, the lack of long term planning put major economic strains on the finances of the government (Panagiotopoulou, 2014).

In a study on the environmental legacy of the Olympics, Azzali (2019) identifies four recurrent practices synonyms with positive implications: Using events as an environment for testing new solutions; Using both temporary and permanent facilities; Ensuring a good physical and social integration of the venue; and using the OG as an opportunity to brand the city. Looking at stadiums, in particular, Erten & Özfiliz (2012) highlight the importance of efficient utilization of urban resources by considering the post-event use of mega stadiums in the design phase. This should help prevent the problem of *white elephants* which are "*A possession that is useless or troublesome, especially one that is expensive to maintain or difficult to dispose of* "(Oxford dictionary, 2019). Indeed, one of the main challenges of Olympic facilities is that they are often over-dimensioned for their post-game use (Steward, 2002). To cope with this problem, two different approaches have been identified: the use of existing facilities and the design of adaptable stadiums.

First, one can take advantage of existing facilities. For example, the figure skating and short track events in the Torino Winter Olympics were held in the Pala Vela. This building, designed for the Italia '61 world expo, was refurbished for its Olympic function (Wikipedia, 2019). This solution has the advantage of requiring minimum investment. Furthermore, once the event is over, the facility can return to its original purpose.

Secondly, adaptable stadiums can be designed. Adaptability is defined by Steward (2002) as *"the capacity of a building to accommodate effectively the evolving demands of its context", p.5.* This can be subdivided into two strategies: the design of flexible arenas which can change their configurations to allow multiple usages, and demountable stadiums that can be rebuilt somewhere else.

An example of a flexible facility is the London Stadium which was built for the 2012 London Olympics. It hosted the opening and closing ceremonies for the Olympics and the Paralympics as well as the athletics competitions. After the games, it was partially transformed to host the new tenants, the football club West Ham United. To maximize its use, movable stands allow it to accommodate multiple sports. Since the Olympics, the London stadium hosted athletics competitions, football, and rugby games, multiple concerts, a motorsport event, and it is set to host games of the MLB, the American baseball league (Wikipedia, 2019a). However, it is worth noting that the costs associated with transformation from football to athletics configurations have caused complaints from the tenants (Gibson, 2016). One reason identified for the important cost is the labor-intensive process of storing the seats in an off-site facility.

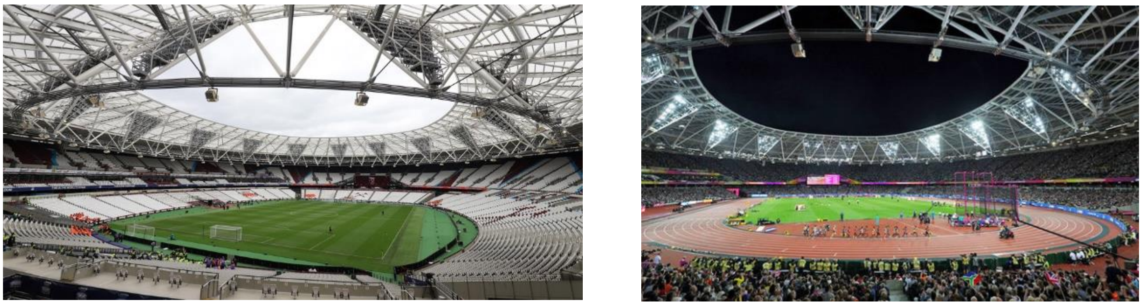


Figure 7 London stadium in football and athletics modes

The other option is to build partly or completely demountable stadiums. The idea is not new. In fact, Pierre de Coubertin, initiator of the modern Olympic games, stated that temporary building would suit the need of the Olympics and warned against the construction of unnecessary permanent stadia (Steward, 2002). The main idea is that the unnecessary parts, or the entirety of the stadium, can be demounted and re-used as one, or multiple facilities, where needed. By doing so, the goal is to reduce the environmental impact as well as the maintenance costs.

A good example of a semi-temporary Olympic facility is the water center for the 2012 London Olympics. Designed by Zaha Hadid Architects, the venue for the swimming, diving, and water polo competitions had a capacity of 15'000 seats using temporary stands and roof. The main structure, however, was a permanent facility compromising the pools and 2'500 seats. After the games, the stands were dismantled, and the complex is now enclosed by a glass façade (Steward, 2002).

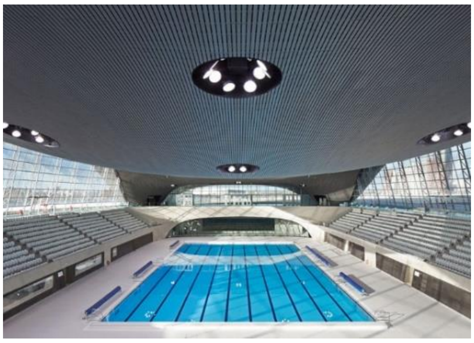



Figure 8 London aquatic center in Olympic and legacy mode

One of the main drawbacks of the demountable strategy is that the dismantlement, storage, transport, and the process to find another user or buyer can prove to be a burden for the host. This caused some temporary structure to stay in place and degrade. (Steward, 2002).

A final example of demountable structures is the stadium for the Swiss wrestling and alpine games festival. This traditional event takes place once every three years in different cities. For the past five editions, Nussli, a Swiss company specialized in temporary structures, has used a mix of their stock and parts sourced from subcontractors to build the arena (Nussli, 2016). The latest edition, in Zug, saw the erection of a 56'000-seats temporary facility, based on 8'500-seats modular stands.

The high modularity of the construction and the repetition of the manifestation helps to mitigate the problems linked with temporary structures. Moreover, having one company owning all the pieces and applying them to different configurations greatly simplify re-use logistics.

Figure 9 Arena in Zug

Another approach to the search for improvement strategies is to look at the opinion of the host population. Indeed, investigating the complaints of the public before the event starts can help discern what areas need to be improved. Giulianotti et al. (2015) identified the main sources of public opposition during the 2012 London Olympics. One of the highlighted complaints is the important public investment required. This was particularly true given the austerity policies in place. The public, therefore, felt that such money could be used for other, more urgent, purposes. Moreover, opponents argued that this considerable investment only benefits a few Olympic elites. Indeed, some of the seats are reserved for high profile personalities chosen by the IOC and referred to as the Olympic family (Giulianotti et al., 2015). Furthermore, some facilities are used by a very limited number of athletes. This is particularly true for the winter Olympics which require highly specialized facilities (Essex & Chalkley, 2004). Finally, residents criticized the promises of the organizers that the Olympics will have an economic impact on the local populations. This general concern about public spending is consistent with the aforementioned cases of Hamburg, Rome, and Boston. Finally, it is worth mentioning that fears for the environmental impact of the constructions were also a point of criticism in the 2012 Olympics (Giulianotti et al., 2015).

Results

MSE are events that happen on a global scale and which have major impacts on the hosts. They are an opportunity to develop and publicize the region. However, given the colossal sums in play, they can also be considerably risky. In the view of recent criticism of MSE, studies of their legacies have been made. Reviewing the existing literature on this subject gave insights on what needs to change but also what opportunities arise from such events. Concerning stadiums and arenas, it has been shown that sustainability is a major issue. The post-event use of stadiums and arenas is a paramount consideration when designing and demountability has been identified as a potential solution when no future use for the stadium can be expected.

Indeed, demountability allows for safer use of public spending while minimizing the environmental impact. However, it can be challenging to find buyers for the demounted structure. Moreover, the cost of mounting and demounting can be relatively important when the structure is only needed for a short period. Furthermore, the public calls for more sensible investments that could benefit the people hosting the MSE in the long term. Solutions to prepare the facilities for their post-event already exist and have been applied in multiple contexts. However, the recent refusal of some cities to host the Olympics shows that they can be improved. Moreover, this preliminary study also showed opportunities. Indeed, MSE have been identified as a good environment to develop and test new solutions.

For these reasons, a multi-usage timber structure will be investigated as a solution to MSE's challenges. Indeed, it reduces the ecologic impact by using sustainable material and by expanding the lifespan of structural elements. Additionally, the possibility to construct other typologies of legacy structures will maximize re-use possibilities and mitigate the problems of temporary arenas. Finally, using the demounted MSE structure to attend to the local population's need ensures that the event leaves positive legacies for the hosts.

In the following chapters, research will be done to further explore the possibility and conditions of re-use. But first, it is important to look at existing research on sustainable construction.

PART II

THEORETICAL FRAMEWORK

Figure 10 A timber connection

CHAPTER I: Sustainability Strategies

In the current context of global warming and resource depletion, designing sustainable constructions is a priority. Indeed, in countries like the U.S., the construction industry represents approximately 40% of all energy used (Sahoo, et al. 2019). Consequently, it is responsible for roughly the same percentage of greenhouse gas emission (GHGE) and waste generation (Kibert, 2007). The purpose of this study is to use innovative solutions for re-using structural components in various contexts to promote the sustainability of constructions.

This chapter focuses on reviewing the existing work on sustainable construction. It is motivated by three goals: Identifying the design strategies for sustainable construction; Deriving a simple and fast method to compare the design alternatives produced in a later stage of this research; Reviewing the work on timber structures to pinpoint sensitive areas to keep in mind during design.

The objectives of this chapter are addressed in three steps. First, sustainable construction will be defined and the current literature on this subject reviewed. In a second step, the life cycle assessment (LCA) method will be explored. Indeed, this method is recognized as an efficient tool for evaluating the environmental impact of a technical system (Danatzko & Sezen, 2011). More specifically, fast track LCA will be described as a means for evaluating alternatives. Additionally, understanding LCA mechanisms is useful for the third part of this chapter which is the review of existing LCA on timber structure to identify hotspots for environmental impact.

Sustainable construction

Sustainability has multiple dimensions. Shen (2007) identifies four different aspects of this concept, namely social, economical, biophysical, and technical sustainability. Social and economical sustainability aim at improving the quality of human life while guaranteeing affordable solutions with little interference with the economy. Biophysical sustainability, on the other hand, means reducing the impact of humans on the biosphere. Finally, technical sustainability highlights the importance of durable, reliable structures.

Given the multi-dimensionality of sustainable construction, defining it is no easy task. However, for the purpose of this study, the definition given by Kibert (2007) is used. Sustainable construction is *"the creation and operation of a healthy built environment based on ecological principles and resource efficiency"* (Kibert, 2007, p.2). Although all the different dimensions of sustainability will be kept in mind during the design, this chapter focuses mainly on biophysical sustainability.

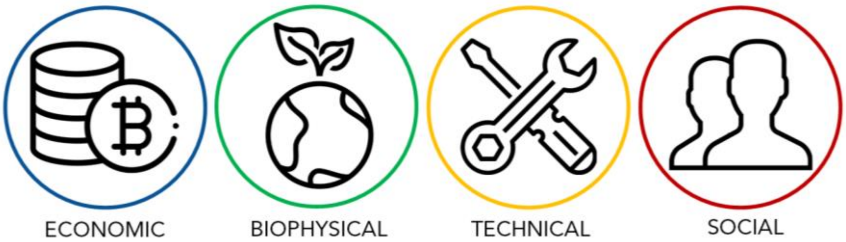


Figure 11 Dimensions of sustainability

Extensive work has already been conducted on the energy consumption of buildings during the operation phase (Kibert, 2007). Indeed, this part of the life cycle has been identified as critical regarding GHGE. For instance, a review of multiple LCA case study (Khasreen, Banfill, & Menzies, 2009) shows that it is responsible for approximatively 80% of the life cycle GHGE. However, with increasing regulations concerning the building envelope or technological improvements such as better insulation, the developments of IGU, or improved ventilation, the importance of the structure is expected to increase in the coming years (Kibert, 2007). It is thus more and more relevant to reduce its impact through sustainable construction.

Five methods have been recognized as enablers of sustainable construction (Danatzko & Sezen, 2011).

The first strategy is to minimize material use. It follows the logical assumption that less material means less environmental impact. It can be achieved architecturally by a more efficient layout. Optimizing floorplans and geometry enables more efficient buildings having more floorspace for the same footprint. Another approach is to use structural optimization and to choose appropriate structural systems to reduce the amount of material required for the structure.

The second method aims at minimizing material production energy. Here, the goal is to use energy-efficient materials. By selecting less resource-intensive materials, the structural designer reduces the impact of the structure. This implies quantifying and comparing the influences of different structural components. In this research, timber was chosen because it is a naturally available material. Moreover, multiple LCA case studies quantified the environmental benefits of timber (Hill, 2019; Sathre & Gustavsson, 2009; Ximenes & Grant, 2013). Although the influence of the substitution varies depending on the authors' hypothesis, the consensus is that using timber enhances the sustainability of the construction.

The next guideline is to minimize embodied energy through design. First, designing with recycled material or promoting the recyclability of virgin resources can greatly reduce the embodied energy. For example, using 100% recycled steel can reduce its environmental cost by a factor 2 (Treloar, Fay, Ilozor, & Love, 2001). To enhance recyclability, three conditions need to be met (Fadai & Stephan, 2019). The materials should be homogeneous to reduce waste management costs, separable to cut disassembly cost and absent of pollutants to increase recycling efficiency. Additionally, minimizing construction wastes and increasing the service life of products are tools to reduce the embodied energy.

Furthermore, maximizing structural re-use plays an important part in sustainable construction. The goal is to avoid wastes from a construction once its life cycle has come to an end. In some cases, flexible floorplans can guarantee that the structure can be re-used entirely if the function changes. Another approach, more applicable to this study, is to design structural components in such a way that they can be dismantled and re-used in other circumstances. The conditions for such a practice will be developed in detail in chapter *CHAPTER* II: Re-Use. The benefits of re-use are multiple. It can lengthen the life span of elements or the entire structure by facilitating replacement (Crowther, 2009). Moreover, it reduces the need for new components.

In a study on prefabricated modular buildings, it was recognized that re-use saves substantial amounts of materials. The associated case study of an 8-story timber building demonstrated that 70% of the embodied energy can be saved for a new structure by re-using structural components (Aye, Ngo, Crawford, Gammampila, & Mendis, 2012). An important condition for re-use, however, is that the legacy structure should be built in the vicinity of the original construction (O'Brien, Guy, & Lindner, 2006). This is due to the influence of transport over GHGE.

Finally, Danatzko (2001) mentions LCA as an important tool for sustainable constructions. Indeed, it allows a greater understanding of the behaviour of the building over the entirety of the life cycle. It is thus possible to comprehend if using materials with more embodied energy will *pay off* by lengthening the life span for example. Additionally, LCAs are useful to identify hotspots in the life cycle that need special attention. Lastly, they allow the comparison of design alternatives in an objective way.

Other researchers cite similar concepts for sustainable construction. Shen (2007) proposes an interesting criterion that is not cited above. In his view, architectural quality should be an objective of the design. While it is a rather abstract concept, it highlights that simply optimizing for environmental impact is not enough. Indeed, a construction that is valued by its users will be better maintained and will exhibit a longer life span, thus reducing the impact of the construction. Moreover, well-designed constructions have positive impacts on the social dimension of sustainability (Shen et al., 2007).

Figure 12 Quality structures have a seemingly infinite lifespan

To conclude, it is important to note that these concepts and methods should not be treated as independent (Danatzko & Sezen, 2011). Indeed, none can guarantee a sustainable construction singlehanded, as they all come with drawbacks. Moreover, the methodologies can sometimes clash with each other. Minimizing material use, for example, might demand less sustainable materials. Maximizing re-use, on the other hand, can produce an under-optimized structure to allow for different usages. The best strategy is, therefore, to keep the different methods in mind while designing and evaluating the alternatives with regards to all six concepts mentioned.

LCA

Now that the concept of sustainable construction has been defined, a procedure is needed to quantify its benefits and to compare different alternatives. The proposed answer is the Life Cycle Assessment method (LCA). This part will first explain what an LCA is and why it is used, then its methodology will be described as well as its criticism and limitations. Finally, fast-track LCA will be explored as a possible variation of the LCA for this research.

A life cycle analysis is defined as a methodology for evaluating the environmental load of a process (Ortiz, Castells, & Sonnemann, 2009). Such an analysis has been used since 1990. A commonly recognized method for LCA is described by the International Organization of Standardization in the documents ISO 14040 and 14044. Following a standardized and recognized procedure is the strength of LCA. Indeed, consistency is a prerequisite for comparison of results but also for their reliability.

As mentioned earlier, the main advantage of the LCA is that it gives the designer an overview of the impacts and performance of a product through its entire life cycle (Danatzko & Sezen, 2011). It was traditionally used in an advanced stage of design to check its compliance with regulations or if it meets the objectives set (Khasreen et al., 2009). However, it is advantageous to use LCA in the early stages of design (Vogtlander, 2014). Indeed, the further the design process goes, the more complicated it becomes to implement changes. Using LCA in preliminary phases allows for comparison of different design alternatives but, perhaps more importantly, it might expose flaws in the project or reveal opportunities. LCA can be particularly useful in the construction industry (Khasreen et al., 2009). Indeed, buildings are very complex by their long lifespan, the multiplicity of stakeholders and the different scales all associated with different impacts. Using such a well-defined tool is thus necessary to deal with this complexity.

They are different types of life cycles analysis. They can be sorted on the scale on which they operate. Ortiz (2009) identifies 3 levels of LCA in construction. Level 3 concerns the whole building frameworks. It deals with methodologies such as BREEAM or LEED for example. Level 2 englobes the whole building design decision support tools and is used to assess the global performance of a complete building. Finally, level 1 concerns product comparison tools by evaluating the impact of one or groups of components. In this study, level 2 will be used when reviewing existing literature. However, since the load bearing system is the focus of this report, level 1 is appropriate to assess the different options for materials, structural systems, and structural components.

A typical LCA study comprises four steps (Khasreen et al., 2009). To give a clear understanding of how an LCA functions, these steps will be shortly described hereafter.

Every LCA begins with the goal and scope definition. This step will determine the outcome of the study and is therefore critical to its success (Khasreen et al., 2009). This starts with the definition of the project. Important characteristics such as the life span of the structure, its function, etc. must be specified here.

The EU norm EN 15978 (Norm Nederlanse, 2020), discerns four different modules to describe the different life cycle phases. Module A englobes the production and construction, module B characterizes the use stage, module C the end-of-life, and finally, module D englobes the recovery beyond the lice-cycle such as recycling or re-use options.

The modules, and their sub-categories, are important to define the scope of the study. Indeed, in the first phase of the LCA, the system boundaries must be specified. This means describing what is included or excluded from the analysis. For example, analysis called cradle to gate focus only on stage or on subphases of module A such as the impact of the extraction of material. These boundaries are also relevant to the possible simplifications of the study. Indeed, a method derived from traditional LCA uses the outcomes from studies focused on module A, for example, to analyse the rest of the life cycle with reduced work (Vogtlander, 2014). Moreover, some modules have less influence depending on the studied subject and can be neglected. In the case of structural design, construction works, and maintenance is often ignored (Ehrbar & Kellenberger, 2003). An exception to this is the transport to the construction site and the use of ancillary (Ehrbar & Kellenberger, 2003). In the case of this study, the same assumptions are used. Additionally, the influence of the structure on the use phase of the entire building is neglected. This is done because it greatly simplifies the analysis and because the maintenance of the structure has marginal effects. Furthermore, the influence of the structure on the building physics performances is relatively low. This is shown by looking at a life cycle comparison of the same building designed with different materials. In Ehrbar & Kellenberger (2003), for example, the author looked at the difference between a modular construction built out of steel or timber. For the annual operational energy used for cooling and heating, the difference between the two constructions amounts to 2.4%. Whereas, the difference in embodied GHGE is roughly 25%. This is because the two structures have the same insulation which is the governing parameter on the use phase. Consequently, its the impact can be neglected.
Also important during the goal and scope definition step is the choice of the functional unit (FU). The FU is defined in (Vogtlander, 2014) as *"a combination of the functionality of the system and the unit in which this functionality is expressed.".* The choice of the functional unit is important since it will define all measurements of the study. Moreover, it will influence the ease of comparison with other studies (Khasreen et al., 2009).

The next phase in an LCA is the Life Cycle Inventory (LCI) (Asdrubali, Baldassarri, & Fthenakis, 2013). This phase contains the data collection and details the calculation procedures. Here, all processes included in the system boundaries are listed. Additionally, the material and energy inputs associated are quantified and reported. Finally, a detailed description of the outputs such as solid wastes is provided. During the data collection, it is important to be attentive to the hypothesis linked with the available data. Indeed, many components are, for example, location-sensitive (Khasreen et al., 2009). The influence of the required electricity, for instance, will depend strongly on the portion of renewable sources in the local grid.

The third phase is the Life-Cycle Impact Assessment (LCIA). Its aim is to *"Examine the product system from an environmental point of view using impact categories and category indicators connected with the LCI results."* (Khasreen et al., 2009, p.687) In this step, we want to aggregate the results from the LCI and measure the environmental impact of the subject. This is one of the main challenges of LCA. How can we quantify the environmental impacts and how can we add them or at least compare them? It is especially challenging since much of these costs are externalities (Shen et al., 2007). There are many different categories of environmental impact: water pollution, acidification, GHGE, etc. Concentring on only one of those can be a risky choice (Shen et al., 2007).

Looking solely at GHGE, for example, completely ignores the radioactive wastes generated by nuclear energy. One solution is to keep the multiple impact categories relevant to the case separated and compare them in parallel.

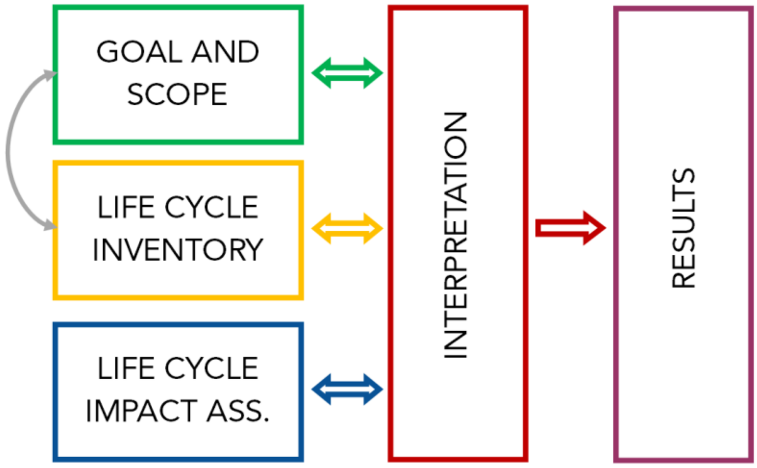


Figure 13 LCA process

The final phase from LCAs is the interpretation of the results. The goal is to analyze and synthesize the results. Additionally, conclusions and recommendations belong to this phase.

It must be noted that LCAs processes are not linear but iterative (Vogtlander, 2014). Indeed, a trial-and-error method is often used to see what processes are relevant to the analysis. In particular, the different dimensions of the first part are closely related and might require multiple iterations until they align.

The main limitation of LCA is its sensitivity to the hypothesis made in the first step. Indeed, two analyses of the same case can produce significantly different results even if both are procedurally correct. The construction industry, in particular, is home to many uncertainties. The life span of a building, for example, is subject to many variations due to criteria difficult to plan. The transport distance for material and components or the content of the electricity mix are other examples of sources of uncertainties. This makes the comparison between different LCA studies difficult. A measure to counteract these drawbacks is to perform a sensitivity analysis of the different parameters and see how robust the results are. Furthermore, to allow for results comparison and interpretation it is paramount to clearly specify the hypothesis made in a study. Another pitfall of the LCA lies in the definition of the system boundary. It is easy to do an analysis intrinsically correct but overlooking crucial elements. In this regard, Vogtlander (2014) gives the example of a comparison between a re-usable plastic container and its single-use cardboard equivalent. Indeed, changes in the system boundary such as ignoring or including the stocking and returning of the plastic boxes in the analysis completely change the outcome of the analysis.

A full LCA analysis is a time-intensive process that can take up to a couple of months (Vogtlander, 2014). This is not appropriate for the comparison of design alternatives, especially in the early stages when the scope isn't well-defined yet. Two alternatives are presented to counter this problem, namely streamlined LCA and short-track LCA.

The main idea of streamlining is to reduce the complexity of LCAs. It can be done in different manners such as limiting the scope, using qualitative information or concentrating on specific impact categories (Airbus, n.d.). Another option for streamlining is applicable for comparing two products. In this version, the analysis is simplified by looking only at the processes that differ between the two alternatives (Vogtlander, 2014). By doing so, the differences between the two products can be highlighted and quantified without substantial losses in precision (Vogtlander, 2014). However, this method has limitations. Indeed, it presupposes that the two products share most part of the process, the same functional unit, and lifespan.

Another alternative is to use the fast track LCA. This method, developed at TU Delft, uses the outcomes of previous studies as input for the analysis (Vogtlander, 2014). In practice, after doing the inventory of the processes and products used in the project, the LCA practitioner uses databases like Ecoinvent to obtain the related impacts. They are then added using software such as Simapro, or simply an Excel sheet. The advantages of this method are that it reduces significantly the required time, from days to a couple of hours, without losing much precision (Vogtlander, 2014).

An aside about the calculation for the end-of-life possibilities is of interest here. Indeed, recycling, energy generation from waste and by-products have a special yet similar way to be accounted for in LCA. The common practice is to expand the system boundaries to the new process and to use the difference between the costs and the benefices of the recovery scenario as a credit for the main product of the study (Vogtlander, 2014). In the case of using wood wastes for electricity generation, for example, the impacts associated with the standard production of electricity can be subtracted with the costs of burning the wood and the resulting savings are used as credits in the studied system.

Timber in LCA

Timber, because of its intrinsic sustainability, is the material of choice for this study. Indeed, it is a renewable material with a comparatively low environmental impact. This is shown by several studies comparing the environmental effects of timber with other construction materials. The impact of substituting wood for steel or concrete varies depending on the study and the potential inclusion of sequestered carbon but typically favors timber. For instance, in an analysis from 21 different studies, (Sathre & O'Connor, 2010) found that the GHGE are, on average, halved when using timber. This is due to diverse factors such as the relatively low manufacture, extraction, and process energy, as well as the capacity of wood to store carbon and energy (Sathre & Gustavsson, 2009). Nevertheless, the use of structural timber still has a substantial environmental impact. The goal of this section is thus to review the existing work, notably existing LCA studies, on this construction material. By doing so, the most impactful processes are underlined and strategies to mitigate them are explored. For clarity, the processes are reviewed in their order on the life cycle of timber.

Extraction & Production

The first step in the life cycle of timber products is its harvesting. Logging, which comprises all on-site processing of cut trees, has a limited influence on the global life cycle. Indeed, together with regeneration, this first step represents less than 5% of the total impact (Puettmann & Wilson, 2014).

Regeneration, the act of replacing cut trees, however, is of crucial importance for the sustainability of timber construction. Indeed, deforestation, mainly due to replacement by agricultural function or to illegal logging (Woodard & Milner, 2016), is a major factor in the environmental crisis. Certifications such as PEFC or FSC are important tools to ensure that the used timber comes from sustainably managed forests. This means that the new wood, replanted or naturally regrowth, compensates for the one extracted (Woodard & Milner, 2016). Additionally, certification attests that wood production is economically and socially sustainable.

Once the trees have been harvested, they need to be transported to the factory for processing. This is one of the main contributors to the impact of timber. This depends on a multitude of factors. First, the transport efficiency depending on the state of the roads and the consumption of trucks has an influence (Chen, Pierobon, & Ganguly, 2019). More important is the distance from the source to the factory. This has a significant impact due to the transport of low-value goods. Indeed, the freshly harvested wood is heavier due to high moisture content. Moreover, a good proportion of the transported merchandise will be lost through cutting and planning. For example, in the production of CLT in the state of Washington (US), a reduction of 11.4% of the total impact can be achieved if a factory situated at 90km from the source is selected instead of an alternative located 431km away (Chen et al., 2019). Additionally, the selected species has an influence on transport costs because of the difference in density. The same Washington study shows a 30% decrease in transport costs when substituting spruce for hemlock (Chen et al., 2019). This influence is limited, however, due to the relation between density and structural properties of wood products.

Figure 14 Timber harvesting

Drying

Harvested timber can have relative humidity contents higher than 100%. This is problematic for its usage in buildings where the equilibrium moisture content is significantly lower (Ramage et al., 2017). Indeed, reducing humidity below the saturation point of timber causes shrinkage. For long elements, this can cause significant displacements which, if constrained, result in stresses in the structure. Moreover, for cut elements, the anisotropic nature of timber results in asymmetrical shrinking causing twist or bow for example. Additionally, moisture content over 20% exposes timber to durability problems such as fungal degradation. Consequently, harvested wood must be dried. Letting this process occur naturally is time-consuming and requires important storage facilities which might prove to be economically unsatisfactory. The alternative method commonly used is kiln drying (Ramage et al., 2017) which consists of heating the wood in an enclosed, ventilated space. Depending on the final product and the LCA hypothesis, this process can represent 50% (Puettmann & Wilson, 2005) to over 90% (Bergman & Bowe, 2012) percent of the total energy consumption. One mitigating factor is that most of this energy comes from burning internal wastes from cutting or harvesting (Puettmann & Wilson, 2005). This means that the amount of fossil fuels used in the production of timber stays relatively low. It is worth noting, however, that counting, or not, the energy from these wastes and the associated carbon emissions is partly responsible for the difference between timber LCAs. This is linked with the question of wood as a bank of carbon and energy which will be discussed later in this chapter. Amongst the alternative solutions to reduce the impact of drying are using more efficient kilns or increase the portion of air-drying (Puettmann & Wilson, 2005). Another solution is to use timber with higher humidity content. However, this requires assemblies allowing for the deformations of timber.

Additional processes

Sawing is responsible for the major electricity use of timber processing (Bergman & Bowe, 2012). Moreover, because of the mismatch between the geometry of trees and of timber products, cutting generates wastes. It has been reported that only half the wood material from the forest is used in final wood products (Asdrubali et al., 2013). Concerning electricity usage, optimizing the cutting processes can improve efficiency. For the wastes, as mentioned earlier, it is partly used in the drying process. Additionally, they can be used in the production of chipboards or OSB panels. This will be discussed in the end-of-life scenarios.

Specific timber products such as plywood Glue Laminated Timber (GLT) or Cross Laminated Timber (CLT) require additional processes. Pressing is one of these steps associated with environmental costs. Another characteristic of these products is the use of glue. Its main drawback is that it requires fossil energy for its production. In a study of the American CLT, it transpired that glue is responsible for 18% of the GHGE (Chen et al., 2019). Moreover, glue might reduce the recyclability of elements once they reach the end of their lifespan. However, since pressing and gluing are intrinsic characteristics of the production method, it is difficult to influence them (Chen et al., 2019). On the other hand, because they use smaller elements engineered wood products produce fewer wastes which reduces their negative impacts. Additionally, they have greater mechanical properties due to the increased robustness of the composite.

A solution to reduce the impact of additional processes is to use roundwood for construction. In addition, to reduce the processing costs, roundwood keeps the geometry of the tree and thus avoid asymmetrical drying. With adequate connection systems, savings can thus be made on the drying process too. The main challenge, however, lies in the uniformity of mechanical and geometric properties as well as the connection systems between these round cross-sections.

Construction & Use phase

Once the wood products are ready, they first need to be moved from the factory gate to the construction site. For the same distance, the impact is smaller than the transport of harvested timber. However, it rises significantly if distances become longer. Passarelli (2017) studied the difference between locally producing CLT in Japan or importing it from Austria. The distances from the forest to the factory were 250km in both cases, while the factory-construction site trip amounted to 700km by truck in the local production scenario. This is an important factor to consider. Indeed, long-distance import from timber is a relatively common practice. The Netherlands, for example, imported 155’000 m^3 of tropical wood in 2016 (Probos, 2017).

The impact of the construction phase is relatively small, 5% of the production in the case study of a multi-story building in Canada (Gustavsson, Joelsson, & Sathre, 2010). Moreover, the possibility to reduce these processes is relatively small. One option would be to maximize prefabrication to produce fewer wastes and to use more efficient processes. However, the influence of this measure is unknown to the author. Of interest in the timber construction, is the impact of additional materials such as connectors.

Figure 15 Timber house under construction

A study of an insulated timber roof structure in Switzerland reported the influence of additional materials and works to be 10% of the overall energy demand (Ehrbar & Kellenberger, 2003).

The use phase of the structure has little influence on the overall performance. What has a huge potential, however, is the lifespan of the components. Indeed, the longer we use them, the fewer resources are required to replace them. This is of special interest in timber construction. Indeed, trees are a renewable resource if the forest production exceeds or equals the usage in construction. If we want to increase timber usage, it is thus important to increase the life span of the structural components to reduce strains on forest productions. Due to the multitude of factors influencing the lifespan in the building industry, the service life of a structural component often exceeds that of the building. Consequently, end-of-use scenarios are of crucial importance and need to be accounted for in the design.

End-of-life

The deconstruction process has little influence on the overall impact (1-3%) (Gustavsson et al., 2010). However, it comes with great opportunities to extend the usage of the wood and thus save resources and energy. Recently, the European Union expressed the will to shift toward a recycling society and minimize waste (Gustavsson et al., 2010). Timber shows great opportunities in that regard. Indeed, its lightweight, the common usage of modular assemblies, and the standardization of elements make it a good candidate for re-use (Hafner, Ott, & Winter, 2014). Additionally, its recycling requires less energy than other materials such as steel (Woodard & Milner, 2016). What is more, the recycling process is relatively efficient with 10% of waste (Mehr, Vadenbo, Steubing, & Hellweg, 2018).

Multiple end-of-life scenarios are possible for timber. However, they are not all equal regarding their sustainability. A commonly used concept is called cascading where obsolete products are gradually downcycled. It is important to note, however, that the feasibility of each step depends on the local market. In the UK, for example, 40-45% of the timber products are recycled (Ramage et al., 2017), whereas in Switzerland about half is incinerated and the other half is exported since no factory can do the recycling processes (Mehr et al., 2018). This causes a change in the valorisation of recycling depending on the transport distance and the value of virgin materials. In an ideal scenario, components are first re-used, before being recycled as many times as possible and are finally used for energy generation, landfilled, or used in other industries such as woodchips for landscaping. In the case of a timber beam, for example, it can first be re-used, then the relatively undamaged parts can be split into smaller parts and recycled to glulam which in turn can be recycled to chipboards. During the whole process, wastes can be used for electricity generation.

Re-use, the first part of the cascading process is discussed in the following chapter *CHAPTER II:* Re-Use. Recycling depends on the aforementioned conditions with the absence of toxic material especially relevant for old constructions where CCA might have been used as preservatives.

Energy generation, which benefits from the energy and carbon stored in timber, is a debated subject. Indeed, comparing it with electricity generation from fossil fuels poses it as an interesting option. However, this ignores the gains from recycling materials which can be later incinerated if necessary. Moreover, the benefits depend greatly on the electricity mix. In a study in the Swiss context, it was found that cogeneration is an interesting alternative as the last link of the recycling chain (Mehr et al., 2018). Additionally, the long lifespan of building structures implies incertitude in the future electricity mix. With, hopefully, the increase of green energy sources, recycling will have a clear advantage over cremation. It can be noted that some of the reviewed LCA studies might have used cogeneration as an easy to quantify end-of-life scenario. Finally, the last option is to use materials in landfill. This option is not advantageous since it produces no value. However, if it must be chosen, special attention should be paid to have anaerobic conditions to avoid the production of methane which has an impact 22 times greater than CO_2.

Wood as a carbon bank

Through photosynthesis, wood processes carbon, water, and solar energy and stores it as carbohydrates. This has led to a description of wood as a carbon bank (Ramage et al., 2017).

This generates a lot of debate in the LCA practice. Indeed, the inclusion or exclusion of fixed carbon in wood can lead to significant disparities between analysis. The reason for including it in LCAs is to consider the advantages of carbon sequestration on climate change. However, the effect would be noticeable only in the case of afforestation. Therefore, this can only be accounted for on global analysis. Since LCA are focused on the product level, many authors suggest neglecting the effect of the stored carbon entirely (Vogtlander, 2014). This means ignoring its positive effects but also the emissions when burning or landfilling. It is of interest, however, to consider the global scale when choosing timber sources. Indeed, selecting timber from regions with afforestation ensures that it is not contributing to climate change. Tropical hardwood, for example, is often linked with deforestation which means the release of carbon from the wood cycle and should thus be treated with special care.

Results

This chapter explored sustainable construction for timber structures and their assessment. The first objective was to explore general work on building sustainability. This work highlighted methodologies to reduce the impact of constructions. This includes minimizing material use and production energy, reducing the embodied energy, maximizing the potential of re-use, striving for quality, and the use of LCA throughout the design to identify the most advantageous strategies. This translates into a careful choice of materials and structural systems. Additionally, connections play an important role in extending the life span of components trough re-use and recyclability.

The second objective concerned finding a method to evaluate design alternatives. LCA is the recognized method for process assessment. Its benefits in the construction industry are plenty. Its time-consuming nature, however, limits its applicability to this project. Fast-track LCA was identified as a viable alternative with reduced calculation time. However, the sensitivity of the analysis toward hypothesis means that important preliminary work still needs to be performed to guarantee the reliability of the results. The limited-time available for this study and for the preliminary stage of construction projects in general poses a problem. Indeed, is there sufficient time for reliable results? In this research, the results of previous studies will be used to assess the differences between different alternatives in a qualitative way.

Finally, the LCA of timber products and construction were reviewed to identify challenges and opportunities. The main factor uncovered is the importance of the provenance of timber. Locally sourced timber from sustainably managed forest can reduce the negative effects of timber production significantly. Additionally, the distance from the forest to the factory has substantial influence although the possibilities for the designer to change it are small.

The study also found that drying has a sizeable effect on energy consumption. Using more humid wood with greater assembly tolerances or researching roundwood can be interesting alternatives to mitigate these effects. Moreover, roundwood positively reduces cutting wastes.

Finally, strategies for lengthening the lifespan of materials and components are applicable in timber. This is important for reducing environmental impact and ensuring the smart usage of forest resources. Recycling is applicable to timber with many products using different quality of wastes. Moreover, using recycled materials can reduce the embodied energy and contribute to market development. More advantageous than recycling is re-use, for which timber lends itself to and which is the subject of the next chapter.

Figure 16 Timber logs

CHAPTER II: Re-Use

Re-use occupies a central place in this research. Indeed, by creating a structure with components that can be reconfigured to support other types of building, it aims at valorizing end-of-life scenario. While this multi-purpose design is an innovative idea, extensive research has been done on reusable structures. This chapter explores the work carried out on this subject. The objective is to expose the design principle enhancing re-use possibilities. First, a short introduction will explain why we should design for re-use. Secondly, the work done to re-use existing structures will be discussed. Indeed, looking at the demolition of structures highlights what factors hinder or promote re-use. Then, from these results, as well as by reviewing existing research, the principles for a re-use-oriented design will be laid out. To conclude, two factors are developed to assess the re-usability of different design alternatives

Why re-use?

In Europe, 40 percent of the total waste production is linked to the building industry (Crowther, 2009). Structural systems play an important role in it. Indeed, on average more than half of a building's mass comes from the structure (Webster & Costello, 2005). Regardless of which part of the building it originates from, the major part of the waste is created in the demolition process. Indeed, while steel already has a good recycling rate, most materials are still landfilled or incinerated to produce heat or electricity. This happens even when structural elements have a life span exceeding the one from the construction (Crowther, 2009). In most cases, this is due to the absence of end of life scenarios. The consequence of this design philosophy is that the energy used to extract materials, to produce building components and to transport them is wasted. Either partially when the material is recycled or completely in case of landfill. On top of the squander of energy and the production of wastes, the lack of planning for the deconstruction phase results in the rarefication of natural resources. Indeed, the building industry, which is responsible for 40% of the world's material flows (Webster & Costello, 2005), has a major impact on the state of virgin material reserves.

Figure 17 Building under demolition

It is thus necessary to change the way we design from a linear cradle-to-grave perspective and aim for a more circular approach. Out of the end of life scenarios, re-use is usually the ecologically most favorable. Indeed, the resources used to produce building components are, in an abstract way, stored in the component itself. Re-using them is thus resource and energy efficient.

An analogy used by Luscuere (2017) sums up the required change of mentality. Instead of seeing buildings as a finished, one-use, products, designers should see them as a material bank where resources and energy are stocked and ready to be re-used once the building reaches the end of its life cycle.

On top of the resource savings and waste diminution, re-use offers multiple opportunities. According to Hradil (2015), the growing waste taxes will make re-using economically advantageous. Moreover, he mentions works in progress to include re-use in sustainability certifications such as LEED or BREEAM. This will recognize the sustainability of construction from salvaged materials. Moreover, being certified is economically advantageous for marketing reasons but also to qualify for subventions. Finally, the principles for re-use imply greater adaptability in the design as well as easier maintenance which could contribute to lengthening the building's life span (Bradley Guy, 2002).

Finally, as mentioned in the introduction, re-use is particularly relevant to MSE. Indeed, the short lifetime of certain structures required for MSE calls for the valorization of the end of life scenarios. Moreover, the components have high chances to be in good condition given their limited utilization.

Re-use of existing structures

Despite its many advantages, re-use also has its limitations. Factors such as toxic elements, weathered components, or chemical connections, for example, can greatly reduce the benefits by increasing the costs and the energy required for re-use. To understand how to design re-usable structures, it is of interest to see what mechanisms hinder the re-use of existing structures.

Figure 18 Workers demounting a timber roof

In reviewing the literature, five different categories of obstacles have been identified. These are: economic, logistic, design, degradation, and deconstruction challenges.

The economic factor is always an important criterion and re-use is no exception. Hradil (2015) describes the lack of resale market as one of the major factors against re-use. Indeed, this practice is still in its beginning, and thus it can be difficult to sell the salvaged components. This problem is exacerbated by the costs associated with the demounting of buildings. Depending on how the construction was designed, it can be difficult to extract the components intact. Such cases require careful demounting which can be a labor-intensive process resulting in an increase in the price of recovered items.

Another financial problem is that elements might need adjustments to prepare the re-use. These can be changes in dimensions or the application or removal of coatings. Such alterations can increase the cost significantly (Hradil, 2015).

To understand the re-usability of existing structures, Hradil et al. (2014) conducted a survey amongst professionals linked with the demolition and construction industry. It transpired that logistic problems such as the lack of legislation and standards are considered as the main impediments to re-use. There is, indeed, no standardized process for disassembly nor for testing retrieved components. In addition to this, there is often a deficiency of relevant information concerning the building elements composition and quality (Durmisevic, et al., 2017). These factors combined make managing the risks in re-used construction difficult. Consequently, it might be hard to insure the building and to convince the authorities of the safety of the structure. Transport is another logistical challenge associated with the re-use of existing structures. Indeed, in some cases, the components need to be stocked or prepared in a factory before their re-use. It is necessary to check whether these added trips are not counterbalancing the ecological benefits of the re-use (Hradil et al., 2014). Moreover, transport and extra processes can significantly increase costs. Finally, coordination can be challenging in such constructions. Indeed, mismatches between the time the materials are ready, and the time when they are needed on the new construction can happen given the variability of the deconstruction process (Hradil, 2015). This can lead to costly delays in the construction if not accounted for in the design phase.

The deconstruction process in itself might become problematic depending on the design choices made during the creation of the building. First, health and safety concerns arise when toxic materials were used. Common examples are the use of asbestos panels or lead paint which require special treatments. This can generate costs overruns or delays. Secondly, Akinade et al. (2017) identify the mixing of different components as a major factor against re-use. Indeed, the integration of HVAC, plumbing of electric equipment within walls or floor is often problematic. Unless the composite can be re-used as a whole, it can be challenging to extract each component intact in an economically sustainable way. Light timber walls, for example, are often mentioned unsuited for re-use because of the integration of electrical systems and plumbing. A similar problem is present in composite structures. It is indeed often difficult to separate the different materials without damages. Problems can also arise when dealing with a system of components. The irreversibility of connections, such as glue lines for timber, is a major setback to re-use. In the case of a welded column-beam steel frame, for example, the angle of the frame needs to be cut away. This takes time but also reduces the size of the component and, de facto, its possible applications. The same applies to connections that are difficult to reach. Moreover, the scale of certain components is also a factor which might force builders to break components into smaller pieces to ensure safe handling (B. Guy, 2002). Finally, if the elements are not self-stable the dismantling process will be more difficult since temporary propping will be necessary. This can also happen for self-supporting structures for which structural information is partly or entirely missing and where conservative hypotheses must be made.

Before carefully deconstructing a structure, it should be assessed whether its components are worth saving. Concerning timber structure, in particular, Hradil et al. (2014) identify the damages which frequently occur in such constructions. First, notches and bolt holes are often present by design in timber elements. They can have an influence on the resistance of the cross-sections and should be considered when checking their capacity. Moreover, cracks can arise from overloading and will require treatment if the section it to be re-used.

Rheological cracks, on the other hand, are of lesser importance since they mostly affect stiffness. Attention should be paid, however, to the increased risk of biotic damage they cause. Additionally, because of creep or humidity, the shape might be distorted. This has little influence on structural purposes but might be problematic for assembling the new structure. Finally, timber should be checked for biotic damages which might require some treatment.

The last group of challenges relates to designing with salvaged materials. Hradil et al. (2014) describe inconsistencies as one of the main difficulties when planning. Inconsistencies can arise in material qualities, as well as in the dimensions. This is especially true if the component comes from different deconstruction sites. Indeed, there is no standardized length or capacity for structural elements. It can thus become very challenging to design with salvaged materials, especially if the source is not known before the design starts. Finally, certain components might have become too obsolete for modern construction. While this problem is less present for structural elements, it applies, particularly, to façade and roof parts. Indeed, such components need to comply with recent building physics regulations.

To conclude this section, an example of a building from reclaimed materials is presented. The C.K. Choi Building at the University of British Columbia was designed with sustainable goals in mind. One of those was to use at least 50% of reclaimed or recycled materials (UBC, 2019). The bricks from the façade, for example, were all reclaimed from different sources. Of interest is the timber structure, composed at 65% of timber salvaged from an obsolete building on campus (Addis, 2012). Almost 90% of the 75 years old timber recovered from the old building was deemed useable for the new construction. However, convincing the authorities of its safety proved to be challenging (Addis, 2012). Moreover, extra flexibility was necessary for the design to allow for the different sizes of timber. In the end, after conducting additional tests on the timber, the authorities were convinced, and the building was built.

Figure 19 Left: Facade of the building, Right: Reclaimed timber structure

Designing for Re-use

The goal of designing for re-use is to maximize the value of an obsolete construction. Having identified the obstacles to reclaiming components from existing buildings, it is now possible to develop guidelines to avoid them.

The lack of standards and legal framework is difficultly influenced by the designer. Indeed, apart from providing identification and documentation for the components used, there is little that can be done on a project scale. However, the increasing occurrence of re-usable structure and the research currently being conducted on a global scale should help with this issue. An interesting example of on-going work on the subject is the development of a material passport (Luscuere, 2017). This research, funded by the EU, aims at developing a tool to track and standardize the re-use possibilities of materials in the building sector. While this project is not fully operational now, it shows that the hindrances caused by the lack of standardization should decrease over time and that institutions such as the UE are incentivizing the development of re-use.

One key concept when designing for re-use is identified (B. Guy & Ciarimboli, 2005) as *scenario buffer.* According to this model, designers should have potential re-use scenarios in mind when developing a project. This gives an opportunity to solve many of the problems identified in the re-use of existing structures. First, the logistics problems are addressed by planning the demounting phase during design. Indeed, knowing the future use of the components from the start eases the coordination between old and new structures. Moreover, by planning a legacy structure needed in an area close to the first construction, transport challenges can be controlled. Second, it solves the challenge of finding a market for reclaimed components. If plans for the legacy structure are ready before deconstruction, they can be sold directly to a promoter. Finally, planning for multiple possible uses of the structure ensures that design problems such as the inconsistencies of dimensions and quality are considered before building the first construction which reduces the costs of re-use.

The scenario buffer strategy applies entirely to the context of this project. Indeed, the short period of MSE simplifies the unknowns related to time and allows for detailed planning. It can be noted, however, that it might prove more difficult to implement for a project with an undefined life span. Indeed, the extra investments required during the design phase will not result in any short-term profits. To cope with this problem, Webster & Costello (2005) recommend adding re-use rewards in certification systems such as LEED. This would help position re-use as a selling point and thus pay for the extra investment.

In addition to planning re-use in the design phase, Webster & Costello (2005) suggest general design guidelines to enhance re-use possibilities. The design should have transparency to allow for easy identification of building systems. Regularity in the materials and dimensions is also helpful to maximize the possible reconfigurations. Finally, the simplicity of the building systems and their connections should help the dismantling process.

Demountability

The aforementioned strategies are to ensure that the demounted structure can be re-used. However, it is paramount to guarantee that the structure can be deconstructed. To do so, the research of P. Crowther on design for deconstruction (DfD) is of great interest.

The basis of DfD comes from the work of Stewart Brand. He proposed to separate the structure in layers depending on their function (Crowther, 2016). The seven layers are the site, the structure, the skin which englobes façade and roofing, the services, the space plan which incorporates the partition walls and systems, and the stuff which is all the furniture.

It is of interest to DfD because every layer has different life spans, functions, and materials. Therefore, Crowther (2016) proposes to have clearly defined interfaces that are easily demountable between each layer. Indeed, it facilitates the replacement of layers when they become obsolete and thus it lengthens the building life span. Moreover, it simplifies the disassembly process of the entire building because individual elements are easily separated and thus ready for re-use.

Based on this theory, and experience from the re-use of existing structures, Crowther (2009) developed a set of 27 design rules to facilitate disassembly. They can be grouped into five categories, namely material selection, assembly design, handling facilitation, design guidelines, and logistic solutions.

Figure 20 DfD categories

First, material selection is important. While the influence over re-use is limited, it has a high impact at the end of the life cycle of a component. Indeed, using recyclable materials without secondary finishes facilitates greatly the recycling process. Additionally, limiting the variety of materials as well as material purity are important to simplify the sorting process. Moreover, choosing lightweight materials will facilitate the handling of the components as well as their transport.

Secondly, special attention is required considering the assemblies. To allow for demounting, they should be separable. Thus, chemical connections must be avoided. Moreover, to ensure fast (de)mounting, assemblies should be accessible and have realistic tolerances. Furthermore, the assembly should be strong enough to resist cycles of mounting and demounting, as well as the hits it might take during transport. Finally, using as few connectors as possible and from the same type should make the (de)construction processes easier.

Thirdly, measures should be taken to simplify handling. Elements should have easily accessible anchor points and be of suitable dimensions. Additionally, if the structural system allows for parallel disassembly, it can accelerate the process. Another structural measure is the use of self-standing elements. Indeed, they allow (dis)assembly without requiring temporary propping.

Fourth, the design should follow certain guidelines. Using a modular design and a standard structural grid, for example, maximize the chances of re-use. Moreover, using standard, mass-produced, elements guarantees that replacement is easy and maximizes applicability. Furthermore, all processes should be documented. Likewise, elements and assemblies must be identified to facilitate the logistics of deconstruction. Additionally, providing on-site storage for these documents and for spare parts is identified as a good solution for the maintenance and demounting of the structure.

The complete list of the design measures is visible in Table 1 which is taken, with small adaptations, from Crowther (2005).

Table 1 Demountability rules

	Principle	Material recycling	Component re-manufacture	Component re-use	Building relocation
	Legend: ● highly relevant; • relevant; · Not normally relevant				
Materials	Use recycled and recyclable materials	●	●	·	·
	Minimize the number of different types of materials	●	●	·	·
	Avoid toxic and hazardous materials	●	●	·	·
	Avoid secondary finishes to materials	●	●	·	·
	Use lightweight materials and components	●	●	●	●
Connections	Make inseparable subassemblies from the same material	●	●	·	·
	Provide realistic tolerances for assembly and disassembly	·	·	●	●
	Use a minimum number of connectors	·	•	●	●
	Use a minimum number of different types of connectors	·	•	●	●
	Design joints and components to withstand repeated use	·	·	●	●
	Avoid chemical connections	·	●	●	●
	Provide access to all parts and connection points	•	•	●	●
Handling	Design to use common tools and equipment	·	•	●	●
	Make components sized to suit the means of handling	·	•	●	●
	Provide and locate means of handling	·	·	●	●
	Allow for parallel disassembly	•	•	●	•
Design	Use an open building system	·	·	●	•
	Use modular design	·	·	●	•
	Separate the structure from the cladding for parallel disassembly	·	·	●	•
	Use a standard structural grid	·	·	·	●
	Use prefabrication and mass production	·	·	●	●
Logistics	Identify points of disassembly	·	•	●	●
	Provide spare parts and on-site storage for them	·	·	·	●
	Retain all information of the building components and materials	·	·	•	●
	Provide identification of material types	●	●	·	·
	Minimize the number of different types of components	·	•	●	●
	Provide identification of component type	·	•	●	•

Transportability

To guarantee good re-use of the structure, it must be transportable. The common modes of transport for such freight are rail, road, or boat. The requirements on the maximum dimensions are country specific. For the scope of this research, the countries of the European Union plus Switzerland are considered. In this region, the three transport modes are compatible with the use of a standard 40ft container. Therefore, using such standardized dimensions ensures easy transfer between the different transport modes, as well as guaranteeing the possibility for international shipment. The inner dimensions of a container are listed below:

Table 2 Container dimensions

	Length (m)	Width (m)	Height (m)	Weight (tons)
40 ft container	12.04	2.35	2.39	30

Re-use of timber

Because timber is the material chosen for this study, its particular requirements will be given. First, it should be protected from decaying agents such as excessive humidity or fungi. Moreover, Webster & Costello (2005) recommend using screws or bolts instead of nails. Indeed, nails are difficult to remove from the timber and might damage the machinery used in recycling. Additionally, glue is to be avoided when connecting members due to its irreversibility. Furthermore, fragile members such as dimension lumber or I-joist are not recommended since they might get damaged during transport or deconstruction. Finally, the safety required when working on roofs might slow the deconstruction process. Therefore, it is recommended to use roof panels that can be dismantled on the ground.

Results

After looking at the impediments to the re-use of existing structures, a set of design guidelines was developed to ensure the re-usability of new constructions. Design for disassembly, in particular, is linked with specific constraints. While it might not be possible to satisfy all of them simultaneously, they provide useful suggestions to ensure demountability.

The set of principles developed in this chapter should be kept in mind while designing. However, a simpler model englobing these rules might be preferable to compare design alternatives. Based on the model proposed in (Durmisevic et al., 2017), two criteria are selected to analyze the potential of structures.

Exchangeability evaluates the possibilities to demount a component or a complete system. On the component scale, this factor depends notably on the handling of the component, and the complexity of the connections. Applied to a bigger scale, it is used to evaluate the ease of mounting and demounting of a structural system. It depends, for example, on the self-stability of the structure.

The second indicator is the re-use potential. The state of the element after demounting, the possibilities to use it in other configurations are examples of factors enhancing this potential. Moreover, looking at how much a structural system can be adapted to fit other demands is part of this criteria. For example, a curved beam will have a smaller re-use potential than a simple beam that can be re-used in multiple circumstances.

Figure 21 House made with reclaimed timber in chile

CHAPTER III: Case studies

To illustrate some of the concepts developed in the literature review, three case studies will be performed. The first concerns the BRIC project in Brussels aiming for circularity. The second is the Brummel city hall where a design for re-use philosophy was applied. Finally, the third concerns a temporary structure to host spectators of a music festival. The first two are based on existing literature while the third is derived from an interview with the project manager.

BRIC

Figure 22 BRIC 1

The BRIC projects stand for Build Reversible In Conception. It is part of BAMB (Building As Material Bank), a project to enhance circularity in the built environment which is funded by the EU Horizon 2020 research (Capelle et al., 2020). The BRIC is an academic project by the interdisciplinary Brussels training center. The goal is to (de)construct, successively, three-building between 2017 and 2020. The project's particularity is that each building uses the building materials from its predecessors. Moreover, each building will differ in function and floor space, changing from an office to an acoustic laboratory via a shop (BAMB, n.d.). Ultimately, the objective is to test the feasibility of circularity in the building industry and to minimize waste production.

Multiple strategies were applied to enhance re-use possibilities. First, a systematic design grid was used. Coupled with standardized dimensions, it ensures that the elements can adapt to the changes in building configuration. Additionally, to minimize the construction and demounting time, modular prefabricated elements are used notably in the façade. Moreover, as part of the BAMB project, the material passport system was used to identify every element and simplify the sorting process. This includes a logistic system, an inventory of the materials and components used and a link between the elements and their digital representation. Furthermore, timber is used because of its re-use and cascading opportunities. Moreover, wood plays a role in the building physics performance of the design. Indeed, it has good insulating properties and the capacity to regulate humidity. Finally, the use of bolted metals plates, screws, and interlocking connections ensures the demountability of the design.

In the latest report, the first structure has been demounted and built again for BRIC 2. Capelle et al. (2020) provided a detailed report of the design of BRIC 1, the aspects related to structural re-use will be exposed hereafter. BRIC 1 is a small office building with a mezzanine and a slanted roof. The roof is the only metallic element and is made from reclaimed undulated steel sheets. Even if it originally has a substantial embodied energy, such standardized material has high re-use possibilities. The roof is supported by hardwood beams. It is noted that GLT was not selected due to fewer recycling opportunities. The beams are supported by columns made from the assembly of four 6x6cm timber profiles connected every 1.2 meters (Figure 23, right). This choice was motivated by the will for a standardized, symmetrical column that could be re-used in any configuration. Furthermore, the space left between the columns allows for an easy beam-column interlocking connection. While it proved efficient for fast mounting and demounting, the columns were relatively fragile and deformed during the lifespan of the first building. A third of the timber for the floor was reclaimed. In practice, it required in-situ adaptability of the connection. The flooring system is a bi-directional timber frame (Figure 23, left). The connections used for the floor are traditional carpentry connections such as mortise and tenon joints or cross-lap joints. Additionally, the façade walls were composed of prefabricated insulating cassettes with I-joist beams and mineral wood encased by OSB panels made from construction waste (Figure 23, center).

Figure 23 BRIC 1 construction

During disassembly and construction of the new building, 10% of the structural elements were lost and brought to recycling (Capelle et al., 2020). This is mainly due to the slanted roof in BRIC 1 which required non-standardized parts. Additionally, it was decided to reduce the spacing of the diaphragms for the columns to control their deformations as well as making them more robust. Another remark concerns the assessment of the state of the prefabricated insulating cassettes which was difficult since the I-joists are hidden inside the component.

This project proved that circularity is a realistic goal in the construction industry. Indeed, only 3.4m^3 of waste were produced (EFP, 2019). Amongst the techniques applied for re-use, standardization was identified as particularly important (Goens, 2017). To assess the benefits of re-use, an LCA was performed. Comparing constructing the three buildings from scratch with re-using the same structure showed an important reduction in the CO_2 equivalent emissions related to the production, construction and end-of-life stages (Figure 24).

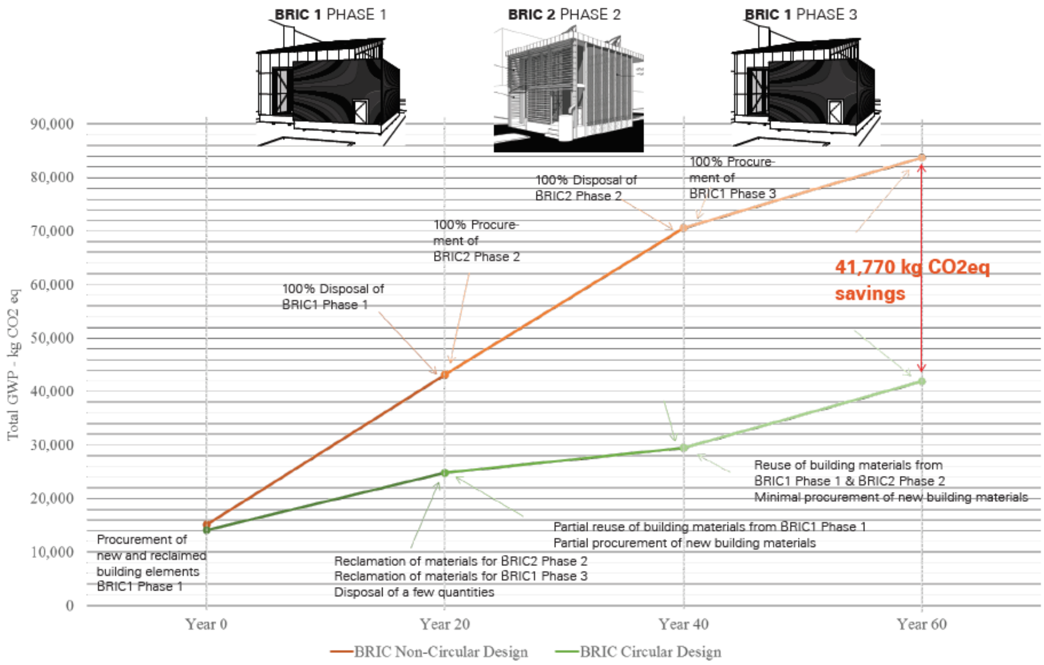


Figure 24 Comparison of re-use vs traditional (Capelle et al., 2020)

Brummen city hall

Figure 25 Brummen city hall

Following the grouping of several municipalities, the town of Brummen in the eastern Netherlands needed new administrative facilities. Unsure of the long-term use of the construction, the municipality called for innovative solutions for a reduced service life of 20 years. This resulted in a design optimized for disassembly and re-use. The construction, made mainly out of timber and glass, is an extension of an historic structure from 1890. According to the designers, 90% of the materials are ready for re-use once the building reaches the end of its service life (CE100, 2016). Completed in 2013, the building received the Dutch award for sustainable architecture.

To maximize re-use possibilities, a combination of strategies was applied. First, the design team decided to use high-quality materials to extend their lifetime (Summer, 2016). Therefore, they used CLT which is an engineered wood product.

Figure 26 Examples of connections (Summer, 2016)

The connections are entirely mechanical and thus easy to dismantle. Indeed, most structural assemblies are made with the help of steel connectors and are easily accessible.

Figure 27 Brummen city hall floorplans

Moreover, a modular, highly regular column grid was chosen (Figure 27). This allows for adaptable the floor plan with multiple variations of partitioning possible as well as maximizing re-use by having uniform components. A side effect of the design for re-use is that the uniformity of the components and their ease of assembly sped up the construction process (CE100, 2016).

Another factor for re-use is the level of collaboration between the stakeholders. Indeed, during the project, architect, client, contractor and circularity specialist worked closely together to achieve the sustainability goals. For example, the timber beams are slightly bigger than necessary following a suggestion from the contractor. Indeed, this augmented size can easily be sold afterward due to its standard dimensions (CIOB, 2014).

Similarly to the BRIC project, a material passport was used to make an inventory of all materials used in the construction. While it can be challenging to motivate the parties involved to invest time in the cataloging of the products, come deconstruction time, it will be an invaluable source of information. This is part of the strategy devised to increase circularity. Asked in an interview about the need for a material passport, the founder of the circularity consulting company gave the example of gold in electrical components and said "*Waste is made up of materials with no identity. To prevent materials losing their identity and becoming waste they need a passport, which Material passports will allow us to know exactly where all the materials are located, including gold, and keep them in circulation.*" (Totaro, 2017, p.18). The end-goal is to have a global inventory of the materials in circulation to promote the exchange of resources and to sensitize owners on the value of used materials. An interesting idea of the circularity focused company is that a change in business model is required to prevent resource depletion. Indeed, a shift from an ownership to a service perspective should give responsibility to the producers and incentivize circularity. However, this is not possible without incentives and changes in regulation from the government. In the Brummel city hall, for example, they wanted to use a concept developed with Philipps where the user pays for light quality and not light equipment. Dutch regulations for public procurement, however, were not prepared for this type of contract (CE100, 2016).

Terrace for the Paleo festival

Every year in July, 280’000 people come to the small town of Nyon for one week of music. Every year, the entire infrastructure is mounted and demounted. Amongst these structures, overlooking the mainstage is a three-floor terrace built entirely out of timber. Initially planned for 8 years, the structure has been constructed and deconstructed every year since 2009. For this reason, it felt interesting to go and interview JPF Ducret, the company responsible project design and construction. Moreover, given the major position of this firm in the timber industry of the region, it also was an opportunity to ask about the state of the timber business in Switzerland. After a brief description of the structure, the main outlines of the conversations will be given. The transcript of the interview is accessible in Annex A.

Figure 28 Paleo's terrace

The structure consists of 9 GLT frames supporting GLT beams and OSB floors. There are bracings in the flooring to guarantee longitudinal stability while the frames take care of the lateral stability. Additionally, the roof and outside façades are composed of a fabric structure stretched between the frames.

The first set of questions concerned the state of the wood industry in Switzerland. The latter has been developing a lot in recent years, thanks to technological innovations and the increasing popularity of sustainable construction. To enhance the sustainability of their construction, the vast majority of the timber used by the company comes from Swiss forests certified by FSC. However, the recycling of wood by-products is still absent from the Swiss market with the major part of the by-products being used for electricity generation. Considering that, 20 years ago, most wood by-products in Switzerland were either landfilled or cremated without energy recuperation, this already represents a shift in mentality. Concerning the drying processes, most of the timber used must be kiln-dried for dimensional stability. This is done by burning production wastes. Additionally, while the application of roundwood was identified in the literature review as a way to reduce the impact of processes, its use is rare because of the additional constraints associated with it.

The re-use of structures is very marginal in Switzerland. With most applications in the timber industry being for aesthetical reasons. According to the interlocutor, the principal obstacle lies in the design briefs. Indeed, constructions are still tuned to the user’s need and it is thus difficult to use components from one building to another.

Moreover, the costs associated with the demounting, treating and adaptation of elements make re-use less competitive compared with new structures. However, the company recognizes the interest and the feasibility of highly modular structures with elements that could be combined to create different buildings. What is lacking, in their opinion, is a demand for such construction.

Concerning Paleo's terrace, most questions related to the demountability of the structure. The design was made so that the structure can be erected in two weeks and demounted in one by a team of six people. The connections were the main focus to allow for fast and easy assembly. The main structural elements are connected using metal plates and bolts. The plates are linked to the timber by a patented method where steel rods are glued inside holes drilled in the timber element. The secondary beams, on the other hand, are connected with more traditional means of assembly with an indentation where vertical forces are transmitted. The OSB flooring, for its part, is connected to the beams with dowels to ensure the diaphragm effect and stabilize the building.

Prefabrication plays an important part in the design. Indeed, it allows for the use of the glued endplates which would be difficult otherwise. Additionally, working in the factory decreases time on the construction site while increasing the precision of the elements. Standardization is a key element in prefabrication and plays an important part in the simplification of the (de)construction processes. There is, however, a balance to find between prefabrication and the size of the elements. In this case, each floor of the frames is prefabricated, and they are then linked together on site. In other scenarios with a more traditional construction site, the company has produced beams close to 40 meters long. Here, the transport is ensured by 20 truck trips. It can be noted that to further reduce the environmental impact of the festival, Paleo purchased storage facilities for the structure close to the festival's site. Finally, marking each element and an integrated stand on the first frame to be mounted to guarantee self-stability are additional measures used to ease installation.

The evolution of the structure with the (de)mounting cycles is of interest. In the ten editions, it was used, only the OSB floorings needed work. Indeed, because of the many people walking, often with muddy shoes, they deformed and degraded. The rest, especially the main structure, shows no sign of use.

PART III

APPLICATION AND ANALYSIS

Figure 29 Timber construction

In the previous part, the foundations for a re-usable, sustainable construction have been laid. This part, on the other hand, aims at applying the lessons learned to the problematic at hand. Indeed, its goal is to research, expose and compare the different design possibilities. It focuses on the different design choices which need to be made before going in details into the case study. For this reason, it is centered on timber construction and the review of existing products, systems, and technologies. While it is still applicable to the timber industry in general, this part focuses on alternatives applicable to the construction of a major sporting event facility to be re-used in other building typologies.

It is separated into four chapters. After a short introduction on the requirements of the selected case study, the joints techniques, the different timber products available, and the various structural systems to choose from will be assessed. The assessment is done by first cataloguing the available alternatives before rating them according to the precepts developed in the previous part.

CHAPTER I: Case study requirements

Origin structure

For multiple reasons explained in CHAPTER III: Problem Context, the Olympics have been identified as a context favourable to innovations and are therefore chosen for this case study. A review of the Olympic arenas most prone to waste generation was conducted and is visible in ANNEX B: Olympic venues. However, additional factors come into play in the selection of the case study. Notably, it was decided to focus on the roof structure and its supports rather than the stands. This was decided in light of the major implementation of re-usable steel scaffolding structures in temporary stands construction. Moreover, due to its lightweight, timber is ideal for roof structures.

Certain venues, such as the speed skating arena, have such specific requirements, notably in the length of the required span, that they were discarded. Indeed, designing for such extraordinary structures will reduce the applicability of this case study. Moreover, large spans required special solutions which are less appropriate to re-use.

Since, most indoor Olympics sports have similar requirements regarding the dimensions of the building, it was decided to design an arena that could host multiple indoor sports. Amongst these disciplines, badminton is the one benefitting the most from re-use, according to ANNEX B: Olympic venues, and the case study will, therefore, focus on this arena.

The requirements for such construction are a minimum of 6000 seats (IOC, 2005) a free height of more than 12 meters, and a playable zone of 30x48m (BWF, n.d.). There is a plethora of additional constraints regarding VIP zones, media areas, etc. which are outside the scope of this study.

Figure 30 Badminton at the 2012 London Olympics

Therefore, this part of the research will concentrate on systems applicable to structures of roughly 50 meters in span.

Legacy structure

As mentioned in Part II, sustainability has multiple aspects. While designing re-usable structures focuses on the biophysical and technical parts of sustainability, its other aspects should not be forgotten. One of them, social sustainability, must be considered in the choice of the legacy structure. Indeed, investments made on the MSE structures must benefit the host population once the event is over. Therefore, the legacy structure should have a social aspect in it. Schools, municipal buildings, or social housing are good example of such construction.

Proximity augments the chances of re-use and the applicability of the developed system. Consequently, the chosen legacy structure should answer to the needs of the local population.

It can be noted that the goal of this project is to develop a highly versatile structural solution and that the selected pre- and post-event usages are here to give context to the study but are not set in stone.

Three constructions were taken as reference for the legacy scenario. In this stage of the project, it serves mainly as an indication for the spans. The Nelson Mandela highschool (Divisare, 2015) in France serves as a school example, while Bunq (Divisare, 2019) and Frauenfeld's new governmental building (Divisare, 2017) exemplify residential and office use respectively. From these projects, it transpired that for residential use, a column grid of around 3x4 meters is well suited while 4x6 fits both scholar and office requirements. Because they require similar spans and have similar loads residential and office uses are grouped in this analysis.

Figure 31 Left: Frauenfeld's governmental building; Top: Bunq; Bottom Nelson Mandela high school

CHAPTER II: Joints

In this second chapter of part III, joints are reviewed. Indeed, multiple way of connecting timber elements are commonly used. The goal of this part is to assess which one is the most suited when designing for re-use.

The first paragraph shortly reviews the different challenges and sensitive areas of timber connections. Then, four types of joints are exposed and assessed. Finally, a summary of the results is made, and conclusions are drawn.

Challenges

In the previous part, guidelines regarding demountability and sustainability were devised. This includes measures such as: providing realistic tolerances for assembly; designing robust joints resisting multiple assembly-disassembly-transport cycles; using connections that require common tools etc.

However, sensitive design points independent of re-use strategies are of importance when designing timber joints. They will be shortly exposed:

The first, and maybe the most important challenge is dimensional stability. Indeed, the humidity of the timber element will change during its service life. Consequently, the timber element will swell or shrink accordingly. It is not a problem as long as these movements are allowed, or if the wood humidity is kept under control. If this is not the case, substantial forces can be induced in the structure. Additionally, the anisotropy of timber requires special care when assembling two elements. Indeed, tension perpendicular to the grain can arise when assembling a beam and a post where the deformation of one will be bigger than the other due to the different grain angles.

Tension perpendicular to the grain is the second challenge of timber assembly. Indeed, wood is very weak for this kind of solicitations and they should be avoided. In addition to shrinkage, perpendicular tension can come from eccentricity or design choices such as hanging connections.

Costs are always an important part of any project and timber construction is no different. The on-site process of connecting components is responsible for a significant part of the costs (Herzog & Natterer, 2004). Indeed, joints influence the costs directly with the number of connectors and the complexity of installation. Moreover, the efficiency of the connection has an indirect impact on timber consumption.

Finally, timber can exhibit brittle behavior which is unwanted in construction. Indeed, civil engineers want their structure to deform before failing so to warn the occupants of the danger. The ductility of a timber structure can be obtained by careful design of the joints. For example, by using materials such as steel, which present inherently ductile failure modes, for connectors.

Assessment criterion

The alternatives will be compared based on the research done in part II and the challenges exposed above. The comparison can be sorted into four categories:

Sustainability

As mentioned earlier, ancillary's influence on the environmental impact of the structure is relatively low. The embodied energy will thus have a minor importance.
On the other hand, joints do influence recyclability significantly and will be judged on that point.

Exchangeability

In the context of joints, exchangeability will assess the ease of (de)mounting the connections. This englobes aspects such as tolerances, amount of on-site work and complexity of the connection.

Re-Use Potential

Here re-use potential has mainly two components.
First, the durability of the connectors and the elements they connect after multiple usages. The resistance to transport and demounting is notably of interest.
Second is the ability of the connection to sustain different types of solicitations. This will directly influence the modularity of the element.

Efficiency

This concerns the efficiency of force transmission.
Eccentricity, ductility, and perpendicular tension are factors that will influence the ratio between the joint resistance and the cross-section capacity.
Additionally, rigidity and potential slip of the connection is of interest for SLS considerations

Carpentry joints

Carpentry joints are the historical way to connect timber elements. They transfer forces exclusively via contact and friction. Although nails or screws are often added for extra security, they do not require extra material. This is made possible by making cuts in the cross-sections so that elements interlock. Such details require high levels of precision and craftsmanship to ensure that the elements fit properly to avoid loose connections. For this reason, the use of carpentry joints rarified with the increasing affordability of steel connectors. However, in the last decades, advances in cutting technology such as CNC-machines made carpentry connections more feasible and accessible (Angsts, 2008).

Carpentry joints are also referred to as traditional joints. Indeed, they have been developed over thousands of years and are therefore different depending on who makes them. In Europe, for example, mortise tenon joints are the most common joint (Porter, 2002). Of interest is also the Japanese carpentry which relies on high precision for its connections.

Figure 32 Mortise tenon assembly

Because of their long history as well as their complex flow of forces, traditional connections are rarely calculated by engineers but rather estimated by experienced carpenters. This means that optimizing them can prove difficult.

The interlocking property of carpentry joints makes them good candidates for demountable construction. Farmers in the middle ages, for instance, often used such joints to move their barns when displacing the livestock (Erman, 2002). However, the required precision, and the lack of geometric tolerances, is a hindrance to such joints in large scale project. Moreover, small elements such as the tenons can deform with time which makes replacing a single piece difficult because of a lack of interchangeability.

Finally, the cuts made to connect the pieces weaken the structure. This means that such joints can only transmit low forces (Herzog & Natterer, 2004). This is worsened by the eccentricities often present in such joints. On the other hand, the absence of metallic pieces facilitates recycling and reduces the need for non-renewable resources.

Sustainability

The absence of metallic pieces reduces embodied energy.
Single material improves recyclability.

Exchangeability

In theory entirely demountable.
Small tolerances.
Although no connector needed, relatively complex connection.

Re-Use Potential

May have fragile components.
May deform during use making it difficult to re-use.
Difficult to adapt to other connections, little modularity.

Efficiency

Difficult to optimize.
Eccentricities and stress concentration reduce the efficiency of the force flow.
Important cuts reduce cross section resistance.
Depending on the precision of the assembly, can have significant slip.

Dowels

Dowels are elements which transfer force laterally thanks to the embedment strength of the timber. They can link timber pieces directly together, or with the help of a steel plate. They have a more controllable flow of forces and many studies have been done on their capacity. It is thus possible to calculate and optimize their number and position. Additionally, by carefully choosing the dowel diameters it is possible to obtain a ductile behavior of the connection. Moreover, the geometry of the joint is easy to control, and eccentricities can be avoided in design. Finally, little reduction of the cross-section is necessary to account for the holes. All this means that the use of dowels represents a significant increase in bearing capacity compared with traditional joints (Angsts, 2008).

Figure 33 Dowelled connection with slotted-in plate

Additionally, it is possible to replace some of the dowels by fitted bolts to hold the assembly together. Even though such connectors have a reduced embedment strength due to the thread, they partly compensate it by the rope effect induced by the washers.

Dowels require little preparation of the timber elements. Indeed, only the predrilling of the holes is needed, and it can be done in a factory. On-site, the installation is relatively easy and does not require complex machinery. Tolerances can be accounted for in design, but this often comes with an increased slip from the connection. When planning for the tolerances and the load transfer, it is important to consider the deformations due to humidity. Otherwise, cracking can occur due to perpendicular tension.

Among the disadvantages of such assemblies is the space it can take. Indeed, a minimum spacing between each hole is required to avoid sudden group failure. When transferring important forces, many dowels are required which thus can take a lot of space. Additionally, assemblies can become relatively thick, if no steel plate is used to link the timber elements. Indeed, moisage are often used to avoid eccentricities and ease assembly. On top of the extra width required, having two members in parallel is not material efficient in a structural point of view.

Dowelled connections have good re-use potential. Indeed, the dowels are easy to replace if they are damaged. Moreover, the same connection can be used to take forces from different directions increasing the modularity of the pieces. Dowels are, in general, demountable although the holes have chances of deforming during the service life which could reduce the exchangeability of pieces.

The environmental impact of dowelled connections depends on the materials used. Using steel plates requires non-renewable resources. On the other hand, it might allow for material savings. The dowels in themselves are usually in steel. It can be noted that research for alternative materials such as compressed wood (Jung, Kitamori, & Komatsu, 2008) is being conducted and could be of interest. It is thus possible, in theory, to have a timber only connection which would facilitate the recycling process. However, thanks to the demountability of the connection, it is relatively easy to separate the materials if steel is used.

Sustainability

Possibility to have timber only connection but less efficient.
Overall good recyclability

Exchangeability

Tolerances can be incorporated in the design,
Simple connections, easy to mount on-site.
Demounting can sometimes be problematic if holes changed geometry.

Re-Use Potential

Easy to replace damaged components.
Connections can be designed modular although it will take more space.

Efficiency

Better than traditional connections.
Can transfer relatively heavy loads
Can take much space and/or be material inefficient.
Can have slip and lower rigidity.

Screws

The use of screws has spread with the development of self-tapping connectors. Indeed, until a certain diameter, it eliminates the need for predrilling. Moreover, their installation is very simple and can be done with hand-held devices. Additionally, the on-site nature of the installation means that there is no problem with tolerances. The consequence of these advantages is that screws are very economical and thus widely used.

Screws are commonly used for connecting timber to steel elements but connecting timber to timber or using them as reinforcements is also possible. These connections rely mostly on the considerable withdrawal strength provided by the threads. However, they can also act as dowels and use the embedment strength of the timber to restrain lateral loads. The thread reduces their resistance compared to traditional dowels, but the rope effect provided by the withdrawal strength mitigates these differences (Sandhaas & Blass, 2017). Because of the biaxial strength of such joints and to lengthen the penetration length, screws are often used inclined at 45 degrees.

The strong axial strength implies high rigidity. This means that such connections will perform relatively well in SLS. Moreover, thanks to the properties of steel, such connections exhibit sufficient ductility.

At the end of the service life, screws can be demounted. This is great for recycling and the demounting of the structure. However, it is difficult to re-use screwed assemblies because it is impossible to use the same diameter of screws in the same holes.

Sustainability

The use of screws doesn't hinder the recycling of timber elements since they are relatively easily removed.

Exchangeability

Screws are easy to mount on-site. Tolerances are not a problem or are related to the use of metallic elements.
Demounting is relatively easy.

Re-Use Potential

The re-use potential of screwed assemblies is low because of the impossibility to put them in the same position

Efficiency

Screws provide ductile and strong assembly at a low cost.
Screwed joints can have good SLS performances.

Glued in connectors

Glued-in joints are hybrid connections where elements are glued in the timber section, usually in GLT or plywood. Such practice results in high performance, concealed joints. A common example is the gluing of steel rods in timber cross-sections to produce trusses. Similarly, it is possible to glue in steel plates, perforated or not. Instead of gluing both ends of the rods or plates, an alternative option is to weld them to a steel connector. The timber element then has connections similar to a steel structure that can be bolted. This allows for the creation of custom assembly which can be demountable and highly modular. It also gives the possibility for complex 3D assemblies.

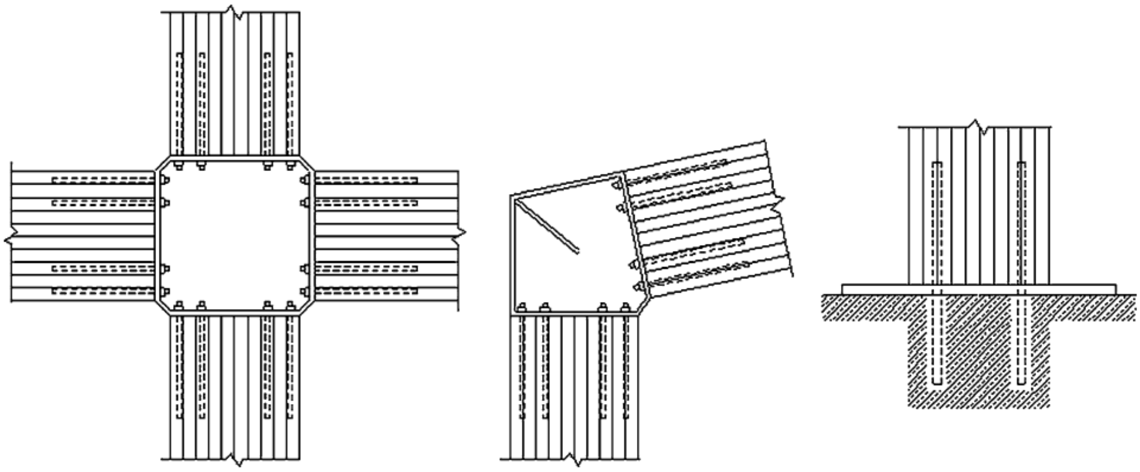


Figure 34 Examples of application of glued-in rods (Tlustochowicz, Serrano, & Steiger, 2011)

Glued-in assemblies display great performances in SLS. Indeed, they have a minimal slip and high stiffness. The downside is that stress concentration can occur which makes ductility difficult to obtain. One solution is to use perforates plates. Indeed, the perforation reduces the strength of the steel plate and causes it enter plasticity under high loads. Moreover, the perforation creates a kind of adhesive dowels (Vallée, Tannert, & Fecht, 2017) which helps to spread the load and reduces the need for adherence from the steel plate.

Using glued-in connections allows connecting timber along its fiber angle. This means that the assembly has a strong resistance and that the glued-in connectors usually necessitate smaller cross-section compared to alternative methods. To transfer the important forces from steel to timber, it is important to have a good adherence between the glue and the wood. This requires clean and freshly cut faces and, consequently, the gluing should be done in a factory.

The durability of the glue is still a subject of research. This is one of the factors that impede the implementation of glued-in connections in the Eurocodes. However, many structures have now been built using such joints. For example, the timber wind turbine in Hannover uses perforated glued-in steel plates, while the terrace of the Paleo from Part II uses glued-in steel rods with metal connectors welded to it.

The environmental performance of such connections is their weak point. Indeed, while research is being conducted to replace synthetic glue with bio-based materials and steel rods by FRP, no solutions are currently available to reduce the embodied energy of such connections. Moreover, recycling is difficult because it requires extra processing to cut the glued parts from the beams. On the other hand, the high efficiency of the connection requires less timber and it is possible to couple them with durable demountable connections.

Sustainability

Difficult to recycle due to permanent connection with other materials.
High embodied energy.
Good performance means less timber necessary.

Exchangeability

Possibility to have steel bolted steel connections. Thus, possible to have easily (de)mountable connections.

Re-Use Potential

With steel connections, possibility to have a highly modular, durable connection greatly enhancing the re-use potential.

Efficiency

Very strong and stiff connections.
Transfer of forces parallel to the grain is a plus.

Additional remarks

Steel connectors

Steel connectors are put here because they are linked to other means of jointing mentioned earlier. Indeed, it is possible to use steel plates, cold-formed sections, or welded elements to facilitate assembly. In dowelled connections, plates can be inserted in the cross-section to avoid having thick moisages. It is also possible to use angles or hangers that are nailed or screwed to the timber elements to provide fast and easy on-site assembly. Special attention must be paid for this type of assembly regarding possible eccentricities and perpendicular tension.

In addition to the problematics of timber connection, using steel requires careful thinking about fire safety and corrosion. It is possible to protect the metallic elements by integrating them in the timber or by adding coatings and paintings.

Finally, steel has a high embodied energy and consumes non-renewable resources. However, the benefits in ease of installation, cost, and durability sometimes outweigh this price. An additional solution to reduce the environmental impact is to use recycled steel.

Split rings and shear plate connectors

Split rings are treated here because they are closely linked with dowel-type connections. Usually made from steel, although solid hardwood is also possible, they are used to increase the shear resistance of a connection. To achieve this, they are fitted into pre-milled depressions in the timber or, in the case of toothed rings, pressed in the wood. The pre-milled connections are demountable and re-useable but slightly reduce the timber cross-section.

Other connections

Other connections such as glue lines, nails or punched metal plates are available and present certain advantages. However, due to their difficulty to be demounted, they are not presented here.

Results

To compare the different connections, their performance in the four categories is reported in the table below. "+++" denotes a great performance while "- - -" relates to poor performance.

Table 3 Summary of joints comparison

	Traditional joints	Dowelled joints	Screwed joints	Glued-in joints
Sustainability	+ + +	+ +	+ +	-
Exchangeability	+	+ +	+ + +	+ + +
Re-use potential	-	+ +	- -	+ + +
Efficiency	- - -	+ +	+	+ + +

The difficulty to re-use screwed joints hinders its applicability. Carpentry joints, although sustainable, lack efficiency and adaptability. However, both connections could be used to connect secondary elements but their applicability to the main structure is minimal. Dowelled joints and glued-in connections are both feasible. Glued-in connections have great performances and a wide range of re-use possibility but perform relatively poorly in sustainability due to the decreased recyclability. Dowelled joints, on the other hand, have good performances in all categories but are less efficient and present less modularity than the glued-in connections. Additionally, it is preferable to use them in combination with metal plates for a more efficient use of material and for a more compact assembly.

Dowelled and glued-in connections are both deemed feasible for re-usable structures. However, given the very high forces related to this project, as well as its demand for a high modularity, glued-in connections are preferred.

CHAPTER III: Timber Products

Timber comes in many forms with different degrees of processing and, consequently, different (dis)advantages. In this chapter, common products are exposed and assessed regarding the precepts developed in the previous chapters. This includes, for example, using recycled and recyclable materials; choosing a lightweight product with dimensional stability to facilitate installation; reducing embodied energy trough local sourcing, cutting wastes reduction and drying demand.

Assessment criterion

The evaluation of timber products uses the same criterion as the chapter on joints. However, their application is slightly different in this section. For this reason, they are shortly explained hereafter.

Sustainability

The major indicator of sustainability here is the embodied energy of materials.
Additionally, using renewable resources is seen as preferable as well as using them efficiently.

Re-Use Potential

Re-use potential is mainly influenced by the capacity of the element to have different function.
Durability also plays a factor in re-use potential.
Finally, having elements that come standardized is a plus to ease procurement and distribution if needed.

Exchangeability

Exchangeability, in this context, is closely related to dimensional stability and the ease of prefabrication.
Additionally, the robustness of the elements during (de)mounting and transport plays a role.

Efficiency

Efficiency evaluates how resistant the product is. Indeed, weight to strength ratio is important for reducing the required material quantity and to ease (de)mounting.
Similarly, the possibility to optimize material use or shape is a plus.

Round wood

Round wood is the simplest form process-wise. Indeed, it is made directly from trunks with little modifications. These include debarking, minimal machining and grading. Additionally, round wood can be air or kiln dried. In such cases, incisions should be made to avoid cracking due to timber’s anisotropic shrinkage.

Round wood, because of the low processing involved, has very good financial and ecological performances (Puettmann & Wilson, 2014). For instance, with air drying or no drying at all, substantial savings can be made. Humid wood, however, is heavier which can augment transport costs. Additionally, it can be difficult to incorporate the geometric tolerances in the design.

Because round wood is not sawn, the original course of fibers is kept intact which results in up to 20% increase in strength compared with sawn wood (Angsts, 2008). However, no sawing or jointing means that the dimensions are restricted to those of the tree. Consequently, it is difficult to span more than 12 meters with a roundwood beam (Herzog & Natterer, 2004). Moreover, it can be difficult to make connections with such material.

Figure 35 Round wood trusses

Finally, the circular shape of the cross-section reduces its adaptability, use for floorings, for instance, requires extra elements. This means that round wood is mainly used for columns and struts. According to the interview conducted in CHAPTER III: Case studies, roundwood is used in Switzerland only for aesthetic reasons and has, therefore, a relatively small market there.

Sustainability

Low processing makes it very good in terms of embodied energy.

Exchangeability

Low precision and dimensional stability can hinder installation.
Can be difficult to connect.
Robust elements.

Re-Use Potential

Easy to impregnate for good durability.
The shape makes it difficult to re-use as beams.
Lack of market.

Efficiency

More resistant than sawn wood because it keeps the original structure of the tree.
Shape is not optimal for bending.

Glulam

Glulam or glue-laminated timber (GLT) is made by laminating sawn wood pieces using glue and finger jointing. Contrary to cross-laminated timber (CLT), the pieces are aligned according to their grain direction. For the gluing to perform well, only dried timber (less than 15% humidity) is used (Angsts, 2008). Additionally, lamellas should have similar humidity during manufacture to avoid non-uniform shrinkage.

The kiln drying required to achieve low levels of humidity in the lamellas implies greater energy consumption than round or sawn wood. In addition, the production of the glue has adverse environmental impacts. However, these negative points are partly balanced using timber by-products as an energy source for drying. Moreover, although indirectly, the more efficient use of timber, as well as the good structural performances of GLT, improves the environmental dimension of this product.

Timber is indeed more efficiently utilized in GLT because smaller pieces can be used, thus minimizing wastes. Additionally, it is possible to shape the cross-section to suit structural or architectural needs resulting in greater material utilization. Having an arched roof, varying a beam depth along its span, or using cheaper, lower quality wood in the center of a beam cross-section are all possible in GLT.

The highly industrialized production process also has advantages. First, because smaller elements are joint together, there is less variability in cross-sectional resistance. Therefore, a GLT product has significantly better structural performances than its sawn timber equivalent. Moreover, the extensive drying process means that elements are very stable dimensionally.

Figure 36 Glulam structure

Additionally, by drying small laminas separately, less drying defects are present in GLT. Moreover, prefabrication is enhanced by the high precision that results from drying and industrialization. Finally, the low humidity content makes GLT a very durable material

All this means that, although it is mostly used as beams for large spans structures, GLT is a very versatile product that can be applied to beams, columns, struts, etc.

Sustainability

Timber needs to be dried which requires energy although it can come from by-products.
Glue does not come from natural resources.
More efficient use of timber.

Re-Use Potential

Versatile product that can be used as beams, columns, struts.
Possibility to use standardized dimensions to maximize re-usability.
Good durability.

Exchangeability

Widely spread technology, easy to find a replacement.
Possible to obtain high precision which helps prefabrication and installation.
Robust elements.

Efficiency

High resistance.
Shape and composition can be optimized.

Sawn timber

Sawn timber, or solid timber, is obtained from sawing, or profiling, round wood. It is usually dried to 20% and can be finger-jointed to make longer elements. With drier timber and stricter grading, it is possible to obtain high-quality timber.

Similarly, to round timber, the major problem is the available dimensions. Indeed, big cross-sections or long elements are difficult to obtain because of tree limitations.

Because of the imperfections inherent to wood such as knots or grain deviation, solid timber has a lower resistance than engineered timber products such as GLT or LVL. Moreover, the anisotropy of timber can cause cracking and distortion during shrinkage.

While the challenges of sawn timber might prohibit its use for the main structure, the large availability of such a product and the low processing it requires makes it a good candidate for secondary elements.

Figure 37 Sawn timber assembly

Sustainability

Low processing required; no glue required.

Exchangeability

Can be dried to be stable dimensionally.
Small elements can be fragile.
Easy to procure.

Re-Use Potential

Dimension limitations and a high standardization make it a good candidate for secondary structure.

Efficiency

Relatively low resistance.

LVL

Laminated Veneer Lumber (LVL) originates from a completely different production process than ordinary timber products. Indeed, after debarking, the logs are steamed to make them more ductile. Then, thin sheets (less than 1mm thick), called veneer, are produced trough rotary peeling of the trunks. In this process, the log is rotated and a blade peels off the outer layer. The veneers are then scanned for impurities and sorted by thickness. Once they have been dried, glue is applied, and the layers are brought together by pressing. In the case of LVL, the veneers are laminated in parallel or with a slight grain deviation of up to 25% (Sandhaas & Blass, 2017). This creates products for 1D spanning, whereas other manufacturing processes, such as the one for plywood, obtain good 2D behavior by alternating grain direction perpendicularly.

Thanks to this process, many of timber impurities, such as grain deviation, knots, etc. are controlled or removed. Consequently, LVL can achieve high strength and stiffness compared to alternative timber products. Additionally, length problems are removed with the possibility to produce beams up to 32 meters long without timber jointing. Moreover, the precise process, dimensional stability, and the general lightness of LVL elements facilitate a fast and easy installation. Finally, because of the structure of the peeled timber, it is easily impregnated to increase its durability.

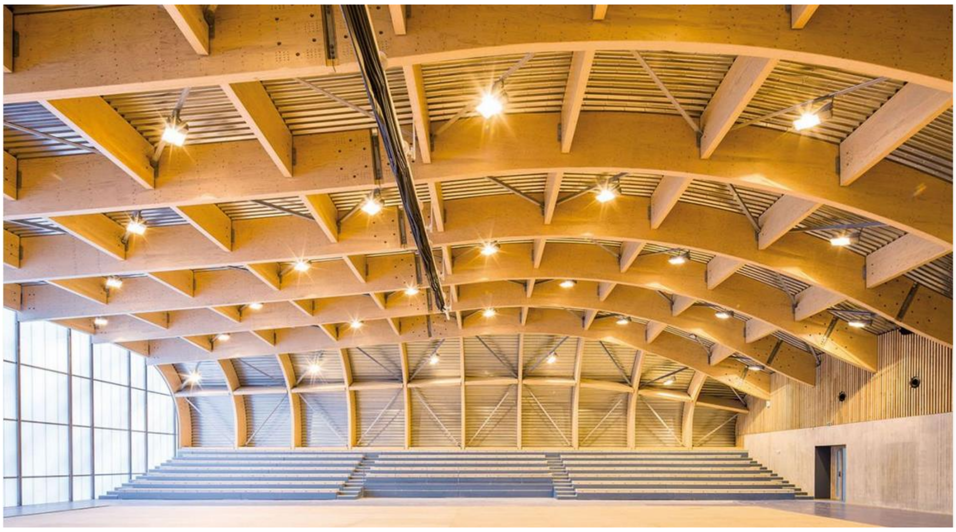


Figure 38 LVL freeform roof

Amongst the disadvantages of LVL and its production technique is the increased embodied energy. Indeed, similarly to GLT, gluing, pressing, and drying are used and recognized as energy intensives. Moreover, while the length of the elements is not a problem, it can be difficult to obtain thick elements. This means that, although LVL columns are possible, it is mainly used in bending. Additionally, the complexity of the production techniques means that few companies produce it. This poses a problem regarding the local sourcing of materials. Finally, the slenderness of LVL elements makes them relatively delicate to handle which could pose a problem in the cycles of demounting-transporting-installing.

Sustainability

The many processes involved, and the use of glue increases the embodied energy.
Very little waste generation.
Difficult to source locally.

Re-Use Potential

Although possible to use as columns, mostly beam-oriented products.
Possible to have high durability with coatings.

Exchangeability

Easy to mount because of lightness, precision, and dimensional stability.
Risks of damages during re-use cycles.
Difficult to procure.

Efficiency

Very high efficiency in bending.

Other products

A plethora of other timber products are commonly available. Worth citing are all board-oriented products such as OSB, plywood etc. Although exploring such possibilities could be interesting, it was decided to focus mainly on 1D elements because of their widespread use in timber structures. It can be noted, however, that board elements will most probably be used as façade, flooring, or roofing making them part of the secondary structure which is outside the focus of this work.

An important omission with growing popularity is cross laminated timber (CLT). Its production process is similar to GLT except for the orientation of the lamellae which are laid in perpendicular layers in CLT.

The decision to ignore CLT is motivated by its inherent board-like qualities. While it can be used in the legacy structure to build walls, slabs and even stability systems, CLT is not adapted for long span roof such as those for aquatic centers or long speed skating tracks. Indeed, GLT is mostly used in such cases because of its applicability to beams or trusses where 3D load transfer are marginals.

Results

To compare the different timber products, their performance in the four categories is reported in the table below. "+++" denotes a great performance while "- - -" relates to poor performance.

Table 4 Summary of timber product comparison

	Round wood	Glulam	Sawn timber	LVL
Sustainability	+ + +	-	+ +	- -
Exchangeability	-	+ + +	+ / -	+ +
Re-use potential	-	+ + +	- -	+ +
Efficiency	+	+ +	- -	+ + +

Sawn timber because of its size limitations will not be used for the main structure, however it can be part of the secondary elements such as joists. Round wood is interesting for its great sustainability performance. However, many parameters such as its shape, availability, and difficulty to connect discard it for this project. LVL and glulam are the most interesting candidates. However, the lack of local sourcing of LVL for the selected area is a determining factor. For this reason, glulam is selected as the material for the main structure. Indeed, its widespread use and production, dimensional stability and good performances makes it ideal. Research is currently conducted to replace the glue and increase the sustainability of GLT. A promising solution is to use dowels made from compressed timber elements to join the laths (Sotayo et al., 2019). While, this technology would be of the greatest interest for increasing the sustainability, the lack of market availability prevents its applicability to this project. However, the design solutions and concepts established would entirely apply to dowelled laminated timber if its development succeeds.

CHAPTER IV: Structural systems

The goal of this chapter is to explore the different structural systems commonly used in timber construction to find the most appropriate for this project. This means focusing on structural systems capable of spanning 50 meters, adapted for re-use, and having components compatible with the inter-modal dimension of this project.

There is a wide range of structural systems available with multiple combinations possible. To gain a comprehensive overview of the available systems, 45 structures with spans longer than 20 meters were reviewed. Given the difficulty to find information consistent across all structures, only the structural system used, and the spans were recorded. This cataloguing has two applications: it lists the possible solutions for long-span roofs while giving an idea of the range of span they can be used for. Indeed, the mere fact that the structure was built gives insights into economic factors, as well as production, transport, and assembly constraints. In addition to the data gathered, TRADA (2007) and Herzog & Natterer (2004) both give similar applicability ranges which can be compared with the one devised. The data collected in this process is given for each structural type and a summary is made in *Results*. A table with every structure and the corresponding sources is visible in ANNEX C: Structural systems.

Assessment criterion

Similarly to the previous chapters, the different structural systems and their (dis)advantages will be compared in the following pages. Most of the comparison is based on criteria and guidelines devised in the previous parts. For example, prefabrication, the possibility of parallel disassembly and the number of connectors all influence demountability. While making a modular design, having a standard grid, or minimizing the number of different components will increase re-use possibilities. An important concept to evaluate re-use is the scenario-buffering process as explained in CHAPTER II: Re-Use which will be used hereafter. On the other hand, the influence of the structural system on sustainability considerations resides mainly in minimizing material use and therefore relates closely to efficiency. Costs are especially important when choosing a structural system. For example, the number of connections or the structural efficiency which influence the manutention costs, and the amount of material used respectively. The four criterions used are summed up below.

Sustainability

Minor influence on sustainability except for material use which is included in efficiency. Therefore, it will not be used as a comparison tool.

Re-Use Potential

Measures how appropriate is the structure for re-use. This includes minimizing the number of different connections and elements. But also, their compatibility with the legacy structure which will be assessed by scenario-buffering

Exchangeability

Exchangeability evaluates how easy it is to mount and demount the structure as a whole. This includes the possibility for parallel disassembly, prefabrication, ease of construction, and standardization.

Efficiency - Cost

Apart from the material efficiency, it can be difficult to assess. However, minimizing the number of connections or maximizing standardization can reduce costs while benefitting exchangeability and re-use. Additionally, the review of existing long-span constructions gives hindsight on costs.

Space frames

Space frames are a sort of 3D truss that is to a slab what a truss is to a beam. Generally built with horizontal members for the chords and incline webs, they are linked by articulations. It is possible to obtain curved shapes by varying element length although this loss of standardization is not adapted to this project. Space frames are usually built up as pyramidal elements, taking advantage of the form stability of triangles. While they are relatively common in steel construction, they are rarely built out of timber. According to Herzog & Natterer (2004), the applicable spans for timber space frames range between 8 and 50 meters which could suit the project.

Space frames consist of axial elements which are usually all the same length and factory-made. It is possible to pre-assemble modular units of the frame to accelerate construction. Because of the axial nature of the loading, steel elements with tubular hollow sections are generally used to increase the buckling resistance.

The form stability of space frames means that the deflections of such structures are often reduced compared to two-dimensional constructions (Trebilock, 2004). Additionally, they can achieve a good weight to span ratio, especially if the ends are continuously supported.

Figure 39 Space truss from case 40

Thanks to the modularity of its components and the simplicity of the connections, a space frame can be rapidly erected. The Arbon Seeparksaal (case: 8), for example, and was built on the ground in two weeks before pushing it into place (Vollichard, 1986). Additionally, because there are no secondary elements, only one type of connection is required. All this means that they can be easily deconstructed and rebuilt elsewhere (Trebilock, 2004).

Re-use of elements in a different structural system might be difficult. Indeed, the elements all have the same length. For columns, it will not be a problem since element length is close to the desired column dimensions. For instance, in the Arbon seeparksaal (case:8) 3-meter-long elements were used to span 27 meters (Herzog & Natterer, 2004). This might be problematic for the beams however and would impose a tight column grid. Additionally, re-using connectors would be difficult.

Another re-use scenario would be to do multiple layers of pyramids in the long-span scenario and only one in the legacy use. However, this is not cost-efficient since it increases the number of connections significantly and will result in a large structural height in legacy mode.

Efficiency - Cost

Efficient structure in long-span mode with good rigidity and low weight-span ratio.
Can be problematic in legacy mode.

Re-Use Potential

Problems for beam length and major difference in optimal shape between rectangular for beams and circular for struts.
Difficult to re-use the same connections.
Good re-use potential for building the same structure.

Exchangeability

Can be quickly erected on the ground.
High standardization and possibility to prefabricate modular components.

2D trusses

Trusses are beams where the material placement is structurally optimized. They come in a variety of forms depending on the requirements. They are, generally, composed of two chords, aligned with the span, working in tension and compression and bracing elements axially transferring shear forces. Depending on the type, they can be used to span from 7.5 to 80 meters (Herzog & Natterer, 2004; TRADA, 2007).

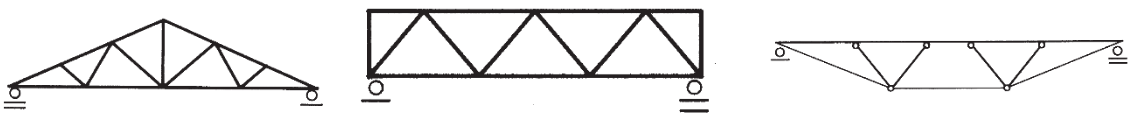


Figure 40 Duo pitched truss; Lattice girder; Under-tied beam (Herzog & Natterer, 2004)

Duo-pitched or arched trusses usually have smaller spans. Thanks to their geometry, they give a slope to the roof which prevents ponding. However, the elements' length varies to achieve this slope which greatly hinders re-use options.

Lattice girders, on the other hand, have parallel chords and standardized dimensions along the truss's length. This type of truss also has the widest applicability range: between 12 and 80 meters (TRADA, 2007).

Beams connected to a tensile chord via compressed struts, called under tied beams, achieve similar results but are of less interest to re-use because of varying members' length.

Trusses excel at taking bending moments and save material compared to solid beams, especially if the structural height is not limited. Although they allow more deformations than space frames, they are still efficient structures.

The connections between elements can be either pinned or clamped and usually link 3-4 elements together. Therefore, with careful design, they should be adaptable to the legacy use of the structure.

Lattice girders elements can be standardized and pre-assembled in a factory which can greatly help the assembling process. Moreover, they often allow parallel disassembly for better deconstruction times.

Using lattice girders can be of interest for re-use. Indeed, the legacy and Olympic structure can be geometrically fitting as illustrated in Figure 41, where the diagonals are re-used as columns and the chords as beams. The challenge resides in the differences in forces between the two configurations. This might result in limitations regarding the span of the structure.

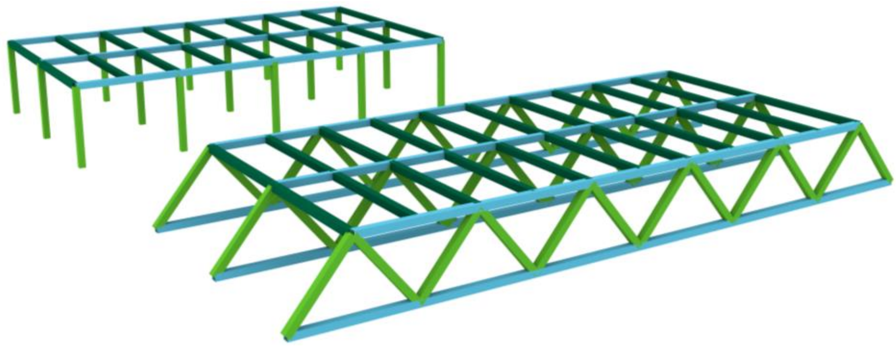


Figure 41 Re-use of lattice girder

Efficiency - Cost

Efficient structure in long-span mode with low weight-span ratio although less rigidity than space frame.

Re-Use Potential

Possibility to re-use the joints.
Geometrically fitting with the legacy structure although the difference in forces might be problematic.

Exchangeability

High standardization of pieces and joint.
Possibility to pre-assemble the trusses.
Parallel disassembly is possible.

Beam systems

Beams are very common for small spans up to 30 meters (Herzog & Natterer, 2004). However, it will not be strong enough for this project. What can be of interest, however, is beam grids. Although (Natterer) fixed their span limitation at 24 meters, there has been construction spanning a lot more such as Stade de Soccer Montreal (Case:42) which spans 75 meters. This difference can be explained by the decrease in Glulam beams production restriction.

One interesting example is the construction of an indoor skating rink in Germany (case:17) where a beam grid was used to span 54 meters (Lennartz & Freitag, 2015). While this solution is not the most material-efficient, it greatly reduces the number of connections and installation time. Indeed, the beams are prefabricated and brought on-site in elements up to 48 meters long.

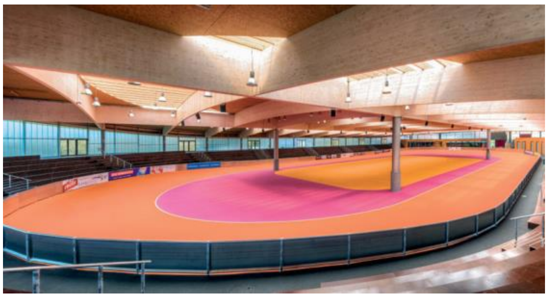


Figure 42 Indoor skating rink in Germany

Re-using the beams, as such, is of course out of the question due to their height of 2.42m. An interesting alternative would be to build the beam out of smaller elements stacked on top of each other. The challenge is then to transmit the longitudinal shear stresses on the interface. Using connectors would greatly increase manufacture time and results in losses of stiffness. A possible alternative would be to produce the 2.4-meter beam and then cut it as to have interlocking interfaces such as illustrated in Figure 43. In addition to covering both the origin and legacy structures, such a method could be used for spans between these two extremes as well by using two elements for instance.

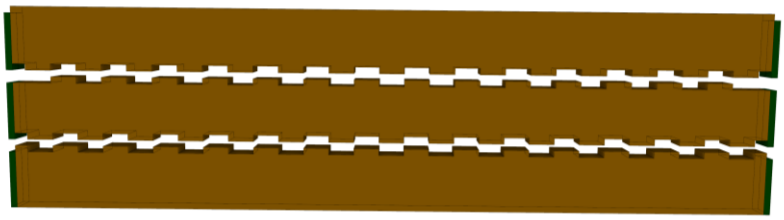


Figure 43 Built-up beam concept

However, some problems remain. Including the length of the elements which would not fit the legacy use. This means that the beams should be divided into 5-6-meter-long elements and that moment-resistant connections would be necessary for the long-span use. Additionally, the indentations would increase the structural height slightly in legacy mode with little to no structural gain. Moreover, this solution would not give the possibility to source the columns from the origin project. But the biggest incertitude in this strategy is the manufacturing of such a beam. Gluing or screwing the notches on the beam would require high precision to minimize slip and could prove costly. Cutting in the 2.4-meter beam could remediate this problem, although the cost and feasibility of such an alternative is unknown.

Efficiency - Cost

Low efficiency of the beam in long-span use. Except for the notches, the beams would be the most adapted for re-use.
Need for moment resistant connections.

Exchangeability

With the interlocking, the elements should be easy to mount on the ground before being lifted.
Non-standard elements which can be difficult to replace.

Re-Use Potential

Good re-use potential for the beams which can be used for different spans.
No source of columns.

Domes & Shells

Domes, shells, or gridshells have been grouped because they all use their doubly curved geometry to carry the loads efficiently axially. This means that such structures can span great length such as 161 meters in the case of the Tacoma dome (TRADA, 2007).

There are, however, multiple problems concerning the re-use of such structures. First, domes often use curved elements which greatly reduces the re-use opportunities. In some cases, such as the Konohama dome (case 7), straight members are used (Iimura, Kurita, & Ohtsuka, 2006). However, this implies varying lengths and many different custom connections.

Figure 44 Konohama dome

Gridshells, on the other hand, use longitudinal laths that are bent into place. However, the construction process is difficult, and the length of the lath is not adapted for different usages.

For all these reasons, doubly curved structures are not explored any further.

Efficiency - Cost

Very high efficiency

Exchangeability

Difficult to mount.
No standardization.

Re-Use Potential

Poor re-use potential due to lack of standardization.

Others

Other structural systems are possible but will not be assessed here. Arches, for example, allow large spans, but require custom, and often curved, elements which prohibit re-use. Worth mentioning, are three-pin frames that could be a possibility to combine with either the beam or truss solutions.

Results

To compare the different structural systems, their performance in the three categories is reported in the table below. "+++" denotes a great performance while "- - -" relates to poor performance.

Table 5 Summary of structural systems comparison

	Space frames	Beams	Trusses	Domes
Exchangeability	+ +	+ +	+ + +	- -
Re-use potential	+ / -	+ +	+ +	- - -
Cost-Efficiency	+ +	+	+ +	+ + +

Additionally, the table below sums up the applicability of the diverse structural systems. (a) denotes the range given by (TRADA, 2007) while (b) describes to the one in (Herzog & Natterer, 2004). These have been plotted in green in the table, while the number refers to the construction reviewed. The details of each construction are visible in ANNEX V.

Table 6 Span ranges

Type	System	Reference spans		Spans in meters												
		(a)	(b)	10	20	30	40	50	60	70	80	90	100	110	120	+
Beams	Beams	2-18	1-30		31	16										
	Beam grids	-	12-24					25 17		42						
Trusses	Duopitched	12-60	7.5-30		41			27								
	Duopitched eave	12-60	20-50				20									
	Arch truss	12-60	20-35			30			19	3		44				
	Lattice girders	12-80	20-50			9	21 15	36 14	10 38		29					
	Undertied beams	12-30	8-80			35	33 43		23							
	Space frame	-	8-50			8 40					12					
Frames	Three pin frames	12-25	15-50					39	38		37					
	Pinned arch	24-98	30-100			24			28	5 34	13 4					
	Latticed arch frame	40-120	30-100				22		18		11		2			
Domes		30-180	-										7			1; 6 ;26

From these results, trusses are selected for this study. Lattice girders, in particular, have a wide range of applicability, standardized elements, good re-use options, and relatively good efficiency. The concept of the built-up beam could be interesting to develop but requires custom manufacturing which might be problematic.

CHAPTER V: System development

Before designing the project in detail, a preliminary analysis was conducted. This part aims at exploring multiple alternatives for origin and legacy structures, and to select the most appropriate one. It is based on the re-use concept of scenario buffering and the alternatives are evaluated according to a sustainability goal which is easy to quantify computationally: material use optimization. This part focuses solely on the roof truss and its re-use possibilities since the conclusions reached on that subject can be applied to other parts of the structure.

As explored in the previous part, the structure will be in glue-laminated timber GL24h which is very common in Switzerland and can be sourced locally. Trusses will be used to span 50 meter which is the first approximation of the required span for the Olympic arena. In parallel, two legacy settings are evaluated: residentials building requiring 3x4 meters column grids and office/school constructions with a 6x4 grid and slightly higher loads.

Methodology

The analysis is separated into three parts. First, the truss needs to be designed and checked. In parallel, the truss elements must be assessed in their legacy use. Finally, the different possible configurations are compared based on their performance both in origin and legacy uses as well as other re-usability and sustainability criteria.

Truss design

To ensure re-usability, standardization has been highlighted as one of the most important concepts. For this reason, it was decided to have a maximum uniformity in the cross-sections. Consequently, the elements are clustered in groups having the same dimensions. The top and bottom chord elements compose the first group, the diagonals the second, and, if applicable, the vertical elements the third. This standardization implies using more material; however, it greatly simplifies the re-use logistics. Similarly, the secondary beams are ignored in the optimization process. Indeed, they are taken as 4 meters long and spaced every meter to be as standard as possible. Moreover, the legacy structure will need more secondary beams than the roof construction which makes the ease of sourcing even more important. Additionally, to ensure transportability, elements longer than 10 meters are disregarded.

A highly important criterion for re-use is the development of connections. They will be thoroughly designed in the case study. However, the geometry of the truss will influence the forces on the connection and should be accounted for in the design.

Computer model

Because multiple alternatives will be generated and assessed, a parametric model was developed. It was decided to use the software Grasshopper, which allows the creation of geometry for Rhino using pre-coded, or custom, python scripts. To do so, the trusses are defined by the following parameters:

- The truss typology: Three different types of trusses can be selected.
- Geometric properties: Such as the truss height, span, and the number of bays.
- Structural parameters: Such as the loads on the truss and the cross-section of the elements.

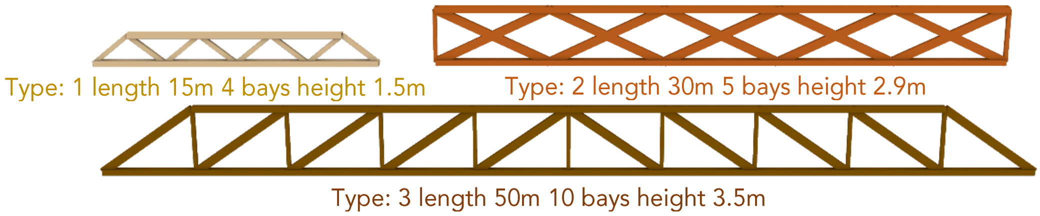


Figure 45 Examples of truss with different parameters

Once the geometry of the truss is defined, it is analyzed in grasshopper using the FEM plugin Karamba, and cross-sections are dimensioned according to the relevant norms using custom python code included in the script.

In parallel, the cross sections are analyzed in their legacy use. The loads depend on the spans produced. With elements shorter than 4 meters subjected to residential loads.

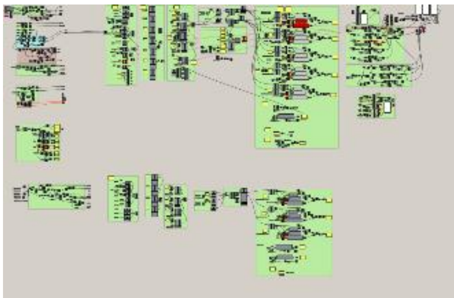


Figure 46 Overview of the grasshopper script

The truss model is subject to the following hypothesis. First, all nodes, as well as the supports, are modelled as pinned connections without any eccentricities. The secondary elements prevent buckling out of plane as well as lateral-torsional buckling; In the nodes, the in-plane buckling is prevented. The calculations done in this preliminary model, follow the same methodology as the ones used in the case study. The reader is therefore referred to ANNEX F: Calculation procedures of timber members for details of the calculations.

Finally, it can be noted that the model was checked against hand calculations and a different model in the FEM software Matrix Frame.

Analysis

The analysis was done in three steps. The goal of the first is to explore many different truss alternatives with minimal processing. It is an exploratory step to give hindsight into the main trends. To do so, an additional plugin, called Colibri, is added to the parametric model. This plugin automatically changes the selected input parameters and records all desired outputs.

In this analysis, the parameters on which the script iterates are the truss height varying between 2.5 and 5 meters, the truss type, and the number of bays between set between 6 and 20. It will also test multiple cross sections and give the smallest possible structurally.

The most important output is the weight per area, which, when minimized, reduces the material use and thus the costs as well as the ecological impact. Additionally, the dimensions of the elements are important for re-use. Indeed, avoiding the need for adjustment when changing from origin to legacy structure is essential to reduce costs. It was quickly discovered that the limiting factor will be the length of the column. For this reason, an additional output parameter was selected. It gives the minimum difference between the length of elements and the length of a standard column, which is taken as 3 meters.

The second and third steps build incrementally from the results of the exploration done in the first stage.

Assessing designs

Because the methodology used generates multiple alternatives, it is necessary to set up assessing criteria to compare them.

The first is the material efficiency both in origin and legacy use. It is an important criterion because it gives an overview of how much unnecessary material is used because of the duality of the structural elements which is closely linked with the ecological performance. Additionally, it provides insight into the cost increase compared to a traditional design.

To quantify the weight efficiency, the weight of the re-usable truss is compared with an "optimal truss". Such an ideal truss is taken as the lightest truss resulting from the first step of the analysis without any re-use constraint.

In parallel, the mass of the column-beam system resulting from re-using the truss elements is compared with the required wood mass to span the same distances if new structural elements were used. In cases where the legacy use needs a bigger cross-section than the original structure, the latter will be updated to meet the requirements.

Connections will be a challenging part of this project. The force they transmit is directly linked with the truss properties and should, therefore, be accounted for when comparing the different trusses. Indeed, reducing them will reduce the complexity of the connection, the amount of steel required, and the number of bolts all of which will influence the sustainability performance and the ease of demountability. It will, therefore, be accounted for by favorizing trusses with minimal forces in the nodes.

Finally, the versatility of the system needs to be accounted for. It can only be done qualitatively by looking at the spans produced, the number of elements, etc.

Results

The exploratory step resulted in more than 500 different trusses. To visualize the data, an online tool called design explorer is used. It plots every solution as a line linking all inputs and outputs values and allowing for filtering of solution. It was, therefore, possible, for each truss type, to choose the ones with the lowest weight per area that have elements close to the length required for the column. These three trusses were then brought back to the model and the cross-sections calculated with buckling and lateral-torsional buckling included.

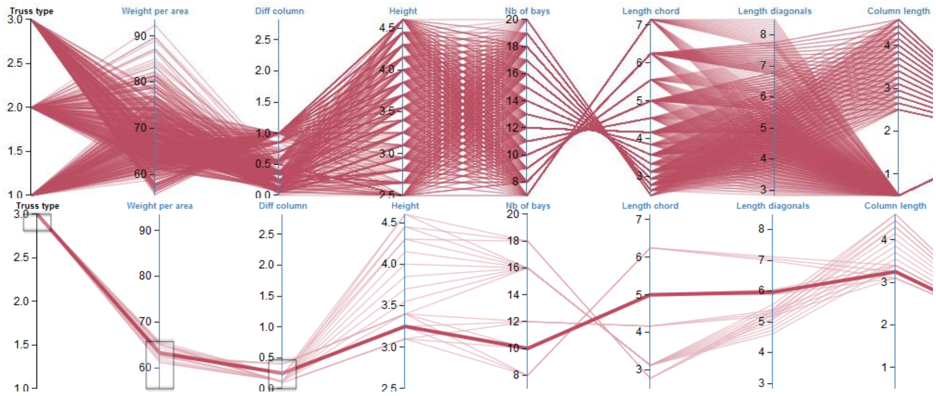


Figure 47 Overview of all possible solution (top) and selection of one for type 3 (bottom)

A full analysis of the three trusses is visible in ANNEX D: Detailed results of CHAPTER V: System development. A summary of the results of this observatory method given here. The truss type 1 showed the best results. Indeed, having crossing diagonals such as type 2 is inefficient in terms of weight and might be problematic when designing the connections. Trusses with vertical elements (type 3) have similar weight efficiency to truss type 1. However, they have an additional type of element which can cause small logistics problems.

Another remark from the observatory method is that re-using the trusses in office/school scenario is preferable. Indeed, the cross-sections required for these larger spans are closer to the one resulting from the truss design. Similarly, it is better to re-use the diagonals as columns and the chords as beams since the cross-sections are similar.

A problem noticed in the first step of the analysis is that restricting the length of elements to have compatibility with columns limits the structural height. This results in higher forces in the connections which might be difficult to transmit trough demountable assemblies.

The second step of the analysis builds on the results of the first. Therefore, it focuses on structure re-usable in office/school buildings. Additionally, to increase the structural height, it was decided to create two columns from one diagonal. This means that diagonals are no longer limited to 3-3.5 meters in length but measure roughly 6 meters long. Although it increases the number of connections and breaks the balance between the number of columns and beams produced, it greatly reduces the forces in the connection. Moreover, by reducing the forces on the chords, it improves its efficiency in the legacy scenario.

The third method was developed in parallel aiming at higher standardization. To achieve that goal, the idea is to have a single element that can be combined to produce bigger cross-sections or longer beams. Therefore, all elements have the length of a column which is roughly 3 meters. In this iteration of the method, two elements are necessary for the top chord and for spanning office buildings while only one is required to span residentials, for the columns or the diagonals. The elements are connected mechanically with two dowels every 35 cm along the beam. This mechanical jointing of the cross-sections will result in a decrease in performance compared with a solid cross-section of the same dimensions. To quantify these losses in inertia and bending resistance, the formulas from the Eurocodes were used. The full calculation is visible in ANNEX H: Calculation procedures of built-up elements.

The figure below compares the best performing trusses from the three steps of the analysis.

The exact cross sections for each element of the analyzed truss are visible in ANNEX D: Detailed results of CHAPTER V: System development.

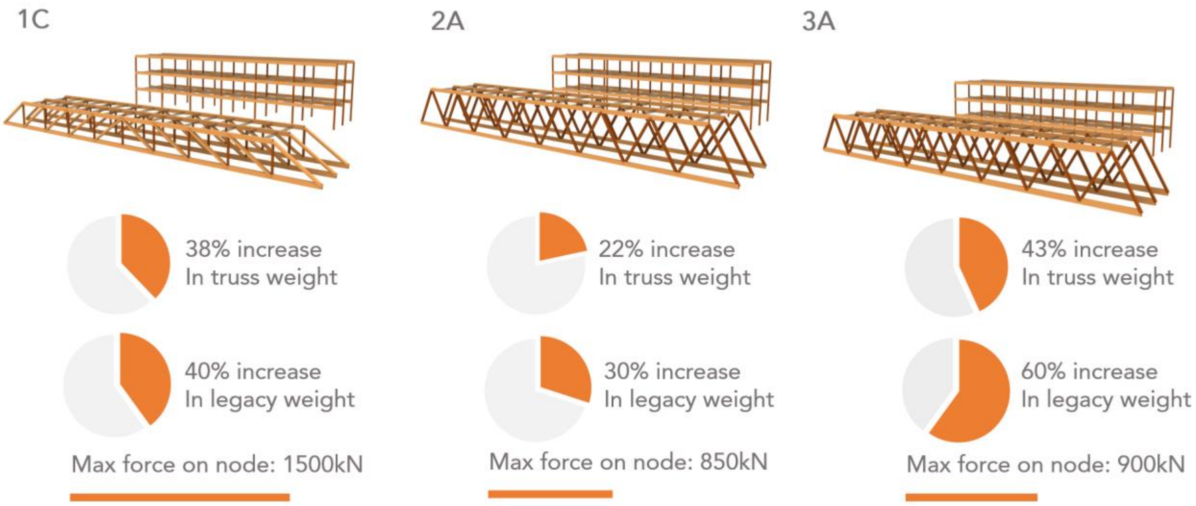


Figure 48 Summary of the system development

As shown above, the second methods yield the best results. Indeed, increasing the column length produced more efficient structures since the forces in the chord in smaller. Moreover, it greatly reduces the connection complexity. The third method is penalized by the inefficiency of the mechanical jointing of the cross-sections. It would be of interest if the aim was to create a system that could be applied anywhere on short term structures. However, it comes at the price of increased structural height and resource consumption. Therefore, it will not be pursued any further.

PART IV

CASE STUDY

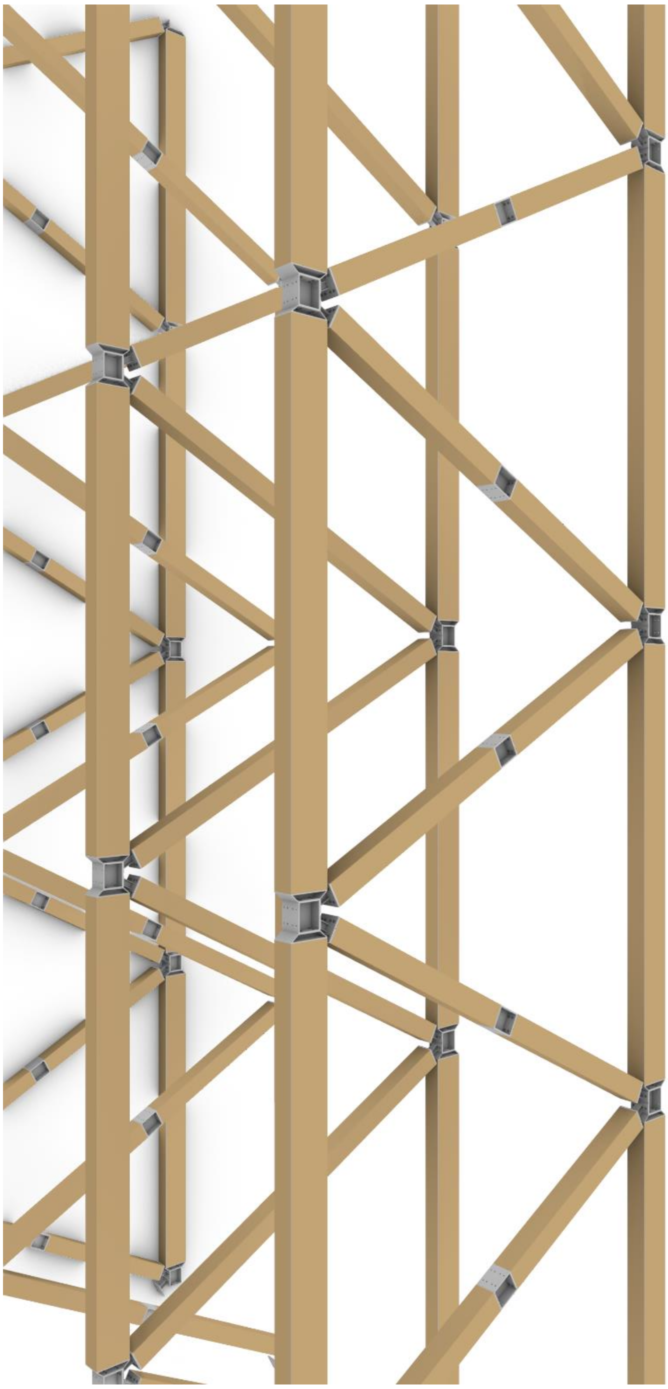


Figure 49 Trusses of the project

The second part accumulated theoretical knowledge on re-usable and sustainable constructions. The task of the third one was to apply it to the selection of timber products and systems. This part's objective is to illustrate and test the principles developed in this research around a case study. It will start with an introduction explaining the brief for the two projects. Afterwards, the structural design and the related decisions will be exposed before moving to the hypothesis related with the structural calculations. Finally, the structure will be assessed both for its re-usability and its sustainability.

CHAPTER I: Introduction

Goal of the case study

The research done in previous parts has shown a multitude of strategies for the re-use of timber structures. The goal of this case study is to illustrate them and to put these concepts to the test. As described in the introduction, Major Sporting Events, such as the Olympic Games, are the ideal environment for such a project. Indeed, they require custom structures that would benefit from re-use. Moreover, the large spans required for covered arenas are of interest to put the concepts of inter-modal re-use to the limit.

To achieve the goals of the case study, an Olympic structure, as well as a re-use scenario, were selected. To increase re-use opportunities, the legacy structure has the possibility serve a different purpose than the Olympic construction. Moreover, re-using in a structure with a social dimension would benefit the host population and increase sustainability as well as the acceptance of the games.

There is a great variety of possible structures to design, the rest of this chapter presents the selected two. However, it is important to note that this case study focuses on highlighting the re-use methods and constraints. For this reason, certain aspects of the design of the case-study have been simplified or ignored. Moreover, this research focuses on structural re-use. Therefore, the re-use of secondary elements such as floors or façade has been ignored. Finally, because the exact briefs of the constructions are outside the scope of this study, the architectural design of the buildings is simplified and focuses mainly on the structural skeleton.

Brief of the origin structure

In the context of the Olympics, it was decided to build the structure of a badminton arena. However, multiple disciplines such as ice hockey, basketball, table tennis, etc. have similar requirements and would require only small adaptations to the project.

The requirements given by the IOC for the building hosting the badminton events are the following:

- Minimum of 6000 seats (IOC, 2005)
- Free height of more than 12 meters
- Playable zone of 30x48m (BWF, n.d.)

The additional requirements are outside the scope of this case study.

To transfer the number of seat requirements into dimensions for the roof, it was necessary to look at the constraints of stadium construction. Since the detailed design of the stands is not included in this research, an estimation of the required space was done by looking at references.

Based on (Neufert, 1998), a spacing between each row of 70cm assorted with a rise of 30 cm have been selected. Additionally, a spacing of 50cm between each seat is common practice. Moreover, some rows were culled to allow for the displacement of people. Finally, a flat ring is present to access the inside of the stadium.

With these guidelines, an arena of 6'700 seats was modeled using grasshopper.

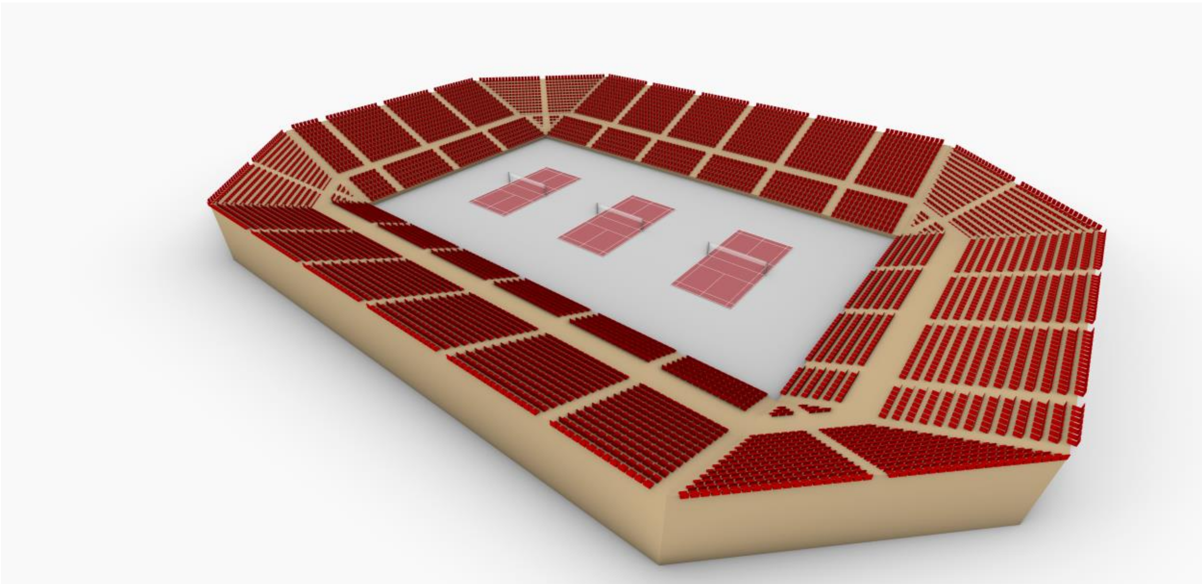


Figure 50 Arena outlines

To cover this arena, a free span of 59x79 meters is required.

Brief of the legacy structures

The legacy structure is intimately linked with the truss geometry. Indeed, the spans and structural heights are directly derived from the length of the truss members. This influence works both ways since the cross-sections of the truss are, in turn, influenced by the requirements of the legacy structure.

A crucial component in the environmental benefits of re-use is the distance between the origin and legacy structure. For this reason, the legacy structure should answer local needs to minimize transportation costs. Since the case study is based in Switzerland, where high schools are overloaded (Turuban, 2019), such constructions are taken as an example. Moreover, this typology of building is in accordance with the social sustainability dimension of the project.

To help the design process, the Nelson Mandela Highschool in France, was selected as reference project. Additionally, reviewing existing swiss high schools showed that a free span of a minimum of 6 meters is standard in classrooms which usually host around 25 students (Lyon, 2002).

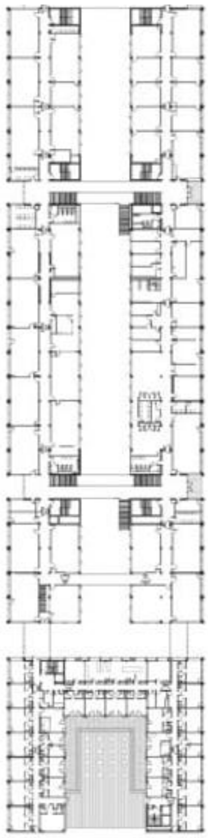


Figure 51 Reference project

The Nelson Mandela Highschool was selected because it is more than a simple beam-column grid building. Therefore, it can be helpful to show that designing with re-used elements of standard dimensions does not necessarily yield a "standard" building. Moreover, as will be explored in the following chapter, multiple spans and structural systems are possible by combining the re-used elements differently. Consequently, a project like this one is interesting to show the different legacy possibilities.

CHAPTER II: Structural design

In this chapter, the structural design decisions will be explained. Although both were developed in parallel, the chapter will start with the design of the origin structure before exploring the legacy scenarios. Afterwards, the connections will be designed, and the mounting constraints addressed.

Design of the origin structure

When designing the arena, the re-use guidelines were kept in mind. It was important to have a structure as uniform as possible. Indeed, standardization and modularity are essential to simplifying all processes of re-use such as demounting, sorting, rebuilding, etc. Additionally, the elements needed to be directly applicable to both the origin and the legacy scenarios. Indeed, the cost of making dimensional adjustments to the salvaged pieces is often a key factor against re-use.
Transparence in the structure was an important criterion. Indeed, it will allow for easy identification of the systems when demounting. Furthermore, because structural re-use is the core of this project, it seemed architecturally fitting to show the load-bearing structure. For a full review of the design for re-use guidelines, the reader is referred to CHAPTER II: Re-Use.
The main part of the structure is the roof truss which spans 60 meters. To simplify the connections of the structure, the truss is rested on two hinged supports.

Figure 52 Truss without connections

The design of the roof truss follows directly from the research of CHAPTER V: System development. It is made up of two different types of members: the chord and diagonal elements. From node to node, the chord elements are 6.67 meters long, and the diagonal elements measure 7.13 meters. The diagonals are then split in two to produce members appropriate to the column re-use. The chords elements, in contrast, can be directly re-used as beams.

The connecting elements reduce the lengths of the timber members. Consequently, the truss is composed by the following members: the chord elements, used as beams in the legacy scenario, are 6.33m long while the columns elements, used as diagonals in the truss, are 3m long.

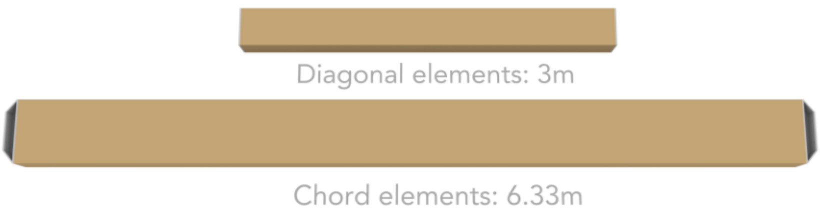


Figure 53 Elements used in the structure

The dimensions of the truss were selected in an iterative process. Indeed, it is a constant loop between designing the truss and seeing its applicability to the legacy scenarios. The main criterion to evaluate the performances of the design was material efficiency. Indeed, it is easy to quantify and, limits the increase in material consumption compared with a standard, one-off, structure.

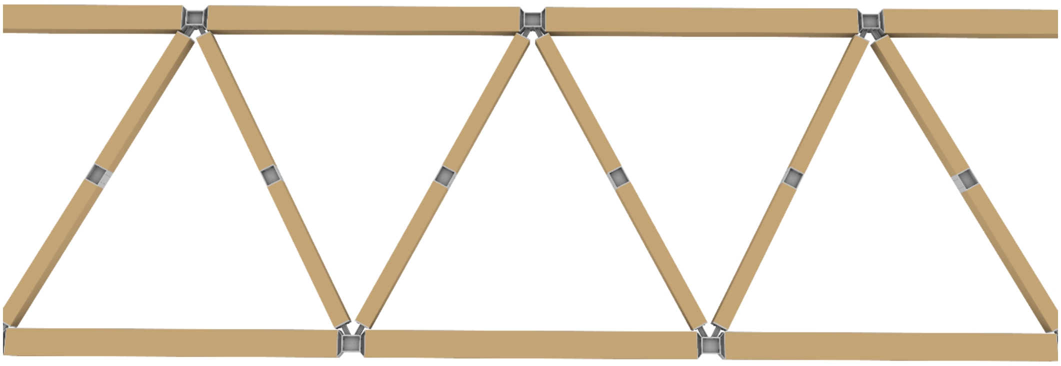


Figure 54 Truss with connections

The secondary beams were chosen to be as standard as possible. A span of 4 meters is slightly more than what is common in timber flooring, but it reduces the number of trusses necessary. However, sourcing them should not be a problem. Additionally, they are spaced by 1.1m.

Concerning the stability of the structure, it was decided to use trussed columns. The motivations for this decision are multiples. First, given the important spans of the structure, it avoids the design of a complex wind truss. Moreover, it greatly simplifies the connections of the roof truss which would otherwise need to be connected to the stability system. Additionally, the trussed columns can be built from the diagonal elements of the truss which reduces the logistical challenges of re-use. Similarly, the buckling support provided by the triangulation allows for smaller cross-sections which are more appropriate for re-use. Finally, this system guarantees the self-stability of each truss farm which accelerates the (de)mounting process.

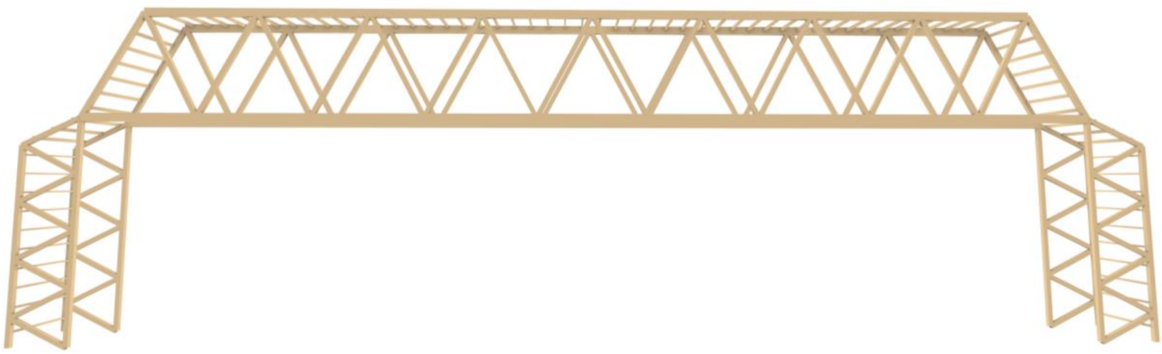


Figure 55 View of two truss farms

Concerning the dimensions of the columns, they are directly derived from those of the diagonals of the truss. This means that the following distances separate each node: along the chord 3.3m; along the diagonal 3.65m.

The same logic is applied to the stability elements in the other direction. Except that they go up until the height of the top chord to take the entire wind load of the façade.

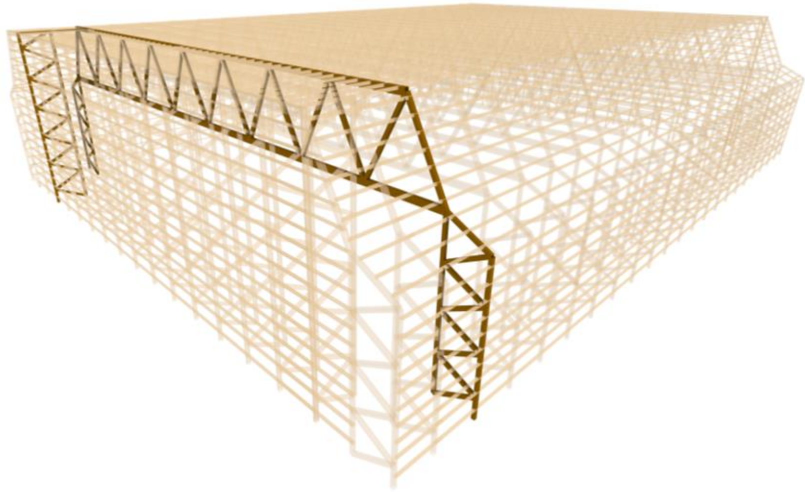


Figure 56 Overview of the structure

Detailed drawings are available in ANNEX J: Detailed drawings of the structure.

Design of the legacy structure

The legacy design was conducted in parallel with the origin structure. However, for clarity, it is exposed here as if it resulted from the design of the origin structure.

A multitude of legacy structures is possible by combining the elements of the original construction. Indeed, the parallel development of both structural systems, as well as the versatility of the connections, helped making every element interchangeable allowing multiple variations in the possible re-uses. To simplify this, the possible legacy structures are grouped into three archetypal constructions exposed hereafter. The final product, the high school, is a combination of all of them.

It can be noted that all elements used in the legacy structure can come from the arena. It is possible, depending on what re-use scenario is chosen, that there are some components lacking. However, for the first buildings designed with the re-used components, they can entirely be sourced from the arena. For a better understanding of the re-use of the connections and components, the reader is invited to look at the detailed drawings of ANNEX J: Detailed drawings of the structure

Office/School setting

In this scenario, the diagonals are re-used as columns. The chord elements, on the other hand, are used as beams. This is the ideal scenario in the sense that the cross-sections fit this re-use configuration the best.
The resulting structure is based on a 4x6.6m column grid.

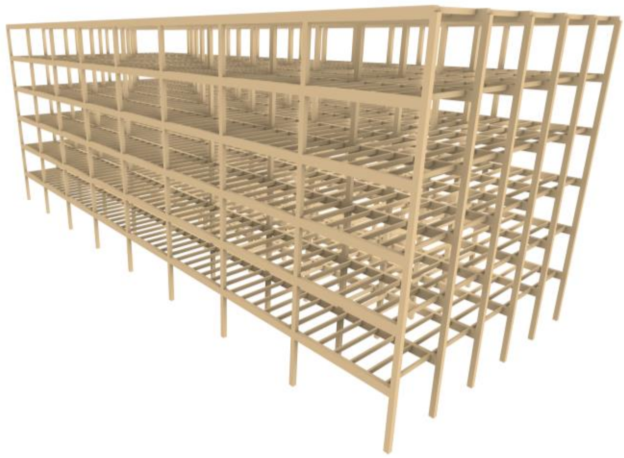


Figure 57 Legacy structure in Office/School setting

Residential setting

Here, the diagonals elements are used as columns as well as beams. This is not an optimal re-use scenario since the cross-section of the diagonal is over-dimensioned for a beam re-use. However, it is still an interesting option for two reasons. First, it uses the extra diagonal elements produced by the truss. Second, while a building using solely these elements would be relatively inefficient, such spans can be used in corridors for example.

The resulting structure is based on a 4x3.3 column grid.

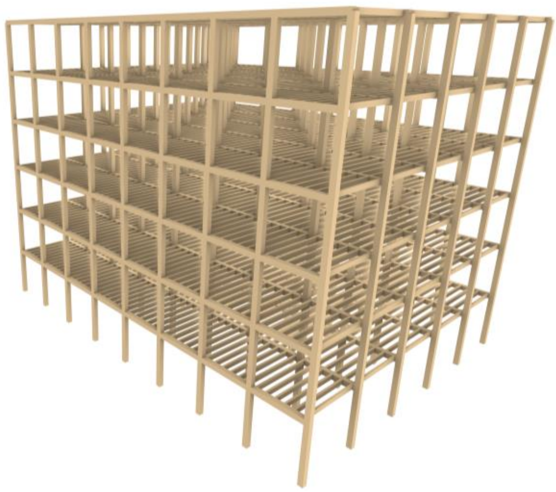


Figure 58 Legacy structure in a residential setting

Industrial setting

Another possibility is to use the diagonal elements to produce a smaller truss. Using the same elements, as well as the same connections allows for a 33.5m long truss. This could be used to cover an industrial hall or a small gymnasium. One of the advantages of this re-use scenario is that it can re-use 100% of the joints of the columns.

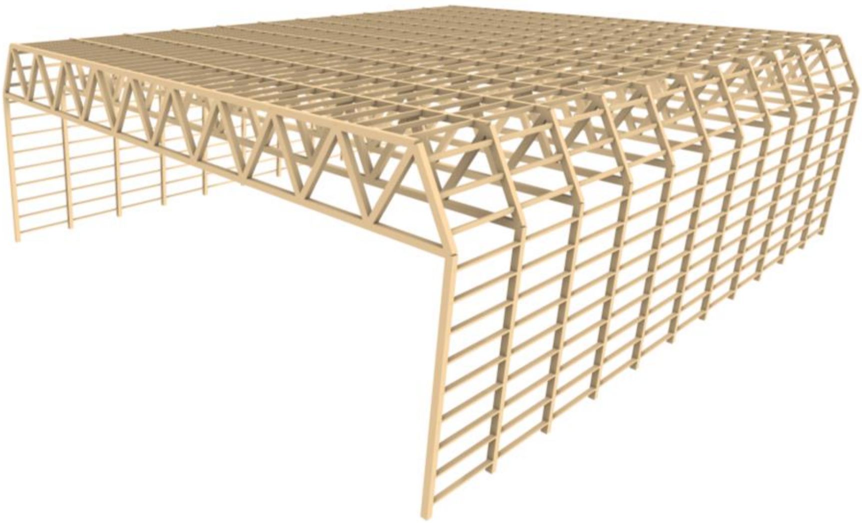


Figure 59 Legacy structure in an industrial setting

Project setting

In this project, the goal was to build a high school. However, it is also interesting to show the multiple capabilities of the re-used structure. For this reason, the office/school setting is used to host the classrooms. The residential setting is well adapted for corridors, while the industrial setting can be used to make a nice entrance of light in the atrium.

Figure 60 Legacy structure in the project setting

Design of the connections

Now that the geometries of the projects are known, it is time to investigate the connections. For better re-use efficiency, the joints should follow the structure in its different configurations. Indeed, it would greatly simplify the re-use logistics. Moreover, connections represent a considerable part of the economic and ecological cost of the construction which should not be wasted after the first utilization.

The challenge is to adapt to the changing requirements between the different settings of the structure. First, the connection must join two chord elements with great normal forces with two inclined diagonals. In the legacy scenarios, on the other hand, it must join two columns (from the diagonals) perpendicularly with two beams which come either from the diagonals or the chords and transmit essentially shear. Additionally, the design ought to avoid any eccentricities in the truss connections to avoid parasite forces.

In addition to the geometrical challenges, the connection must be easily (de)mountable. This means using separable means of assembly. Additionally, using as few connectors as possible and from the same type greatly simplifies the logistics. Moreover, the joint should have realistic tolerances, be accessible, and necessitate only common tools.

The joint will also influence the handling of the component. Ideally, it should be useable as a hoisting point since trusses are designed to have forces on the nodes. Finally, robustness is important to avoid damaging during transport.

Considering these constraints and the major forces to transmit in the truss, steel connectors seemed appropriate. On top of the versatility provided by an isotropic material, tolerances are easy to incorporate in steel and they are very robust connections. Moreover, steel can add ductility to the structure.

The geometric constraints, as well as the goal of minimizing the number different of connections, mean that the joints should be the same between two chords elements in the origin scenario and two columns in the legacy use. Therefore, a steel piece is added to the chord elements to reduce the dimensions of its cross-section to those of the diagonals. It was not possible to reduce the timber dimensions because the entire cross-section is necessary to fit the glued-in rods. The loss of structural height is not a problem since the members are modeled as hinged.

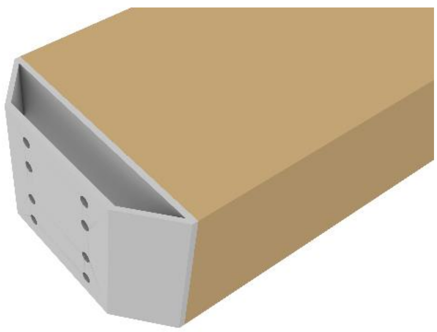


Figure 61 Steel element on chord

The angle of the diagonal poses a problem for re-use. Indeed, in the legacy scenario, the beam will be perpendicular to the columns. After exploring multiple alternatives, it was decided that a standard block will connect elements axially or perpendicularly and that another, smaller, element will join the inclined members with the block. With this design, there are only three different components to the connection: the standard block present everywhere and two different inclined elements, one for the roof truss and one for the column trusses. While the inclined element for the roof will be difficult to re-use since it is designed to correspond to one angle only, the one for the columns can be re-used in the industrial setting where the angles of the trusses correspond. For the elements that would not be re-used, recycling is a good option to minimize wastes.

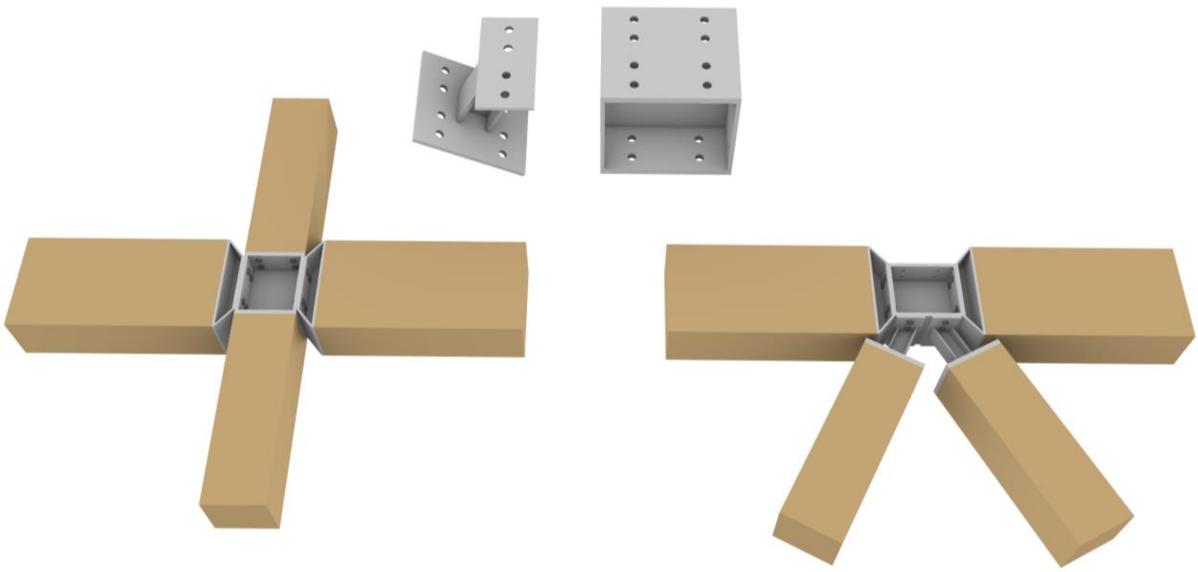


Figure 62 Connection in legacy mode (left); origin mode (right)

The elements connecting the different plates are welded I profiles. This was done because no standard extruded cross-section fitted the required dimensions. However, it is possible to slightly increase the dimensions of the timber profiles to fit standard I elements. The decision to use welded plates was motivated by the will to minimize material use. However, it might be more profitable financially to increase timber dimensions.

To simplify all re-use logistics and avoid mistakes during mounting, the connections are the same in the entire structure. Similarly, only M20 bolts are used everywhere for uniformity. Additional measures were taken to facilitate the demountability of the structure. First, the top part of the connecting block can be used to hoist the construction into place. Additionally, attention was given so that every bolt is easily accessible with common tools. In practice, this means having at least 40mm between the center of a bolt and any potential obstacle (Stahlbau Zentrum Schweiz, 2005). Finally, tolerances are easy to accommodate in this type of plate against plate assemblies. Indeed, thin sheets are commonly available to fill the possible space between the plates.

The last part of the joint is the connection between the steel elements and the timber members. This is done by using glued-in rods. Because the number of necessary rods did not correspond to the number of bolts, the rods will be welded to a plate and then glued to the timber. On the other side of the plate, threaded rods are also welded for the bolted connection.

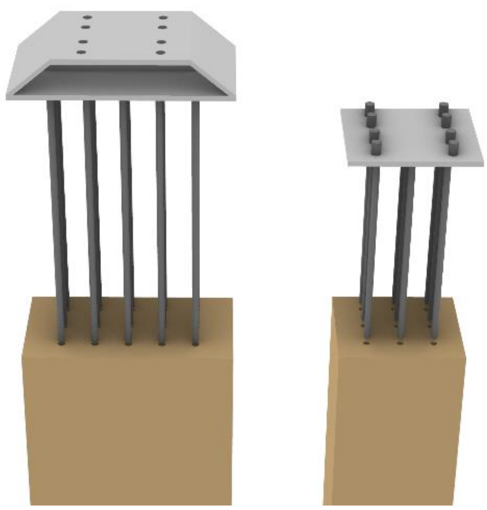


Figure 63 Steel-Timber interface

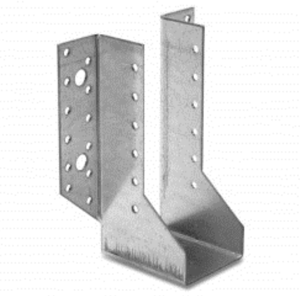


Figure 64 Example of joist hanger

Concerning the connection between the secondary beams and the chord, it was decided to use a simple solution. Indeed, such a connection is very standard and is often done with the help of a steel hanger. The hanger should be screwed to the timber and not nailed to guarantee that it can be demounted at the end of the life cycle of the timber beam. Indeed, nails are often prohibiting recycling due to the difficulty to remove them. Another advantage of such hangers is that they are easy to install a posteriori on the bottom chords which did not have any secondary beam in the truss scenario.

The use of traditional carpentry joints could be an alternative solution to reduce the steel consumption. However, this increases the structural height in legacy mode which would require higher columns and, consequently, lower efficiency of the truss.

(De)Mounting

The exact mounting sequence should be decided in collaboration with the contractor. However, some key points are worth discussing beforehand.

Since the stability members are separated from the roof truss, it is possible to install them first before putting the roof trusses. This reduces the required number of temporary propping and allows to work on both sides of the building in parallel.

Due to the dimension of the roof truss, it is easier to transport the pieces separately, mount the trusses on the ground and lift them into place. This is greatly facilitated by the uniformity of the pieces and connections. Moreover, no special transport is required for this solution.

To minimize the amount of work to be done on the roof, the trusses can be lifted two by two with the secondary members already in place. Consequently, only half the joists need to be put in-situ. Additionally, it helps to stabilize the trusses during lifting and installation. Once the truss pair has been put into place, the connecting joist should be installed to guarantee the stability of the building.

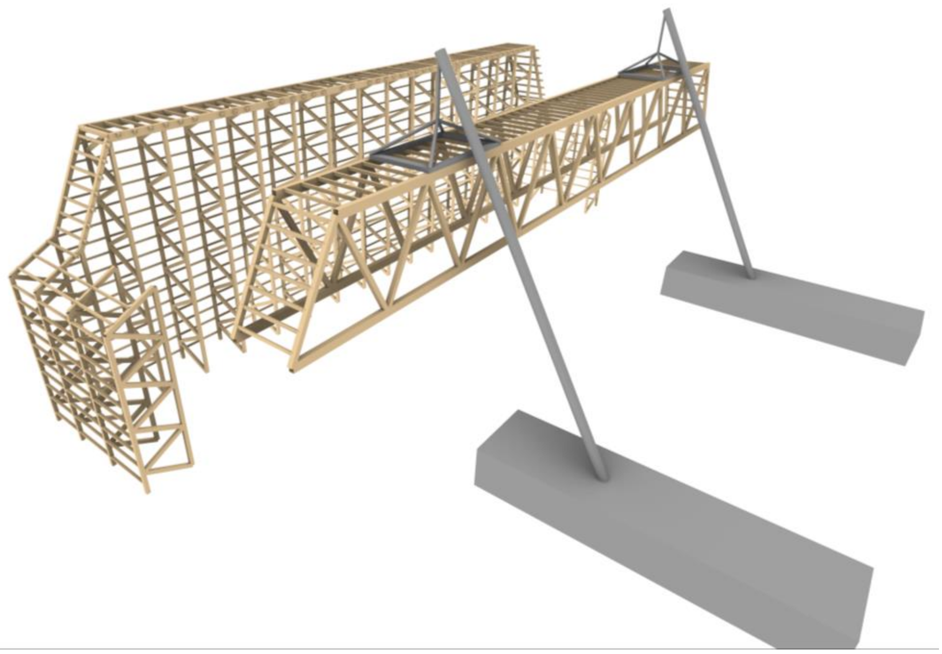


Figure 65 Mounting of the trusses

To ensure the feasibility of the building sequence, an additional load case was added. Consequently, the hoisting points were selected to reduce the buckling length in the absence of stability elements. Additionally, the weight and height of the truss are compatible with common wheeled cranes. This was based on the loading abacus of a GMK 4100 available in Switzerland with the weight of two trusses with secondary beams, a cantilever of 15meters, and a height of 25m (Petit levage SA, 2020).

CHAPTER III: Structural calculations

In this chapter, the hypothesis regarding the structural calculations are exposed. It will start with the requirements in terms of loads and material properties. Then, the conditions for the calculations of the different elements will be exposed.

Structural requirements

Although the concepts developed in this case study are applicable anywhere, a geographical focus is required for the loads acting on the structures. Since the porject is designed for Switzerland, the loads follow from the Swiss norms SIA 261 (SIA, 2003b) and SIA 260 (SIA, 2003a). The main hypothesizes for the loads are exposed hereafter. Tables with detailed load calculations, load cases, and timber properties are visible in ANNEX E: Loads and timber properties. It can be noted that in the tables, the dead load of the structure is not written because they are directly added by the software. Additionally, the characteristic values of the structural dead loads were increased by 10% to account for the assemblies.

Origin structure

The building is subject to snow load, wind load, maintenance loads, and dead loads. The snow load, which depends on the location and altitude of the project, amounts to 1.2 kN/m^2 in the selected town of Sion, Switzerland. The reference wind load is 1.2 kN/m^2 which is then multiplied with the building-related coefficients to obtain the loads on the elements. Note that no internal pressure was accounted for since the building is taken as closed. Moreover, the most unfavourable wind coefficient is taken for the entirety of the roof. Maintenance loads are irrelevant since their contribution as secondary load in ULS or SLS is null. Finally, dead loads are taken with the hypothesis of standard timber construction and amount to 0.94 kN/m^2 for the roof and 1.1 kN/m^2 for the façade.

For the ULS of the origin structure, three cases are studied. The first has the snow as the main load while the other two have the wind, one with the dead load as favourable and the other unfavourable.

Concerning SLS, the same cases as ULS are studied. Frequent combinations are used with a limit in vertical displacement set at l/500 to avoid ponding. The horizontal sway due to wind loads is also limited to h/500. It can be noted that the load coefficients were increased according to a creep coefficient of 0.6 to account for the long-term behaviour of timber.

Legacy structure

The legacy structure is assessed separately according to the different re-use scenario. Moreover, because it depends strongly on the chosen stability system, lateral loads are ignored. Beams are checked individually under the service loads and dead loads for building floors. Columns are checked by calculating the maximum number of floors they can support. The roof loads are ignored since they are smaller than the floor ones and the same beams are used in both cases. The service load depends on the affectation but, to include as many usages as possible and because it is the subject of this case study, the load for schools, i.e. 3 kN/m^2 are selected. Concerning the flooring, a standard timber flooring was taken for reference load which amounts to 1.8kN/^{2}.

Material used

The selected timber is GL24h which is commonly available in Switzerland. Additionally, such a material is usually produced with local timber in regional industries which greatly reduces the environmental impact of the construction. All structural properties are taken from SIA 265 (SIA, 2003d) with the hypothesis of class 1 building and k_h=1.

The steel grade for the assemblies is S355. Ideally, it should be sourced it from recycling branches to reduce its sustainability cost.

Dimensioning hypothesis

The calculation methods, as well as results table, are exposed in Annexes F-I.

The dimensioning of the timber structure is done according to the norm SIA 265 (SIA, 2003d) while the steel parts follow the SIA 263 (SIA, 2003c).

For both the legacy and origin structures, the following hypotheses are made:

- Glued-in rods are known to be very rigid (Sandhaas & Blass, 2017). Moreover, the steel elements used are significantly stiffer than the timber members they connect. Indeed, EA_{steel}=2.8E9>EA_{timber}=1.6E9 and EI_{steel}=4.7E13>EI_{timber}=3.3E13. For these reasons, the additional deformations caused by the assemblies are ignored.
- The case study is limited to a pre-project stage. Consequently, calculations are limited to first-order analysis. Fire safety, fatigue, foundations as well as seismic considerations are ignored.

The service limit state considers the frequent combination of loads with a maximum deformation of L/500. The long terms effect of the creep of timber is included by increasing the loading coefficient of the semi-permanent loads.

Both the origin structure and the legacy truss have been modelled in the software Matrix frame according to the loads mentioned in ANNEX E: Loads and timber properties.

Origin structure

The top chord is subject to compression and bending. The following hypotheses apply to its calculation:

- The secondary beams support the buckling in the weak axis which reduces the buckling length to the spacing of the secondary elements i.e. 1m
- The diagonals support the buckling in the strong axis, which reduces the buckling length to the space between nodes i.e. 6.67m
- The secondary beams support the lateral-torsional buckling. The related length is therefore taken as 1m.
- Note: the aforementioned lengths are taken as conservative because continuity of the chord between the secondary beams is ignored and that the nodes are taken as perfect hinges.

Most diagonals are subject to compression only. Their buckling length is taken as the length of the diagonal which makes the hypothesis that the connection between two elements does not increase the buckling length. This is possible thanks to the rigidity of the assembly which is more than 5 times stiffer than the diagonal members.

The outermost diagonals must support the roof and are therefore subject to bending. Their buckling length in the weak axis is reduced by the presence of secondary beams. The same applies to lateral-torsional buckling.

The columns are trusses made from the same element which compose the diagonals of the roof truss. They are subject to lower forces and buckling lengths than in the truss scenario. The only exception concerns the inside chord of the columns. Indeed, they have no support in the weak axis. The required cross-section to satisfy the buckling length of 13.5 meters are too big would not be fit for re-use. For this reason, it was decided to add one secondary beam per span to reduce the buckling length.

The secondary beams are subject mainly to bending and are calculated with the hypothesis of no lateral-torsional buckling due to the roof/floor/façade support. Additionally, they are subject to 10% of the normal force of the element they need to stabilize against buckling.

Legacy structure

The beams are subject to bending and are free of lateral-torsional buckling thanks to the support of the floors.

The columns are subject to normal force and have a buckling length equal to their length.

Connections

The flow of forces in the connection is relatively complex. However, for this project, simple checks are undertaken. The bolts are controlled in traction, shear, and in bearing of the plates. In addition to transmitting the shear force, the connections of the legacy scenario need to take the moment induced by the eccentricity of the beam.

The plates are designed to be Class II to avoid local instability problems. Therefore, only shear, normal force, and the resistance to a local force are controlled. The thickness could be reduced by conducting an in-depth analysis, but it is out of the scope of this project.

Results

The following cross sections were selected:

Table 7 Selected cross sections

Chord elements							
Dimensions				Cross section			
Length	l	6.36	m	Width	b	285	mm
Unity check	0.92			Height	h	500	mm
Weight	w	416.9	kg/piece	Material	GL24h		
Diagonal elements							
Dimensions				Cross section			
Length	l	3.02	m	Width	b	285	mm
Unity check	0.98			Height	h	300	mm
Weight	w	118.8	kg/piece	Material	GL24h		
Secondary beams							
Dimensions				Cross section			
Length	l	4	m	Width	b	125	mm
Unity check	0.3			Height	h	250	mm
Weight	w	57.5	kg/piece	Material	GL24h		

CHAPTER IV: Results

This chapter will expose the results of the case study. First, impressions of the final constructions are shown. Secondly, the construction will be assessed concerning its re-usability. Finally, the sustainability of the structure will be assessed qualitatively, while the roof truss and its legacy setting will be explored in more details.

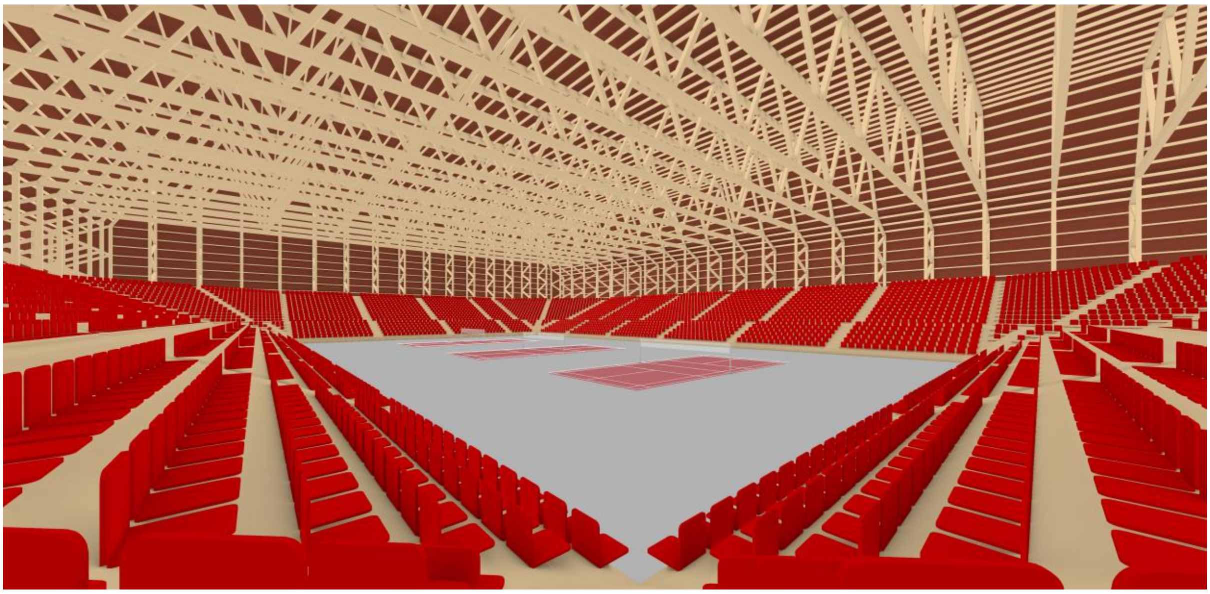


Figure 66 Interior view of the arena

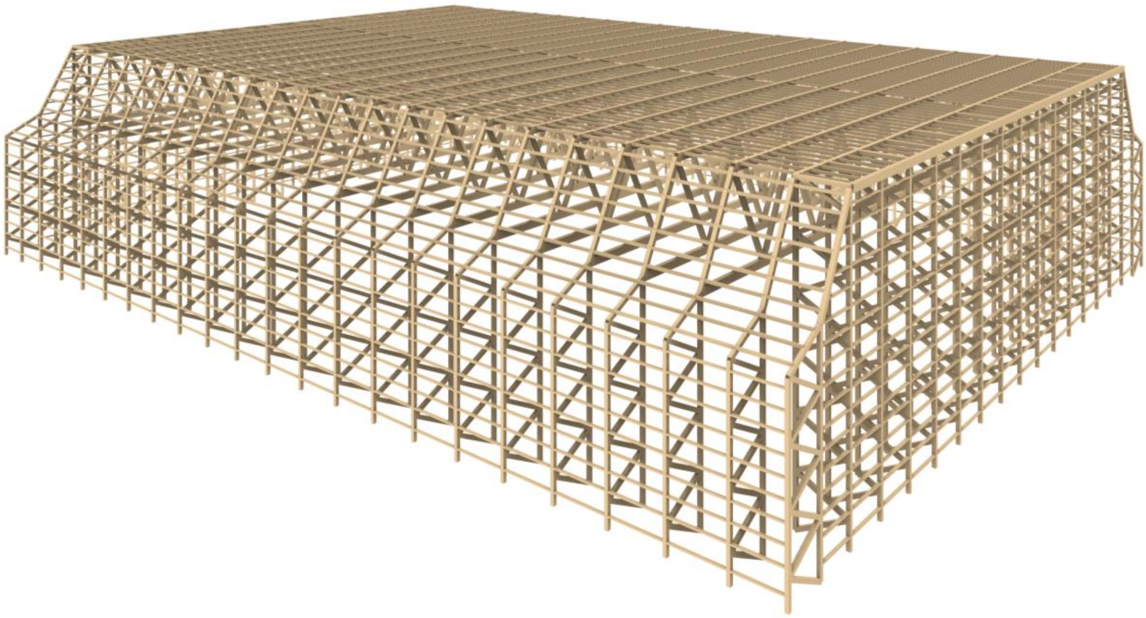


Figure 67 View of the structure or the arena

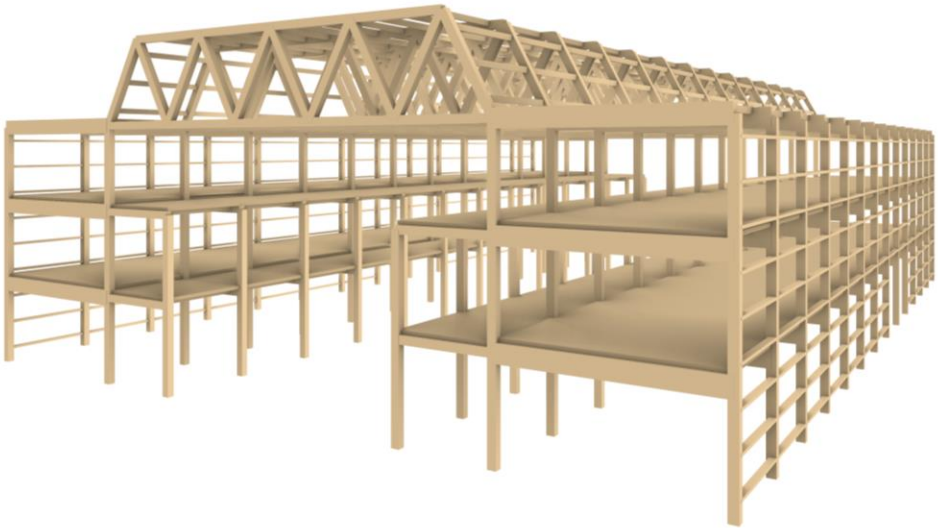


Figure 68 Structure of the high school

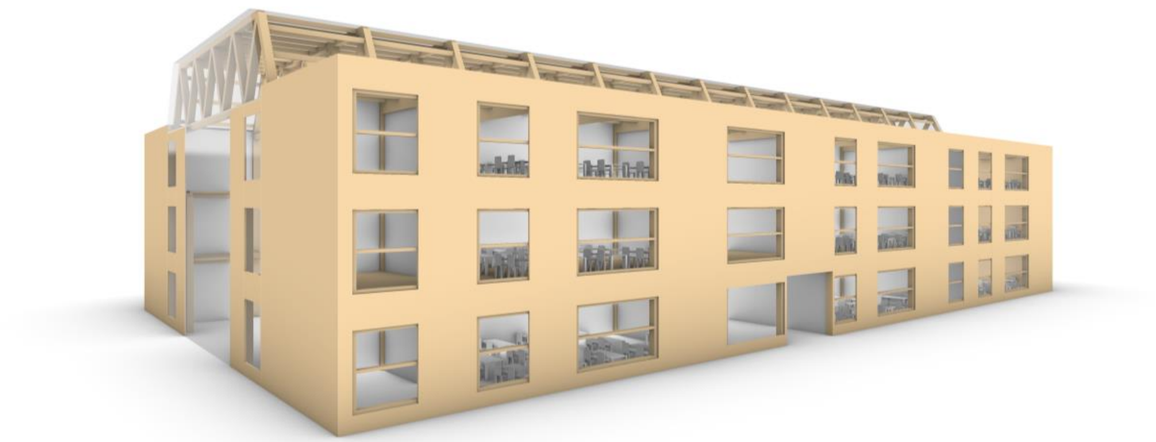


Figure 69 Outside view of the high school

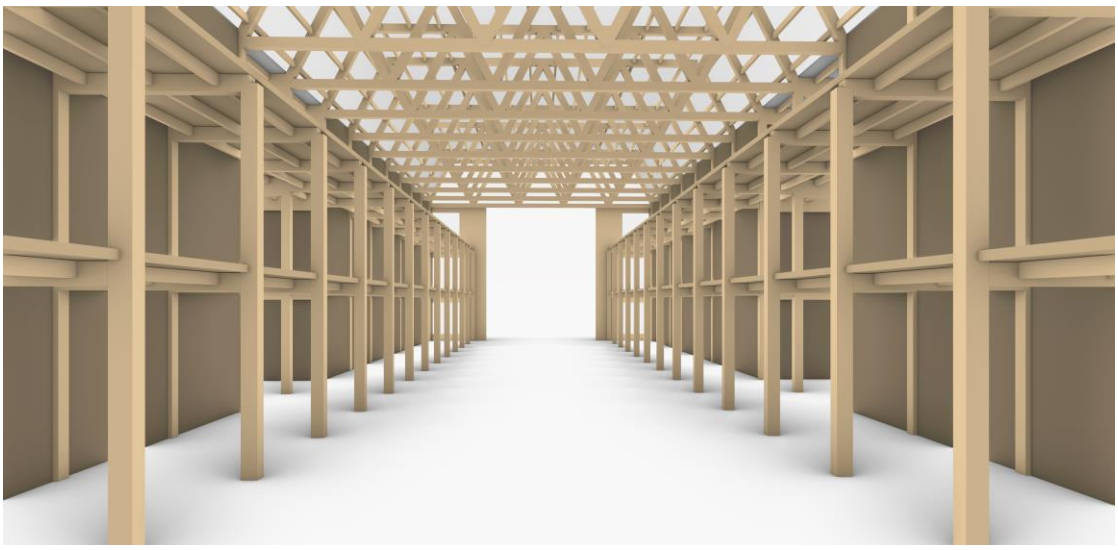


Figure 70 Interior view of the high school

More detailed drawings are accessible in ANNEX J: Detailed drawings of the structure.

Assessing the re-usability

To assess the re-usability of the structure, we can analyse it with the re-use principles developed in Part II.

The concept of scenario-buffering was intensively applied to this project. Indeed, the re-use scenarios were devised in parallel with the origin structure. Consequently, the problematics of finding a resale market, often cited as a major impairment to re-use, is greatly reduced. Similarly, no adjustments of the members and connections are necessary to produce the legacy structure. This can help drive the costs down significantly.

Considering the lack of legislation that hampers re-use, little can be done on a project scale. However, the fact that the project was already dimensioned for its legacy use should help this process. Additional measures should be implemented in a later stage of the project to further simplify the acceptance of re-use. This includes a thorough examination, and documentation of all the demounted elements.

Furthermore, the project uses standardized element length and connections. This means that some members are over-dimensioned. However, it will greatly simplify the demounting and sorting processes.

Finally, both members and connections are generally interchangeable which reduces the constraints of designing with salvaged elements. However, there are still architectural challenges to solve. Indeed, since every element is connected on its neutral axis, the main problem is the difference in floor height when using the diagonals or the chords as beams.

Concerning the demountability of the structure, it can be assessed using the demountability table devised in CHAPTER II: Re-Use. Table 8, on the next page, shows every demountability criterion and its application in the project. It reveals that the designed structure ticks most boxes. The major problem concerns the final demounting of the structure when the materials need to be prepared for recycling. Indeed, the permanent assemblies made with glued-in rods increase the complexity of material sorting. Additionally, the table shows that measures should be put in place in a later stage of the project to create a complete documentation of the structure and its materials.

With the elements salvaged from the structure, there are enough diagonals, chord, secondary members, and connecting elements to build two high schools. In the case where a re-use market is available, the best solution for the remaining pieces is to put them to sale. Another solution is to buy extra secondary beams and central connecting blocks to build roughly 4000m^2 of office buildings and the roof to cover 3800m^2 of industrial buildings. This would yield a 100% re-use for all timber members, as well as 83% of all steel used.

Overall, the designed high school shows that the structure has a good re-use potential with the possibility to create diverse spans without any adjustments on the origin structure. Moreover, the overall structure minimizes the constraints linked with the demounting and sorting of the components.

Table 8 Assessing the demountability

	Principle		Project application
Materials	Use recycled and recyclable materials	✓	Both timber and steel have good recycling properties.
	Minimize the number of different types of materials	✓	Only GL24h and S355 steel are used.
	Avoid toxic and hazardous materials	✓	No toxic materials used.
	Avoid secondary finishes to materials	~	No secondary finishes are designed, although intumescent painting might be required for the steel parts.
	Use lightweight materials and components	✓	Both timber and steel can be considered lightweight.
Connections	Make inseparable subassemblies from the same material	✗	This criterion is not respected due to the glued-in rods. This will make recycling more difficult.
	Provide realistic tolerances for assembly and disassembly	✓	Tolerances are easy to handle with the use of filler plates between the assembled elements.
	Use a minimum number of connectors	✗	The number of bolts could be reduced if we optimized each connection. However, this contradicts the next point.
	Use a minimum number of different types of connectors	✓	Only one type of bolt is used, and three different connecting elements are used.
	Design joints and components to withstand repeated use	✓	The steel connections are robust.
	Avoid chemical connections	✓	The connection between elements respects this rule. However, the glued-in rods will make recycling more difficult.
	Provide access to all parts and connection points	✓	All bolts are easily accessible.
Handling	Design to use common tools and equipment	✓	Only bolts are to be installed on-site which does not require any special equipment.
	Make components sized to suit the means of handling	✓	The members are easy to transport separately, whereas the truss requires two cranes, but its size is decided by the brief.
	Provide and locate means of handling	✓	The connections can be used to connect to the crane. The final plans should clearly highlight where the truss should be hoisted since it is important to the hoisting load-case.
	Allow for parallel disassembly	✓	Each truss farm is self-stable in one direction. Disassembly can be done on both sides of the construction simultaneously.
Design	Use an open building system	✓	The legacy structure uses an open building system.
	Use modular design	✓	The design is modular.
	Separate the structure from the cladding for parallel disassembly	~	This subject is not treated in this project.
	Use a standard structural grid	✓	The grid is close to standard dimensions.
	Use prefabrication and mass production	✓	All members can be prefabricated. It is also possible to prefabricate elements of the truss if the transport costs permit it.
Logistics	Identify points of disassembly	✓	All bolts are clearly visible.
	Provide spare parts and on-site storage for them	~	This is not accounted for in the project but easily implementable.
	Retain all information of the building components and materials	~	To be added if the design goes into construction stage.
	Provide identification of material types	~	To be added if the design goes into construction stage.
	Minimize the number of different types of components	✓	Only two types of components are necessary.
	Provide identification of component type	~	To be added if the design goes into construction stage.

Assessing the sustainability

This subchapter will start with a brief LCA-based calculation to highlight the sustainability trends of the structure. Additionally, it will be used to compare the designed structure with a non-reusable equivalent. Finally, the application of the design for sustainability precepts to this project will be assessed.

LCA-based evaluation

A full LCA would be of interest to gain a complete understanding of the structure's ecological performance. However, this would require an amount of work outside the scope of this project. For this reason, LCA tools are used here to provide an overview of the ecological performance of the constructions.

Scope of the study

Two scenarios are envisioned: the first considers the structure designed for re-use and the second a more standard, single-use, construction. For both scenarios, only one roof truss is analysed with similar conclusions reachable for the columns and the secondary elements.

The global warming potential (GWP) is used as a metric of sustainability. GWP is a measure which converts gas emissions to equivalent CO_2 quantities. Considering only this indicator might overshadow other impacts such as resource depletion and acidification of the soils. However, it will give sufficient results to highlight important trends without too much complexity.

A standard LCA evaluates the structure in all stages, or modules, of its life cycle. However, to simplify this evaluation, both re-use and one-off settings have simplifying hypotheses. Firstly, the results of the production stage (module A1-A3) from cradle until the gates of the factory are taken from environmental product declarations (EPD) made available by producers.

For timber, the data comes from a glue-laminated timber company in Germany (IBU, 2013). It can be noted that for the reasons mentioned in CHAPTER I: Sustainability Strategies, the carbon naturally sequestrated in the timber, as well as the related environmental gains are ignored.

Concerning the steel elements, the GWP data on structural steel plates from another German company is used (IBU, 2018). This ignores factors such as welding, drilling, etc. but greatly simplifies the calculation process. Moreover, the same data is used for the rods since only minor differences are present.

Finally, the glue used for the glued-in rods is also considered. The related information is based on polyurethane resins (IBU, 2015).

Stage A4, the transportation from the factory to the construction site, is based on a 90km trip with 12t lorries for all materials and scenarios. As highlighted in CHAPTER I: Sustainability Strategies, the assembly (A5) and disassembly (C1) stages, as well as the use phase (B1-B7) have little influence on the environmental impact of structural elements and are, thus, ignored. The other life cycle stages differ depending on the scenarios.

The first scenario is based on the re-usable structure. Concerning stages A1-A4, the production stages, the required quantities of each material are known from the design and can be directly multiplied with the associated GWP.

The end-of-life step, on the other hand, is more difficult to assess. First, the transport of the demounted structure needs to be accounted for. Additionally, concerning re-use, it is common practice to credit the emissions avoided by re-using the structure to the original construction (Vogtlander, 2014). The difficulty lies in evaluating how much can be credited. Indeed, simply crediting the GWP of the material re-used ignores the fact that a more material-efficient, one-off, structure could have been built. To obtain an exact value, a complete, single-use version of the legacy structure should be designed which falls outside the scope of this study. For simplicity, a variable called efficiency of re-use is added. It is composed of two values multiplied. First, the re-use percentage which represents the extent to which the construction is re-used. This accounts for damaged elements and eventual mismatches between the offer and the demand for salvaged pieces. Due to a lack of data on this parameter, it is taken, arbitrarily, as 90%. Second, is the re-use efficiency which is the ratio between the material re-used and what would have been necessary for the same function. This parameter depends on the elements re-used and their configuration. For the members re-used as beams, it is relatively simple to compare the salvaged cross-sections with the ones which would be necessary for the same span. For the re-use as columns, it will depend on the number of floors designed. Finally, for the re-use as a truss in an industrial setting, it can be estimated by comparing the truss from re-use with a one-off truss optimized using the script developed in CHAPTER V: System development. Using the same hypothesis as mentioned in CHAPTER III: Structural calculations, we can obtain the following efficiency values:

Table 9 Re-use efficiency

Designed legacy truss							
Parameters				Cross sections			
Height	h	6.3	m	Diagonals	300	x	285
Nbe of spans	n	10		Chord	300	x	285
Length diagonal	l_d	3.7	m	Volume			
Length chord	l_c	3.35	m	Timber volume	V	11.8	m^3
"Optimal" legacy truss							
Parameters				Cross sections			
Height	h	3.7	m	Diagonals	210	x	220
Nbe of spans	n	4		Chord	600	x	210
Length diagonal	l_d	5.6	m	Volume			
Length chord	l_c	8.38	m	Timber volume	V	9.4	m^3
Truss efficiency				**80%**			
Chord elements							
Dimensions from re-use				Required cross-section			
Length	l	6.36	m				
Height	h	500	mm	Height	h	520	mm
Width	b	285	mm	Width	b	255	mm
Efficiency as beam				**93%**			
Diagonal elements							
Dimensions from re-use				Required cross-section			
Length	l	3.02	m				
Height	h	300	mm	Height	h	300	mm
Width	b	285	mm	Width	b	165	mm
Efficiency as beam				**58%**			

The re-use efficiency of the connections is more difficult to calculate without re-designing a complete non-re-usable connection. For this reason, it will follow the efficiency of the elements it connects. This will reduce the precision of the study, but it allows for a simple comparison.

The second scenario concerns the design of the roof truss without any re-use constraints. Again, the cross-sections are based on optimization of the structure weight using the script from CHAPTER V: System development. The connections are difficult to evaluate without designing a complete alternative structure. For this reason, the hypothesis is made that the joints of the re-usable structure are used here. However, the diagonals do not need to be separable in this scenario and the connecting element can be ignored.

Finally, end-of-life scenarios are difficult to take into account. Indeed, most people use cremation and co-generation when dealing with the recycling scenario of timber in LCA. However, the results depend greatly on the electricity mix chosen. For this reason, and because the end-of-life stage of both scenarios will be very similar, this stage is ignored.

It can be noted that the life expectancy of both scenarios is ignored to simplify the calculations. Indeed, I made the hypothesis that the components will have the same value when they will be re-used.

Inventory

All calculations are based on the dimensions devised in the case study. We have the following material consumption for each case:

Table 10 Inventory of materials

LCI - Scenario 0				
Name	Units	Volume (m^3/pc)	Density (kg/m^3)	Weight (kg/pc)
Steel				
Middle assembly	37	5.66E-03	7800	4.41E+01
Diagonal assembly	36	1.92E-03	7800	1.50E+01
Chord endpate	34	3.77E-03	7800	2.94E+01
Diagonal endplate	72	1.03E-03	7800	8.00E+00
Rods	708.84	2.01E-04	7800	1.57E+00
Total steel	-	**6.23E-01**	**7800**	**4.86E+03**
Note: The rods are noted per unit of length				
Glue				
Glue for the rods	708.84	8.247E-05	2000	1.65E-01
Total glue	-	**5.85E-02**	**2000**	**1.17E+02**
Note: The glue for the rods is noted per unit of length				
Timber				
Diagonal	36	2.56E-01	483	1.24E+02
Chord	17	8.75E-01	483	4.22E+02
Total timber	-	**2.41E+01**	**483**	**1.16E+04**

LCI - Scenario 1				
Name	Units	Volume (m^3/pc)	Density (kg/m^3)	Weight (kg/pc)
Steel				
Middle assembly	17	5.66E-03	7800	4.41E+01
Diagonal assembly	32	1.92E-03	7800	1.50E+01
Chord endpate	30	3.77E-03	7800	2.94E+01
Diagonal endplate	32	1.03E-03	7800	8.00E+00
Rods	708.84	2.01E-04	7800	1.57E+00
Total steel	-	**4.46E-01**	**7800**	**3.48E+03**
Note: The rods are noted per unit of length				
Glue				
Glue for the rods	708.84	8.2467E-05	2000	1.65E-01
Total glue	-	**5.85E-02**	**2000**	**1.17E+02**
Note: The glue for the rods is noted per unit of length				
Timber				
Diagonal	16	3.80E-01	483	1.84E+02
Chord	15	1.14E+00	483	5.50E+02
Total timber	-	**2.32E+01**	**483**	**1.12E+04**

The table below exposes the global warming potential for each material. All values have been transferred in kg of CO_2 equivalent per m^3 of material.

Table 11 GWP of each material

GWP: kg CO2 eq per m³ of material				
Stage A1-A3				
Name	Supply of raw material (A1)	Transport (A2)	Manufacture (A3)	Total A1-A3
Timber [1]	Ignored	3.21E+01	6.82E+01	1.00E+02
Steel [2]	Aggregated in the data			8.81E+03
Glue [3]	Aggregated in the data			8.20E+03

Concerning the freight impact, a value of 0.148 kg of CO_2 eq. per ton of merchandised transported per kilometer is taken (ProBas, 2000). This already includes the empty truck returning from the delivery site.

Impact assessment

Now that all categories and their impact are known, the GWP for each scenario can be calculated. The results are visible in the table below. Note that the tables are made with the best possible re-use scenario.

Table 12 GWP of the trusses

LCI - Scenario 0				
Stage A1-A3				
Name	Volume (m³)	GWP/m³	GWP/material	% of stage
Timber	2.41E+01	100.30	2.42E+03	28.82%
Steel	6.23E-01	8814	5.49E+03	65.47%
Glue	5.85E-02	8200	4.79E+02	5.72%
Total	2.48E+01		8.39E+03	100.00%
Stage A4				
Name	Weight (kg)	Distance (km)	GWP/material	% of stage
Timber	1.16E+04	90	1.55E+02	70.05%
Steel	4.86E+03	90	6.47E+01	29.25%
Glue	1.17E+02	90	1.56E+00	0.70%
Total	1.66E+04	90	2.21E+02	100.00%
Stage C2				
Name	Weight (kg)	Distance (km)	GWP/material	% of stage
Timber	1.16E+04	90	1.55E+02	70.05%
Steel	4.86E+03	90	6.47E+01	29.25%
Glue	1.17E+02	90	1.56E+00	0.70%
Total	1.66E+04	90	2.21E+02	100.00%
Stage D				
Name	GWP/material A1-A3	Re-use efficiency (km)	GWP/material	% of stage
Timber	2.42E+03	83.70%	-2.02E+03	28.82%
Steel	5.49E+03	83.70%	-4.60E+03	65.47%
Glue	4.79E+02	83.70%	-4.01E+02	5.72%
Total	8.39E+03	83.70%	-7.02E+03	100.00%
Total				
Name	GWP/material with re-use	GWP/material without re-use		
Timber	7.04E+02	1.17E+04		
Steel	1.02E+03	4.86E+03		
Glue	8.12E+01	1.17E+02		
Total	1.81E+03	1.66E+04		

LCI - Scenario 1				
Stage A1-A3				
Name	Volume (m³)	GWP/m³	GWP/material	% of stage
Timber	2.32E+01	100.30	2.32E+03	34.50%
Steel	4.46E-01	8814	3.93E+03	58.38%
Glue	5.85E-02	8200	4.79E+02	7.12%
Total	2.37E+01		6.73E+03	100.00%
Stage A4				
Name	Weight (kg)	Distance	GWP/material	% of stage
Timber	1.12E+04	90	1.49E+02	75.68%
Steel	3.48E+03	90	4.63E+01	23.53%
Glue	1.17E+02	90	1.56E+00	0.79%
Total	1.48E+04	90	1.97E+02	100.00%
Total				
Name	GWP/material			
Timber	1.12E+04			
Steel	3.48E+03			
Glue	1.17E+02			
Total	1.48E+04			

Results

The LCA-based study, although limited by the many simplifications, highlights important trends. First, the increase in GWP caused by the design for re-use is small in comparison with the possible gains. Indeed, even with no re-use of the elements, the increase in GWP due to designing for re-use amounts only to 12%.

Additionally, in the ideal scenario, with a high re-use efficiency and a short distance between the origin and legacy structure, re-using reduces the GWP by almost 90% from a non-reusable structure.

The analysis also shows the impact of steel on the overall GWP of the truss. Although, steel only corresponds to 2.5% of the entire volume of the truss, its significantly higher GWP makes it the major contributor to the ecological cost. Therefore, it raises the importance of optimizing the connection, of using steel from recycling sources or to replace the steel connections with another material such as high resistance LVL. Re-using to a maximum the connections is also important to reduce the environmental impact.

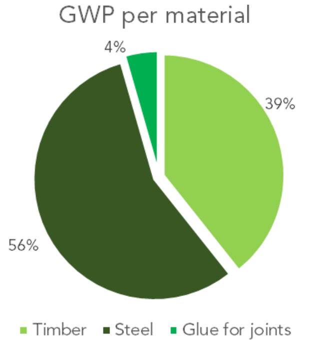


Figure 71 GWP by material

Moreover, it is of interest to look at the importance of re-use efficiency. As exhibited by Figure 72, re-use efficiency has a strong influence over the GWP of the construction. Indeed, in the worst-case scenario where the diagonals are re-used as beams, the gains from re-using the structure drops significantly. Nevertheless, it can be noted that it still represents substantial savings, more than 65%, over the non-re-usable design. Additionally, this graph shows the importance of re-using each element as efficiently as possible. In an ideal scenario, the diagonals would serve only as columns with re-use possible in trusses for the remaining elements. Finally, it shows the need for further research to quantify re-use efficiency to a finer extent and have more precise results.

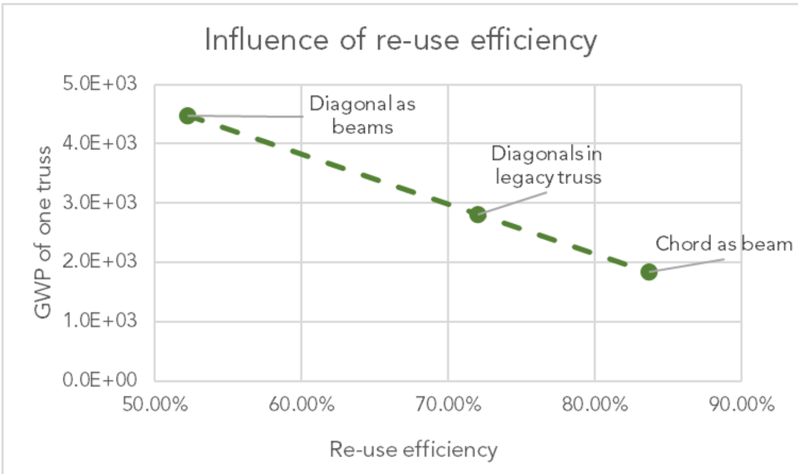


Figure 72 Influence of re-use efficiency

Finally, Figure 73 shows the influence of the distance between the two structures on the GWP. For clarity, and because there is no difference in the savings, the re-use gains are not included in this figure. As expected, fret related emissions can reach a significant portion of the total GWP if the transport distance increases. However, for short distances, its impact is low.

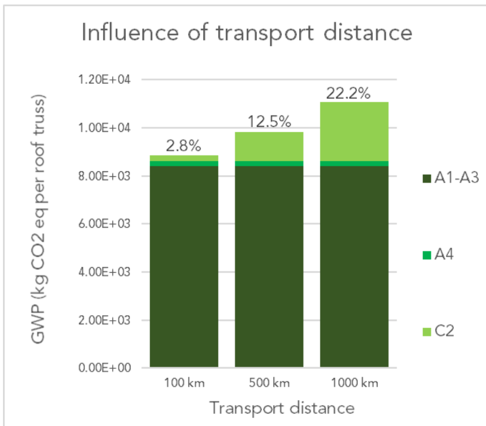


Figure 73 Influence of transport distance

Application of the design for sustainability guidelines

In CHAPTER I: Sustainability Strategies, five strategies were identified as enablers of sustainable construction. They were applied throughout the project and will now be assessed in light of the case study.

The first strategy was to minimize material use. It was applied in length to the timber part of the structure. The challenge was that this guideline should be followed in both the origin and legacy scenarios. Indeed, applying this strategy to both contexts increases re-use efficiency which has a major impact on the GWP of the structure. Material optimization was not applied to the connecting elements. However, considering the importance of steel on the GWP, the joints should be further optimized.

The choice of timber as the main structural material was motivated by the second strategy: minimizing material production energy. This shows in the LCA-based study since timber, representing 97% of the structure's volume corresponds only to 40% of the GWP. Efforts are still required, however, to reduce the production energy for the connections. Using recycled steel could be one alternative. Developing a high-density LVL connection could also prove beneficial.

The next guideline was to minimize embodied energy through design. This objective aims mainly at increasing the recyclability of the structure. This is hampered by the glued-in rods which make separating timber from steel difficult. However, this was done in favor of the next objective: maximizing structural re-use.

The study showed an important reduction in GWP allowed by maximizing re-use. The methods applied to ensure the re-usability of the structure have been assessed earlier in this chapter.

Finally, as expected, LCA proved to be a valuable tool to highlight the trends of the construction. Although further research is required to reach precise conclusions, the analysis highlighted the importance of steel in the GWP of the structure. This contradicts the assumption that means of connection represent a small part of the environmental impact. For this reason, it would be of great interest to optimize these steel elements. Moreover, additional work of designing complete non-reusable alternative structure should be done to have more precise results. However, a full LCA is a time-consuming process that necessitates resources lacking accessibility. This might reduce the applicability of this guideline to common practice.

Overall, the guidelines helped in creating a more sustainable project. Although meeting all of them is difficult because some objective might be in conflict, keeping their essences in mind is essential to sustainable construction.

PART V

CONCLUSIONS

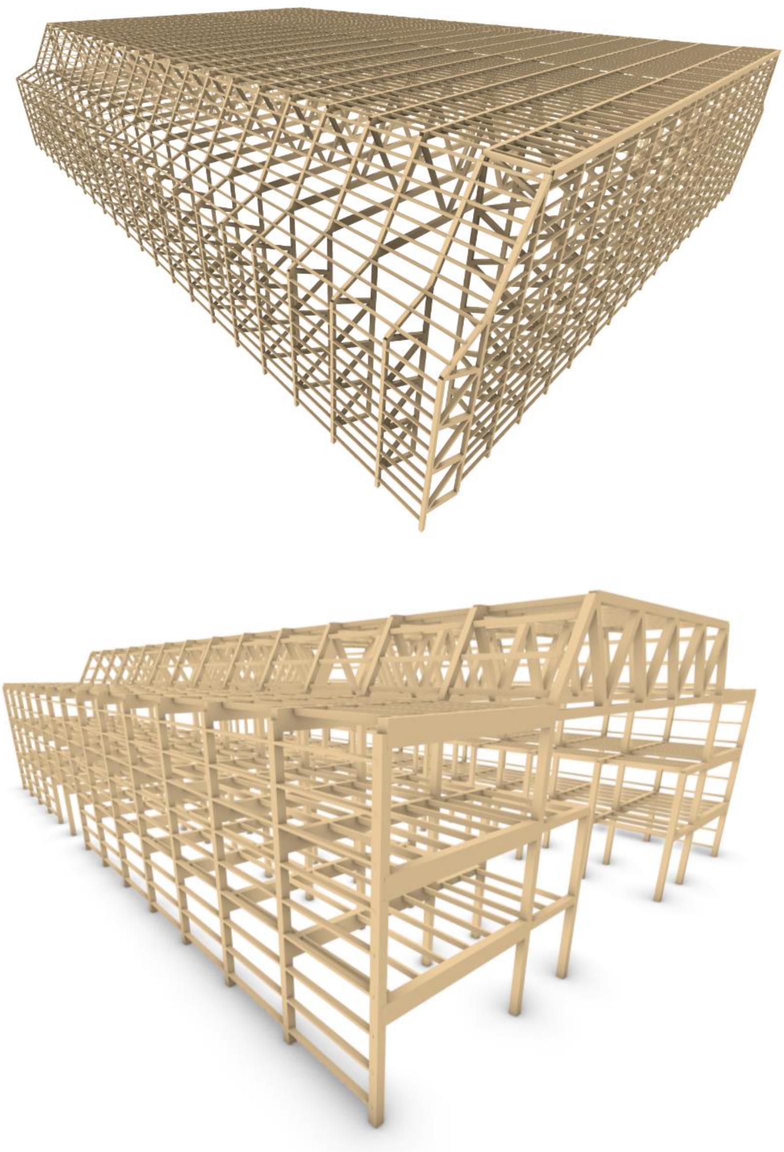


Figure 74 Origin and legacy structures

CHAPTER I: Conclusions

The goal of this project was to explore multi-purpose re-use as an opportunity to reduce wastes and resource consumption in the construction industry. In this chapter, the main findings of the report will be exposed by answering the research questions.

The main question of this research was:

How to design a timber, multi-use, structural solution to maximize re-use possibilities?

Answering this question first requires research on sustainable design.

> *How to design more sustainable constructions?*
>
> Sustainability, especially resource consumption and waste generation, was the guiding principle of this thesis. To design more sustainable constructions and minimize the environmental impact of the structure, a set of guidelines was established. These include minimizing material use through structural optimization, reducing production energy by careful material selection, diminishing embodied energy trough recyclable design, maximizing re-use, and assessing the environmental performance throughout the project. To achieve the last goal, the research studied LCA and its variations to evaluate the design. However, given the time-intensive nature of LCA, simpler variations were explored. Consequently, short track LCA, which reduces the complexity of the study by using the outcomes of previous studies as a starting point for calculations, was selected.
>
> Nevertheless, traditional LCA provided useful information on the design of sustainable timber constructions. Investigating existing studies showed the benefits of using such a material. However, special attention regarding local sourcing, drying, and cascading is necessary to improve sustainability.

This project poses re-use as a strategy to reduce the environmental impact of constructions. Indeed, the literature review showed how designing for re-use significantly reduces wastes and GHGE. This raises the question of how to design for re-use.

> *What are the important guidelines and constraints for a re-usable structure?*
>
> Looking at the re-use of existing structures highlighted the absence of legislation, the costs of member adjustments, and the lack of resale market as the major impediments to re-use. Additionally, the distance between the old and new construction diminishes the environmental benefits of this practice.
>
> Consequently, a set of guidelines for re-use was developed. While the lack of legal frameworks is outside the scope of this study, the costs of re-use can be significantly reduced by increasing standardization. Additionally, scenario buffering, the act of designing with the end of life scenario in mind, is the main tool to ensure that the salvaged elements are adapted to future uses and can be sold easily. Finally, developing multi-purpose re-use facilitates resale and local re-use.

Demountability is the main constraint when designing for re-use and was therefore explored thoroughly. The most important findings revolve around one concept: simplifying the logistics. This implies standardization, prefabrication, planning, and documentation.

Once the guidelines for a sustainable, re-usable structure have been set, timber solutions were selected accordingly. The final decisions are addressed in the following questions.

What timber products should be selected for re-use?

Although it is more energy intensive, GLT was selected for its great structural capacities, and wide availability. More importantly, it shows great dimensional stability, which is essential for re-use and demountability.

What assembly should be used when designing for re-use?

The assemblies are realized with glued-in rods and steel plates. This increases the modularity of the connection, a crucial design point given the major differences between origin and legacy structure. Moreover, the use of steel provides ductility to the structure. On the other hand, the main disadvantage of such joints is the reduction of recyclability that comes with making permanent assembly from two materials.

What structural systems are appropriate to multi-use?

Using scenario buffering, a truss system was chosen for the origin structure mainly because of its inherent standardization. The efficiency of such systems and their ease of installation were convincing factors as well.

These five questions answer the main research problem. However, it was of interest to test the given answers with a case-study.

Is it structurally feasible to re-use an Olympic construction in residential or office settings?

To test the feasibility of the devised concept, a case study was performed. It consists of the design of a badminton arena for the Olympics to be re-used as a high school. Applying the devised guidelines allowed for the design of a structurally feasible concept. Indeed, almost all elements have standard re-use scenarios for which they are adapted geometrically and structurally without the need for any adjustments. Applying scenario buffering was particularly useful for this process. Additionally, minimizing material-use proved to be a very powerful tool thanks to its compatibility with computer optimization and the increased re-use efficiency it resulted in. While this was applied completely to the timber members, more optimization is required for the connections. Indeed, the goals of sustainability and re-use were more difficult to conciliate for the joints given the major forces present in the truss. However, being almost completely re-usable greatly reduces the impacts of this problematic. The only exception concerns the elements connecting the diagonals to the chord in the roof truss. Indeed, they required a special inclination which has no alternative re-use option. For these elements, recycling is recommended.

Using an LCA-based study on the project provided valuable information. First, it showed that the structure approaches its goals of sustainability by reducing significantly the GHGE compared with a single-use construction. Moreover, the analysis highlighted the importance of the steel assembly in the environmental impact. This proved wrong the hypothesis, based on previous studies, that connections are a marginal portion of the overall impact. The LCA-based study, however showed that more time is required for a full study with precise findings.

Overall, this project proved the structural feasibility of multi-purpose re-use. The designed guidelines were tested in the case study and showed satisfactory results. It is the author's opinion that re-use has an important role in reducing the negative impacts mankind has on its environment. Hopefully, such a research is a small step towards a broader integration of re-use principles. Multi-purpose re-use, although pushed to an extreme in this case study, is necessary to simplify re-use logistics, and, consequently, reduce re-use costs. However, additional research on that field is recommended and is described in the following chapter.

CHAPTER II: Recommendations

Re-use and the construction industry are intrinsically multi-disciplinary fields. This research focused on the structural aspect of these problematics with a particular interest in sustainability. However, diverse aspects need to be explored further to apply multi-purpose re-use to concrete projects. They will be shortly presented hereafter.

The structural dimension was extensively covered in this project. Although certain elements were simplified, further research on this topic would not significantly advance the problematic. An exception is the optimisation of the connection. Indeed, in-depth modelling should allow for sizeable thickness reductions and, consequently, important changes in the environmental costs of the construction.

Building physics are an important part of sustainable construction. Indeed, the operational energy represents the major portion of the GHGE linked with the built environment. Therefore, it would be of the greatest interest to develop a demountable solution for the roofs and facades of the two projects.

Money is always the crux of any project. While costs were considered in the choices of structural systems and re-use strategies, no detailed cost analysis was performed. It would be of interest to quantify the economic costs, and possible benefits at the end-of-life, of re-use.

Sustainability was widely discussed in this project. However, the application of the LCA-based study was subject to many simplifying hypotheses. A full LCA would be of great interest to precisely quantify the environmental implications of re-use.

Finally, it occurred to the author that the greatest obstacle to re-use is its lack of integration with the current design philosophy. It would, therefore, be of major importance to research what can be done to incentivize such practices. Adding re-use to certification systems such as BREAM could be a good starting point. Moreover, the growing waste taxes might help put re-use as the most profitable alternative and thus increase its popularity. Finally, developing the re-use market by setting up databases for salvaged elements is of crucial importance.

APPENDIXES

ANNEX A: Interview

Questions générales sur le marché du bois en Suisse :

Quelle influence a l'intérêt grandissant du public pour le développement durable sur l'industrie du bois suisse ?

Oui très clairement, on ressent maintenant une grande différence par rapport à il y a 30 ans en arrière où le bois était utilisé principalement dans la construction de chalets ou de fermes. Maintenant on a eu évolution incroyable, notablement au niveau de la technologie, et le développement durable nous aide beaucoup aussi. Le fait que l'on puisse stocker 1 tonne de CO_2 *dans* $1m^3$ *de bois ça a sensibilisé énormément les gens.*

Comment se reflète ce changement de mentalités sur les pratiques de JPF Ducret ?

On a un bon changement avec le sous-produit qui est beaucoup utilisé en bois énergie. Il y a 20 ans les sous-produits étaient à bien plaire, brûlés comme déchet. Maintenant, je ne pense pas qu'en suisse il y ait de filière pour compresser des panneaux OSB. [Commentaire ajouté plus tard] Chez JPF Ducret, un de nos arguments de vente est que la grande majorité des produits vendus sont issus de production Suisse certifiée FSC.

Et est-ce que vous utilisé du bois massif pour réduire les impacts liés au séchage et découpage ?

On n'utilise de moins en moins le bois massif pour la simple et bonne raison qu'on préfabrique énormément. Et que, pour des raisons de stabilité dimensionnelle, on travaille avec du bois sec, pour quoi le lamellé collé est plus approprié. Actuellement, on utilise le bois massif pour les fondations. Typiquement pour la fête des vignerons on a appliqué des fondations en bois qu'on a pu retirer à la fin.

Le processus de séchage, justement, est reconnu comme ayant un impact important, comment est-il réalisé au sein de votre entreprise ?

Il est réalisé de manière artificielle au four. Effectivement, il est réalisé avec des sous-produits. Cependant, chez nous, nous achetons le bois déjà séché et découpé.

Les éléments structurels ont souvent une espérance de vie plus importante que celle du bâtiment. Est-ce que vous construisez avec des éléments récupérés de vieilles constructions ?

Nous très peu, je ne dirais même quasiment pas. Hormis pour les constructions provisoires ou on le récupère pour autre chose. Sur les bâtisses qui ont fini leur cycle de vie, il faut se demander pourquoi elle a fini son cycle de vie. Il y a des entreprises spécialisées pour récupérer la structure, notamment pour des chalets, la nettoyer et la réutiliser. Cependant c'est plus pour une utilisation, je dirais, luxueuse du bois.

Selon vous, quels-sont les obstacles qui empêchent la réutilisation ?

C'est une question de cahier des charges. Pour un bâtiment qu'on voudrait juste déplacer c'est possible. Mais pour avoir un bâtiment par exemple rectangulaire qu'on voudrait faire en losange, ça va être difficile au niveau de la longueur des pièces et de la section des pièces de réutiliser des éléments déjà façonnés. C'est vrai qu'avoir comme une boîte de lego avec laquelle on pourrait construire un bâtiment A comme un bâtiment B serait intéressant. Même s'il n'y a pas encore une solution pour ça, on a des procédés qui pourraient nous y amener très facilement je pense [Commentaire ajouté plus tard] Le problème est aussi que les adaptations géométriques risquent de coûter plus que les nouveaux éléments.

Outre pour les structures temporaires, quelle est l'importance du démontage lors de la construction de nouveau bâtiments ?

On ne design pas, à proprement dit, avec sa en tête. C'est vrai que ce serait intéressant de faire cette démarche-là. Cependant c'est une démarche qui doit être faite en amont.

Questions sur la terrasse du Paléo :

Quelle influence a la nature temporaire de l'ouvrage sur le choix du système structurel ?

Bien entendu, il a fallu être inventif pour pouvoir monter la structure dans le temps imparti. Moins d'une semaine pour le montage et une grosse semaine pour le démontage. Il faut avoir des assemblages très simples à manutentionner. [Commentaire plus tard] L'identification est aussi importante, chaque élément a un nom selon où il se situe et est répertorié dans le 3D. Additionnellement, la préfabrication joue un grand rôle pour la stabilité dimensionnelle et la précision des éléments. De plus, les éléments sont répétés le plus de fois possible pour faciliter la production et minimiser les problèmes de montages.

Comment la stabilité de l'ouvrage est-elle garantie, notamment pendant la construction ?

L'entier de la structure est stabilisé par un système de contreventement avec des plaques scellées. Pendant la construction, les premiers cadres du bas ont des béquilles intégrées qui garantissent la stabilité. Ensuite dès que deux éléments sont liés, on connecte les contreventements et les éléments sont tout de suite très stables.

Comment avez-vous trouvé l'équilibre entre la préfabrication et les contraintes de montage ?

Actuellement, la structure tient en 20 semi-remorques pour l'amener depuis son lieu d'hibernage. Les cadres sont déjà pré-composé et sont boulonnés sur place. Ils sont amenés un niveau de ferme à la fois. Toujours dans l'optique de réduire l'impact environnemental du festival, le Paléo s'est procuré des hangars pour stocker la structure plus proche du site.

Quelles connexions ont été sélectionnées pour garantir une (dé)installation rapide et répétée ?

Pour la structure, on est sur des assemblages avec des plaques métalliques qui sont scellées dans le pied et la tête des structures qui nous permettent de venir *simplement boulonner sur place. [Commentaire plus tard] Ces assemblages sont basés sur le système ferwood breveté par l'entreprise où on perce le bois pour y mettre un connecteur métallique qui est joint avec la pièce en utilisant une résine. Pour le plancher, on a des épaulements dans les sommiers pour nous appuyer. Sur quoi, on a des panneaux qui débordent connecté par des boulons pour assurer l'effet du diaphragme.*

Comment la construction évolue-t-elle dans le temps ?

La structure avait été prévue pour 8 ans et elle a été rallongée après examen. On n'a vraiment pas eu de soucis à continuer avec ce projet, les éléments se portent bien. Surtout ce qui est structurel se porte très bien.

Des éléments (type assemblages, poutres) ont-ils dû être réparés ou remplacés à la suite de l'utilisation ou des cycles de montages-démontages ?

La seule chose qu'on a dû changer c'est les plancher avec l'usage et la manutention. On avait fait le choix d'un simple panneau OSB qui a pris quand même l'humidité selon les éditions. De plus il y a quand même beaucoup de passage et donc d'usure.

ANNEX A1: Translated Interview

General questions on Switzerland's timber industry

What impact has the growing climate change awareness on Switzerland's timber industry?

Today, we feel a big difference compared to 30 years ago when timber was used primarily in the construction of cabins and farms. We've had an incredible evolution, notably thanks to technology developments, and with great help from sustainability movements. Knowing that we can stock 1 ton of CO_2 in $1m^3$ of timber, for example, has greatly interested clients.

Do you feel that this change of mentality influenced the company's practices, notably in recycling?

We've had great changes concerning timber's byproducts. Twenty years ago, it was discarded or burnt as wastes. Today it is mostly used for energy production. Concerning recycling, to my knowledge, there is no market in Switzerland.

Roundwood is known to reduce environmental impact by reducing drying and cutting needs, is it enhancing its usage?

We use less and less roundwood because we try to prefabricate as much as possible. This requires good dimensional stability and therefore we prefer to work with dried timber. Presently, apart from renovations or architectural choices in traditional cabins, roundwood is sometimes used for foundations. For example, during the winemaker festival in Vevey, we made a temporary structure resting on roundwood piles that we extracted when demounting.

Amongst the most energy-intensive processes is drying, did you take measures to reduce its impact?

We don't dry the timber ourselves. However, it is done in a kiln using timber byproducts for the heat generation.

Structural elements often outlive their buildings. Do you re-use components from older constructions?

No, very rarely. Unless for temporary construction where we re-use elements. Buildings reaching end of life needs to be assessed and often reach this stage for a reason. There are companies specialized in recovering and treating old timber for re-use. However, it is more for a luxurious utilization of timber.

Why is re-use not more implemented?

It's a question of client specifications. If we wanted to move a building, it would be possible. However, the length of elements and their cross-section might be difficult to adapt if we change from a rectangular shaped building to a diamond floorplan, for example. Moreover, geometric adaptations might cost more than new components. It is true that having lego-like components that could be used to build building A as well as building B would be interesting. Even if such a system doesn't exist yet, I believe we would have the technology to achieve such a concept.

Such re-use requires to think, during the design phase, about the dismantling of a construction. Is it something you take into account besides temporary structures?

We don't design for disassembly per se. It would indeed be an interesting approach. However, it must be done upstream and with a client's interest.

Questions on Paleo's terrace

What influence had the temporary nature of the work on the choice of the structural system?

Of course, we had to be inventive to mount the structure in the allowed time. Less than one week for construction and a good seven days for deconstruction. It requires very simple connections with easy manutention. Identification is also important. Every element has a name referring to its position and cataloged in the 3D model. Additionally, prefabrication plays a big role in dimensional stability and precision. Moreover, elements are repeated multiple times to ease production and decrease construction problems.

How is the stability of the construction assured, notably during construction?

The entirety of the structure is stabilized using a system of bracings and plates. During construction, the first frames have integrated struts that guarantee stability until the bracings are connected.

How did you find the equilibrium between maximizing prefabrication and mounting constraints?

The prefabricated elements were designed to fit in twenty trucks which are used to bring the structure from its hibernating place to the festival. The frames are prefab and are bolted together on-site. One frame element is one story high.

What joints did you use to guarantee a fast and repeated (de)mounting?

For the main structure, we used metal plates with glue-in rods that we bolted on-site. They are based on the company's patented fermwood system where we drill a hole in the timber, and, using resin, glue steel rods. For the floor, the joists are connected with shoulders on the main beams. Finally, we have OSB boards bolted to the beams for flooring and diaphragm effect.

How did the construction evolve in time?

The structure's lifespan was planned for 8 years and was lengthened after an examination. We had no problems with this project, the elements are in a good state. The structural components, in particular, are in perfect state.

Did you have to replace or repair certain elements?

The only thing we changed is the floorings due to usage and manutention. We had simple OSB boards that were damaged by water and the many people walking on it.

ANNEX B: Olympic venues

The purpose of this annex is to find what MSE facilities would benefit the most from re-use. To do so, the pas six Olympics were reviewed and each facility evaluated according to metrics defined hereafter.

MSE facilities

The Olympics were taken as a basis for cataloguing the possible sports. This decision is due to the diversity of this competition with a total of 48 sports between the summer and winter editions. Some sports were excluded from the selection because of the nature of the infrastructure. This includes, for example, downhill skiing or outdoor cycling because they require either no infrastructure or stands that are perfectly suited for steel scaffolding systems. For the remaining sports, the past 6 Olympics were reviewed. The table describing these events is accessible at the end of the annex.

Once reviewed, the sports were placed in the following categories: The event took place in a facility made for a different activity (+0.5); A facility was made specifically for the OG (+1); The event took place in an existing venue made for this sport (-1); A flexible solution was used, either completely or partially demountable, or adaptable (+1); The arena is now used for a different activity (+0.5); The facility is now demounted (+1); The venue is still in use (-1); The facility is unused, destroyed because of lack of use, or in financial difficulty (+2); The event took place in the same facility as another Olympic event (-1). Each event is therefore placed at least in one pre-event and one post-event category unless this facility is used for other sports from the Olympics. For partially demountable facilities, they can be in two categories.

Each category was then given a score (in brackets in the list above), a negative score means that re-use options are not necessary for these facilities while a positive score means the opposite. Additionally, requiring the same facility as another sport is treated as a negative point to avoid having the same venues twice. It can be noted that using a facility from another, non-Olympic, activity has less importance because it means that the infrastructure is not wasted. Similarly, an unused stadium has more impact.

In the end, the number of cases fitting the category are multiplied with their relative score and added. In the end, since some sports require multiple arenas, the total score is divided by the total number of venues for this particular sport. The final scores are also visible in ANNEX B: Olympic venues.

From this process, the five events with the highest scores were selected and their requirements are exposed below.

Athletics

With a score of 1.5, Athletics is the joint third-highest score. The reason for this score is that the IOC demands a stadium fitting 60'000 people for this event. Consequently, it is later used for other sports such as football, although certain flexible stadium kept the possibility to host athletics competitions. Additionally, this stadium will be used for the opening and closing ceremonies. It is usually built for the event to serve as a symbol of the Olympics.

Figure 75 Beijing Athletics stadium

In most cases, the symbolic nature of the construction hinders the re-use options. Indeed, in the case of the London Olympics for example, Wembley stadium would have been fit to be the main stadium, but the London Stadium was built anyway.

Moreover, extensive research has already been conducted to make this type of stadium demountable and scaffolding steel structures are perfectly adapted for it.

Aquatic sports

Grouped together, the sports needing a pool obtained a score of 1.42. Swimming is the one requiring the biggest capacity with 12'000 seats needed. In the past 6 Olympics, such facilities were left unused in two instances: Rio, where it was built as a temporary arena but was never dismantled, and Athens.

The venue must fit a 50 by 25 meters swimming pool to host the swimming competitions. It can also host the water polo competitions and requires an extra pool if diving is to be held there.

A possible lead to explain why this venue scored so high is the cost of maintenance of swimming pools and the difficulty, for this sport, to fill 12'000 seats on a regular basis. Amongst the strategies used in the reviewed Olympics is the case of the semi-temporary venue in London already discussed in chapter 3 of part I.

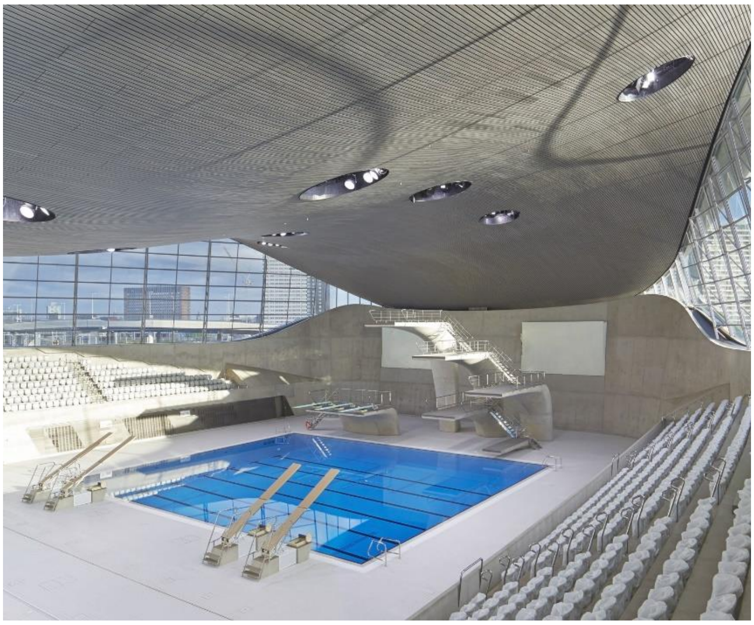


Figure 76 London aquatics venue in legacy mode

Aquatics venues could be of interest to re-use. Indeed, because it takes place indoor, the timber would be protected from the rain. Moreover, the structure for the roof is of interest to prove the versatility of the structural system. However, the swimming pool would then have to be used as an outdoor facility.

Beach volley

Figure 77 Beach volley venue in Athens in decrepitude

Often built as temporary scaffolding stadiums, beach volleyball scores second with 1.8. It was built permanently in Athens and Beijing with the former never used after the OG. The geometry of the stadium with high stands and exposure to rain, sand, and sun means that it is more appropriate to build it as a scaffolding type temporary structure such as Rio, London and Sydney's committees chose. However, it could be interesting to try and compete with such a structural system.

Hockey

Field hockey is the highest scoring sport with a score of 2. Indeed, the 10'000 seats necessary seem out of proportion with the number of people practicing this sport in certain regions. While it is popular in Canada and in the Netherlands for example, in France it has 60'000 licensed players, a third of what badminton has (INJEP, 2018). It mostly takes place in semi-temporary venues where the seats are demounted at the end of the competition. Its applicability to this project is similar to beach volley venues.

Figure 78 London's hockey venue

Speed skating

Speed skating scored 1.5 and is the only winter Olympics sport in the top 5. Again, its score is due to the lack of public in certain regions compared with the required 6000 seats. This concerns mostly long track speed skating which requires a track of 180 by 90 meters.

Most of the reviewed competitions re-purposed the venues into exhibition centres once the games were over. However, such a venue could be of interest for this project. Indeed, the length of the stadium means that no high stands are necessary. Additionally, the long span roof is of interest to this project as a test for the versatility of the system developed. Finally, the indoor requirements mean that the timber would be protected.

Figure 79 PyeongChang's speed skating venue

Summer Olympics									
			Rio	**London**	**Beijing**	**Athens**	**Sydney**	**Atlanta**	**Score**
Sport	Seats		2016	2012	2008	2004	2000	1996	
Archery	4000	*Origin*	Use of already existing samba stadium	Use of cricket stadium already existing	Built temporary	Use of 114ad stadium	Built for the OG	Temporary structure	**0.7**
		Legacy	Still in use (for samba)	Still in use (for cricket)	Now dismantled	Still in use	Still in use	Rebuilt abroad	
Athletics	60000	*Origin*	Built for OG	Built for OG	Built for OG	Built for OG	Built for OG	Built for OG, partly built for deconstruction	**1.5**
		Legacy	Unknown yet	Rented to football team	Partially used	Rented to football team	Used for other sports	The permanent part is home to a baseball team	
Aquatics	12000	*Origin*	Built temporary for OG	Partly demountable stadium	Build for OG	Built for OG	Existing facility with temporary seating for the OG	Existing facility with temporary seating for the OG	**1.42**
		Legacy	Never dismantled, unused	Demounted and permanent part still in use	Repurposed	Unused for 10 yrs. Then refurbished	Still in use	Still in use	
Badminton	5000	*Origin*	Use of existing congress centre	Use of existing indoor arena	Built for OG	Built for OG	Built for OG	Originally basketball arena for local university	**1**
		Legacy	Number of places reduced after, use unclear	Still in use (multipurpose)	Still in use	Privately refurbished as theatre	Now used as exhibition hall	Still basketball arena for local university	
Basketball	15000	*Origin*	Built for OG	Use of existing indoor arena	Built for OG	Use of existing basketball hall	Built for OG	Adaptation of existing stadium	**-0.25**
		Legacy	Number of places reduced after, use unclear	Still in use (multipurpose)	Used as a multi sport stadium (also ice hockey)	Still in use	Used for multiple shows	Still in use	
Boxing	6000	*Origin*	Same as badminton	Use of existing indoor arena	Indoor arena renovated for the OG	Created for OG	Use of existing convention centre	Use of existing basketball stadium	**0.25**
		Legacy		Still in use (multipurpose)	Still in use (multipurpose)	Adapted for reuse	Still in use	Still in use	
Canoe/kayak/rowing	10000	*Origin*	NA	Use of existing facility with addition of temporary seatings	Built for OG with mostly temporary seatings	Built for OG	Built for OG	Use of existing facility	**0.2**
		Legacy		Temporary seats demounted, still in use	Temporary seats demounted, still in use	Still in use	Still in use	Still in use	

			Rio	London	Beijing	Athens	Sydney	Atlanta	Score
Sport	Seats		2016	2012	2008	2004	2000	1996	
Cycling (track only)	5000	*Origin*	Build for OG	Built for OG	Built for OG with temporary seating	Refurbished for OG	Built for OG	Same as archery	**0.33**
		Legacy	Still in use but unclear	Adapted for legacy	Temporary seats demounted, still in use	Still in use	Still in use		
Equestrian	12000	*Origin*	Built for OG	Built with temporary seatings	Used of another city's existing facility	Built for OG	Built for OG	Built for OG	**0.5**
		Legacy	Unknown now	Demounted	Still in use	Still in use	Still in use	Still in use	
Fencing	4000	*Origin*	Built for OG	Same as boxing	Built for OG	Built for OG	Same as boxing	Use of an existing congress centre	**0.83**
		Legacy	Multiple reuse planned but unclear		Used as convention centre	Unused since		Return to original use	
Gymnastic	12000	*Origin*		Same as badminton		Adaptable stadium built for OG	Same as basketball	Same as basketball	**-0.55**
		Legacy				Still in use (multipurpose)			
		Origin	Use of existing hall	Same as basketball	Built for OG	Same as basketball	Same as badminton	Use of existing basketball stadium	
		Legacy	Used for basketball		Repurposed as multifunction hall			Still in use	
Handball	10000	*Origin*		Same as basketball	Same as gymnastics	Same as basketball		Same as basketball	**-0.55**
		Legacy							
		Origin	Built as a temporary arena meant to be reassembled	Same as fencing	Renovated for the OG	Built for OG	Same as badminton	Same as fencing	
		Legacy	Never dismantled		Still in use	Still in use			
Hockey	10000	*Origin*	Renovated for OG	Built for the OG with partially demountable seatings	Built with temporary seatings	Built for OG	Built for the OG with partially demountable seatings	Use of existing stadium	**2**
		Legacy	Now unclear	Temporary seats demounted, still in use	Demounted	Unused	Temporary seats demounted, still in use	Still in use	
Football	50000	*Origin*	Used a mix of existing stadiums and new ones for the world cup	Used existing stadiums	Mix of new and existing stadiums	Mix of new and existing stadiums	Mix of new and existing stadiums	Used existing stadiums	**-1.33**
		Legacy	Unclear	Still in use	Still in use	Still in use	Still in use	Still in use	

			Rio	London	Beijing	Athens	Sydney	Atlanta	Score
Sport	Seats		2016	2012	2008	2004	2000	1996	
Judo	8000	*Origin*	Same as fencing	Same as boxing	Adaptable stadium built for OG and university	Built for OG	Same as boxing	Same as fencing	**-0.42**
		Legacy			Still in use	Now used by tv			
Shooting	3000	*Origin*	Make existing bigger	Mix of temporary and existing venue	Adaptable stadium built for OG	Built for OG	Built for OG	Use of existing facility	**-0.33**
		Legacy	Now unknown	Temporary seats demounted, still in use	Still in use	Still in use (repurposed)	Still in use	Still in use	
Table tennis	5000	*Origin*	Same as fencing	Same as boxing	Built for the OG with partially demountable seatings	Same as gymnastics	Use of an adaptable existing structure	Same as fencing	**-0.67**
		Legacy			Temporary seats demounted, still in use		Still in use		
Taekwondo	5000	*Origin* / Legacy	Same as fencing	Same as boxing	Same as judo	Same as handball	Same as table tennis	Same as fencing	**-1**
Tennis	10000	*Origin*	Built for OG	Use of existing stadium	Built for OG	Built for OG	Built for OG	Built adaptable for OG	**0.58**
		Legacy	Repurposed for volleyball	Still in use	Still in use	Still in use	Still in use	Split in 3, fell in disrepair in 2007	
Indoor volleyball	15000	*Origin*	Use of existing facility	Use of existing facility	Use of existing multisport facility	Use of existing multisport facility	Use of existing multisport facility	Use of existing multisport facility	**-2**
		Legacy	Still in use	Demolished (age)	Still in use	Still in use	Closed in 2015 (age)	Closed in 1997 (age)	
Beach volley	12000	*Origin*	Built temporary	Built temporary	Built for OG	Built for OG	Built temporary	Built for OG	**2**
		Legacy	Demounted	Demounted	Still in use	Unused	Demounted	Unclear	
Weigh tlifting	5000	*Origin* / Legacy	Same as badminton	Same as boxing	Use of existing gymnasium	Built for OG, repurposed	Same as boxing	Same as fencing	**-1**
Wres tling	800 0	*Origin* / Legacy	Same as fencing	Same as boxing	Same as judo	Same as judo	Same as boxing	Same as fencing	**-1**

Table 13 MSE re-use tables

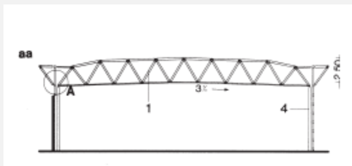
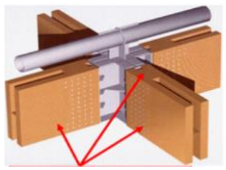
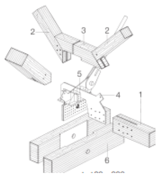
Winter Olympics									
			PyeongChang	**Sochi**	**Vancouver**	**Turin**	**Salt Lake City**	**Nagano**	**Score**
Sport	Seats		2018	2014	2010	2006	2002	1998	
Curling	3000	*Origin*	Used existing stadium	Designed as a portable venue for OG	Built for OG	Built for OG	Used existing facilities	Built for OG	**0.33**
		Legacy	Still in use	Stayed, in use but financial problems	Repurposed as multipurpose	Unused then repurposed as ice hockey	Still in use	Still in use	
Figure skating & short track	12000	*Origin*	Built for OG	Designed as a portable venue for OG	Used existing facilities	Renovated an existing arena	Used existing facilities	Built for OG	**-0.75**
		Legacy	Used for concert (rarely)	Stayed, still in use	Still in use (ice hockey)	Still in use	Still in use (ice hockey)	Still in use	
Ice hockey	10000	*Origin*	Use of an existing gymnasium	Built for OG	Built for OG	Use of existing exhibition hall	Built for OG	Built for OG	**0.88**
		Legacy	Still used as gymnasium	Still in use	Still in use	Still in use (as exhibition hall)	Still in use	Used as aquatic centre	
		Origin	Built for OG	Built for OG	Used existing facilities	Built for OG	Used existing facilities	Built for OG	
		Legacy	Still in use	Still in use	Still in use	Used for concerts	Still in use	Used as multipurpose arena	
Speed skating	6000	*Origin*	Built for OG	Built for OG	Built for OG	Built for OG	Built for OG	Built for OG	**1.5**
		Legacy	Unclear future use	Plans for exhibition centre	Used as multipurpose arena	Used as exhibition hall	Still in use	Still in use	

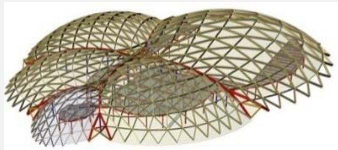
ANNEX C: Structural systems

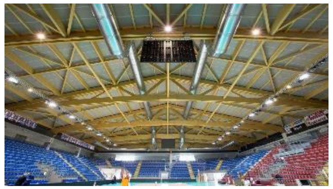
The following tables contain a collection of reviewed timber structures with spans exceeding 20 meters. Table 14 is a summary linking the structural systems with their range of span. Column (a) refers to the values found in (TRADA, 2007) while (b) comes from (Herzog & Natterer, 2004). Each number on Table 14 refers to a reviewed structure which can be found in Table 15. Finally, the green ranges are the span range according to (a) and (b)

Table 14 Spans and structural systems

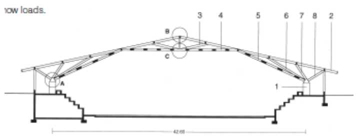
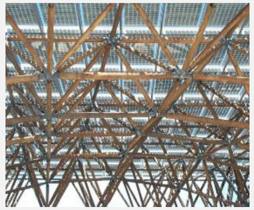
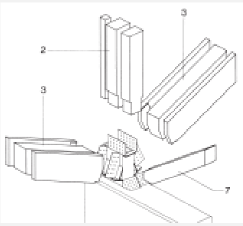
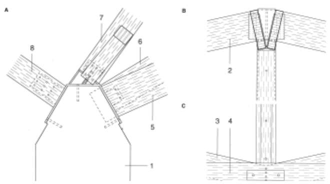
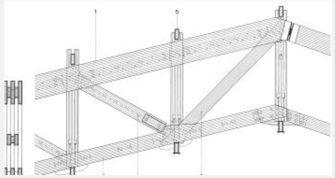
Type	System	Reference spans		Spans in meters												
		(a)	(b)	10	20	30	40	50	60	70	80	90	100	110	120	+
Beams	Beams	2-18	1-30		31	16										
	Beam grids	-	12-24					25 17		42						
Trusses	Duopitched	12-60	7.5-30		41			27								
	Duopitched eave	12-60	20-50				20									
	Arch truss	12-60	20-35			30			19	3		44				
	Lattice girders	12-80	20-50			9	21 15	36 14	10 38		29					
	Undertied beams	12-30	8-80			35	33 43		23							
	Space frame	-	8-50			8 40					12					
Frames	Three pin frames	12-25	15-50					39	38		37					
	Pinned arch	24-98	30-100			24			28	5 34	13 4					
	Latticed arch frame	40-120	30-100				22		18		11		2			
Domes		30-180	-										7			1; 6 ;26

Name	**1. Joensuu Multipurpose arena**	**2. Hamar Olympic center**	**3. Amphitheatre Of The Lights Of The North**	**4. Hamar Håkon Hall**	**5. Bois de Boulogne sport center**
Span	150m	96m	70m	83m	72m
Picture					
Type	*Dome*	*Latticed arch frame*	*Arch truss*	*Latticed arch frame*	*Pinned arch*
Remark	Dowelled connections.	Fitted in steel plates with dowels.	Truss height 6.5m.		
Source	1 &2	1 & 3	1 & 6	1 & 4	24
Name	**6. Tacoma Dome**	**7. Konohama dome**	**8. Lake side center**	**9. Weiherhof halle**	**10. Grefrath ice rink**
Span	161m	102 x 122m	27m	30m	60m
Picture					
Type	*Dome*	*Dome*	*Space frame*	*Latticed girder*	*Latticed girder*
Remark	Dowelled connections 15m long beams Ring force at the bottom 750mm deep elements	 Straight members 150*1100	Roof mounted in two weeks. Mounted on the ground and pushed up.		
Source	1 & 5	6 & 28	18 & 8	8	8 & 9

Name	11. Davos ice rink	12. Oguni dome	13. Chaveau soccer stadium	14. Eissporthalle Meranarena	15. Congress And Exhibition Center
Span	77 m	67m	72.1m	50m	40m
Picture					
Type	*Pinned arch*	*Space frame*	*Pinned arch*	*Latticed girder*	*Latticed girder*
Remark	Dowelled connections			Dowelled	
Source	8 & 11	7	24	13	14
Name	16. Sargans sports halle	17. Skating rink	18. Scunthrope sports academy	19. Ice rink Zuchswill	20. Sion airport halls
Span	30 m	54m	60m	60m	40m
Picture					
Type	*Beam*	*Beam grid*	*Dome*	*Arch truss*	*Duopitched with eaves*
Remark		2.42m high beams.	Dome with linear elements.		Truss height 4.5m.
Source	15	15	16	19	23

Name	21. Migros Nyon	22. Neydens aquatic center	23. Raleigh Durham airport	24. Mactan Cebu airport	25. Graz sports park
Span	32 m	43m	58m	30m	47.6m
Picture					
Type	*Latticed girders*	*Latticed arch frame*	*Under tied beams*	*Pinned arch*	*Beam grid*
Remark		Max height 20m		Height 18m	Beam height from 2.55 to 3.25m
Source	20	20	21	21	22
Name	26. Enel coal storage	27. Civitanova marche stadium	28. KwaSizabantu mission auditorium, Durban	29. National Cycling Center, Sangalhos	30. Payern military airport
Span	143	51m	57m	79m	31.3m
Picture					
Type	*Dome*	*Duo pitched truss*	*Pinned arch*	*Latticed girder*	*Arched truss*
Remark	Height 50m	Truss height 9.2m		Prefab in 20m long elements	
Source	22	22	22	22	23

Name	31. Minganie aquatic complex	32. Horborcenter	33. Meredith center arena	34.National Cycling Center, Sangalhos	35. Uqac arena
Span	24m	42.2m	33.9m	68m	32.2m
Picture					
Type	*Beams*	*Lenticular structure*	*Under tied beam*	*Pinned arch*	*Under tied beams*
Remark					
Source	24	24	24	24	24

Name	36. Bridge over River Simme	37. South surrey arena	38. St Ulrich ice rink	39. Roanne sports center	40. Solar Canopy, the Earth Centre
Span	50 m	75m	61m	45m	35m
Picture					
Type	*Latticed girder*	*Three pin frame & Duopitched truss*	*Three pin frame & Latticed girder*	*Three pin frames*	*Space frame*
Remark					Roof mounted in two weeks. Mounted on the ground and lifted up
Source	8	8	8	8	27

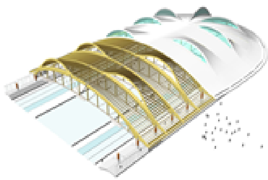
Name	41. Bercher salle de gym	42. Stade De Soccer de Montréal	43. Ice Rink of Liège	44. Inzell Speed Skating Stadium
Span	20m	75m	45m	90m
Picture				
Type	*Duopitched*	*Beam grid*	*Under tied beam*	*Arched truss*
Remark		Beam can be 4100mm high		*Steel used*
Source	25	26	26	26

Table 15 Reviewed structures

SOURCES for table

1: (Herzog & Natterer, 2004)
2, Retrieved Mar. 5 2020 from: https://fi.wikipedia.org/wiki/Joensuu_Areena#/media/Tiedosto:Joensuu_areena21.jpg
3, Retrieved Mar. 5 2020 https://architectureofthegames.net/1994-lillehammer/lillehammer-1994-vikingskipet-hamar-olympic-hall/
4, Retrieved Mar. 5 2020 https://edition.cnn.com/2013/11/05/sport/sochi-2014-lillehammer-winter-olympics/index.html
5, Retrieved Mar. 5 2020 https://i.pinimg.com/originals/5a/4d/03/5a4d0370e5efd495817896173626394c.jpg
6, Retrieved Mar. 5 2020 Reticulated Timber Dome Structural System Using Glulam with a Low Specific Gravity and its Scalability
7, Retrieved Mar. 5 2020 https://www.architecturerevived.com/oguni-dome-kumamoto-japan/
8 (Herzog & Natterer, 2004)
9, Retrieved Mar. 5 2020 https://rp-online.de/
10, Retrieved Mar. 5 2020 https://www.basketeurope.com/wp-content/uploads/2019/04/Roanne-e1554563627902.jpeg
11, Retrieved Mar. 6 2020 https://i.pinimg.com/originals/d7/98/e5/d798e5369b82589cbcfc67ac1829cb7b.jpg
12, Retrieved Mar. 6 2020 https://i.pinimg.com/originals/d7/98/e5/d798e5369b82589cbcfc67ac1829cb7b.jpg
13, Retrieved Mar. 6 2020 https://www.altoadigepertutti.it/de/poi/meranarena-eissporthalle
14, Retrieved Mar. 6 2020 https://divisare.com/projects/413809-studio-bressan-studio-botter-simone-bossi-congress-and-exhibition-center
15, Retrieved Mar. 6 2020 New_Architecture_in_Wood_Forms_and_Structures_----_(Pg_68--140)
16, Retrieved Mar. 6 2020 https://www.designingbuildings.co.uk/wiki/Scunthorpe_Sports_Academy
17, Retrieved Mar. 7 2020 https://ladungssicherungssymposium.ch/images/Bilder/Design/IMG_3610.JPG
18, (Vollichard, 1986)
19, Retrieved Mar. 7 2020 https://www.holzing-maeder.ch/de/referenzen/offentlicher-bau/eishalle-zuchwil/
20, Retrieved Mar. 7 2020 http://www.jpf-ducret.ch/fr/references/
21, Retrieved Mar. 7 2020 https://www.arup.com/projects/
22, Retrieved Mar. 7 2020 https://www.rubner.com/en/holzbau/references/
23, Retrieved Mar. 7 2020 https://www.rothburgdorf.ch/referenzen/luftwaffenbasis-payerne
24, Retrieved Mar. 7 2020 https://www.nordic.ca/en/projects/structures/
25, Retrieved Mar. 7 2020 https://www.volet.ch/N1010/2014-salle-de-gym-bercher-pailly.html
26, Retrieved Mar. 7 2020 https://www.archdaily.com/
27, Retrieved Mar. 7 2020 https://carpenteroak.com/projects/solar-canopy-the-earth-centre/
28, Retrieved Mar. 6 2020 https://www.pinterest.ch/pin/343399540308720036/?lp=true

ANNEX D: Detailed results of CHAPTER V: System development

Here are the detailed results for the different trusses tested in chapter V

Method 1

Three trusses were extracted from the first method. Indeed, the goal was to take the most weight-efficient truss of each type with either the diagonals' or the chords' length close to 3 meters. In this method, a lot of trusses were reviewed by the code, but also manually to explore what solutions are available.

Truss A

Parameters

Height:2.7m; 8 bays; Re-used as: Residential

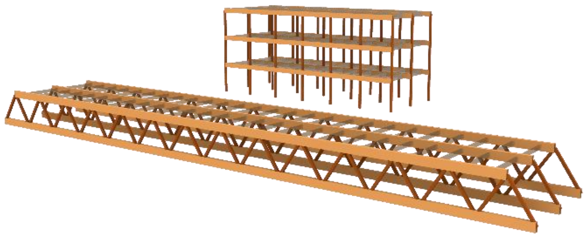


Figure 80 Truss A

Weight efficiency

While it is relatively efficient as a truss, re-using it for residential constructions is suboptimal. Indeed, although the buckling length of the main chord element is smaller, compared to truss C for example, the forces remain the same and thus the cross-sections are too big for the legacy use.

Ease of connectivity

Because this truss has the lowest height, it has the highest loads on the connections. This might increase the cross-section dimensions to fit the complicated connections. Moreover, it has a relatively high number of bays which increases the number of connections.

Re-use potential

Because of the low efficiency and the complexity of the connections, the re-use potential is low.

Truss B

Parameters

Height:4.6m; 16 bays; Re-used as: Offices/School

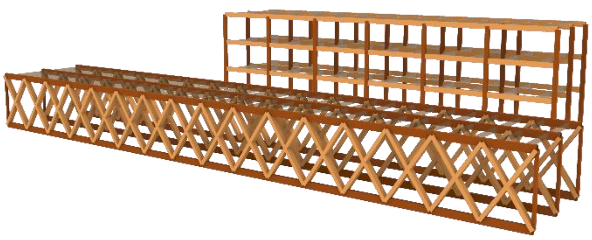


Figure 81 Truss B

Weight efficiency

The weight efficiency is greatly reduced because the diagonals are re-used as beams. Indeed, they need to be made bigger to satisfy the constraints of the legacy use. Additionally, the chords, re-used as columns, yield unnecessarily big cross-sections.

Ease of connectivity

The increased structural height reduces the loads significantly. However, the typology of the truss introduces new challenges to avoid having crossing diagonals.

Re-use potential

The use of diagonals as beams is penalizing re-usability. Additionally, the complex connections required to solve the intersection of diagonals will be difficult to re-use.

Truss C

Parameters

Height:3.5m; 10 bays; Re-used as: Offices/Schools

Weight efficiency

The weight efficiency of this truss is good both in legacy and origin uses. We can note that having legacy structures with long spans coming from the chords is a good solution since both require similar cross-sections.

Figure 82 Truss C

Ease of connectivity

The low structural height necessary to have the vertical elements re-usable as columns is increasing the forces in the connections which might make them difficult to realize.

Re-use potential

Apart from the connection problem, there is a lack of columns. Indeed, using the diagonals as main beams as well means that we will have twice more beams as columns. This might be penalizing because of the increased logistic complexity.

Method 2

The first method showed that the low structural height imposed by the column's length constraints can be problematic. Moreover, re-use as offices or school buildings seems a good solution since the required cross-sections are closer to those of the truss. Finally, truss type 1 seemed the most appropriate to re-use because there are less logistic and connectivity problems. For these reasons, the idea for method 2 is to increase the structural height, thus reducing the forces in the chord, by having two columns per diagonal.

Truss 2A

Parameters

Height:5.4m; 8 bays; Re-used as: Offices/School

Weight efficiency

This truss is the most efficient both in origin and legacy mode. Indeed, its optimal cross-sections in legacy and origin mode are very similar which reduces the unnecessary weight.

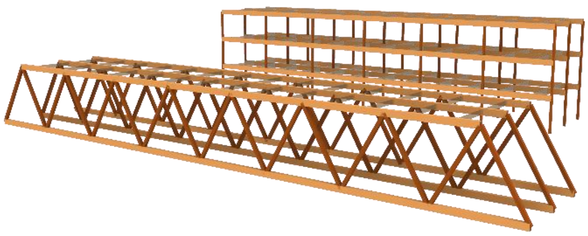


Figure 83 Truss 2A

Therefore, the 6-meter span coupled with the reduced force in the chords seems like a good solution.

Ease of connectivity

The increased height reduces the forces in the connections simplifying their design.

Re-use potential

There is a higher number of connections due to the spitting of the columns. Additionally, we have more columns than beam elements which, similarly to truss C might increase the logistic complexity.

Method 3

The results of the other methods, while providing satisfying solutions to a problem where the origin and legacy constructions are known, lack flexibility. Indeed, it is not possible to use the derived system for trusses with longer or shorter spans, nor is it feasible to change the spans in legacy contexts. Additionally, the best working solutions have slight logistic problems with a non-equal number of columns and beams. For these reasons, the third method was developed aiming at higher standardization. To achieve that goal, the idea is to have a single element that can be combined to produce bigger cross-sections or longer beams. Therefore, all elements have the length of a column which is roughly 3meters. In this iteration of the method, two elements are necessary for the top chord and for spanning office buildings while only one is required to span residentials, for the columns or the diagonals. The elements are connected mechanically with two dowels every 35 cm along the beam.

Truss 3A & 3A'

Parameters

Height:5.4m; 8 bays; Re-used as: Offices/School or residential

Weight efficiency

The mechanical joining of the beam significantly reduces the performance compared to a solid cross-section. Indeed, the inertia for stacked beams is reduced by 56% and the moment resistance by 35%. For this reason, this system has the highest weight per m^2 in office mode. The impact on the truss structure, however, is less important because bending moments are smaller in this situation.

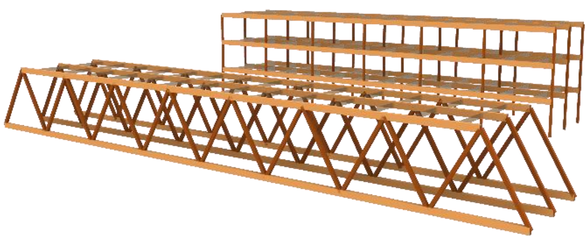


Figure 84 Truss 3A

Ease of connectivity

Because it is based on truss 3A, it has similar ease of connectivity. However, an additional problem arises from connecting two elements subject to bending. Moreover, adding mechanical connections can increase the cost of construction.

Re-use potential

If a simple solution is found for connecting two bent elements, this solution has high re-use potential. Indeed, its high modularity offers a lot of opportunities, especially in scenarios where the legacy structure is unknown.

Comparison

Table 16 shows a summary of the results of the re-use analysis. The first part gives the cross-sections required for the truss structures, while the second focuses on legacy structures and the third combines the two. Highlighted in green are the determining cross-sections. The weight was calculated by considering only timber and by ignoring the secondary beams.

Table 16 Truss comparison

Origin												
Name	Type	Height	Nb bays	Length chord	Cross section	Length diagonal	Cross section	Length Column	Cross section	Length Secondary	Cross section	Weight (kN/m^2)
Opti	3	4.6	8	6.25	41x32	4.6	28x28	4.6	13x23	4	14x23	0.37
A	1	2.7	14	3.57	24x60	3.3	19x19	-	-	4	14x23	0.43
B	2	4.6	16	3.125	25x43	5.6	22x22	-	-	4	14x23	0.49
C	3	3.5	10	5	28x47	6.1	26x26	3.5	15x15	4	14x23	0.42
2A	1	5.41	8	6.25	27x46	6.25	24x27	-	-	4	14x23	0.45
3A	1	5.41	8	6.25	24x62	6.25	24x31	-	-	4	14x23	0.53
Legacy												
Name	Use	Use of chord	Use of diag	Length Main	Cross section	Length Columns	Cross section	Length 2nd	Cross section	Length Secondary	Cross section	Weight (kg/m')
A	R	M	C	3.57	19x28	3.3	17x17	-	-	4	14x28	36.8
B	O	C	M	5.6	22x45	3.125	21x25	-	-	4	14x28	59.0
C	O	M	M	5	22x39	3.5	20x20	6.1	22x48	4	14x28	52.3
2A	O	M	C	6.25	22x45	3.125	21x21	-	-	4	14x28	55.7
3A'	R	M/C	M'	3.125	16x26	3.125	17x17	-	-	4	14x28	32.4
3A	O	M/C	M/C	6.25	24x62	3.125	20x23	-	-	4	14x28	79.0
Global												
Name	Weight legacy (kg/m')	Weight Origin (kN/m^2)	Weight increase legacy	Length Main	Cross section	Length Columns	Cross section	Length 2nd main	Cross section	Length Secondary	Cross section	Highest force in truss kN
A	81.6	0.43	2.2	3.57	24x60	3.3	19x19	-	-	4	14x28	1700
B	79.7	0.77	1.4	5.6	22x49	3.125	25x47	-	-	4	14x28	1120
C	75.0	0.51	1.4	5	30x49	3.5	20x20	6.1	22x48	4	14x28	1500
2A	72.0	0.45	1.3	6.25	27x46	3.125	24x27	-	-	4	14x28	850
3A'	67.3	0.53	2.1	3.125	24x31	3.125	24x31	-	-	4	14x28	900
3A	85.6	0.53	1.08	6.25	24x62	3.125	24x31	-	-	4	14x28	900

Truss 2A has the best performances in most categories. Although there is an excess of diagonal elements, it is possible to imagine changing their dimensions slightly to allow for short spans such as a corridor. It is also possible to try and resell them.

Truss 3A adds an interesting edge to the modularity of the system. However, the drops in efficiency and the related cost increase might be prohibitive.

ANNEX E: Loads and timber properties

Loads

The loads for the calculations are listed in the table below. Note: for the wind load on the roof, the worst zone is taken for the entirety of the roof.

Table 17 Loads

ROOF DEAD LOAD				
Index	Name	Thickness (mm)	Density (kN/m^3)	Surface load (kN/m^2)
1	Beams	-	5	-
2	Joists	95x200@700	5	0.14
3	OSB	22	8	0.176
4	Insulation	220	0.3	0.066
5	Waterpoofing			0.002
6	Vapor barrier	-	-	0.002
7	Roofing			0.55
	Total			0.932
	Rounded total			**0.94**

WIND LOAD			
Name	Symbol	Value	Unit
Reference wind pressure	q_{po}	0.9	kN/m^2
Reference height	z_g	450	m (Zone III)
Roughness coefficient	α_r	0.23	(Zone III)
Building height	z	30	m
coefficient	c_h	1.33	
Dynamic Pressure	q_p	1.197	kN/m^2
q_p		**1.2**	**kN/m^2**
Note: Reference SIA 261 § 6.2			

FLOOR DEAD LOAD				
Index	Name	Thickness (mm)	Density (kN/m^3)	Surface load (kN/m^2)
1	Beams	-	5	-
2	Joists	95x200@700	5	0.14
3	OSB	22	8	0.176
4	Insulation	30	1	0.030
5	Screed	60	22	1.32
6	Finition	15	8	0.12
	Total	127		1.782
	Rounded total			**1.79**

Wind coefficient			
Name	Pressure coeff	Value	Wind pressure (kN/m^2)
No interior pressure	c_{pi}	0	
Zone A (upwind)	c_{pe}	0.7	0.84
Zone B (downwind)	c_{pe}	-0.25	-0.3
Zone C	c_{pe}	-0.35	-0.42
Zone D	c_{pe}	-0.35	-0.42
Zone E	c_{pe}	-0.5	-0.6
Zone F	c_{pe}	-0.5	-0.6
Zone G	c_{pe}	-0.25	-0.3
Zone H	c_{pe}	-0.25	-0.3
Note: Reference SIA 261 table 33; Hypothesis: wind perpendicular, flat roof, height widht ration between 0.3 and 0.05			
Highest roof load		**-0.6**	**kN/m^2**

SERVICE LOADS			
Name	Symbol	Value	Unit
Floor load school	$q_{u,C}$	3	kN/m^2
Roof load	$q_{u,H}$	0.4	kN/m^2
Floor load residential	$q_{u,A}$	2	kN/m^2
Floor load offices	$q_{u,B}$	3	kN/m^2
Floor load school	$q_{u,C}$	3	kN/m^2
Note: Reference SIA 261 table 8			

ROOF SNOW LOAD			
Name	Symbol	Value	Unit
Wind exposition coeff	C_e	1	
Thermal coeff	C_t	1	
Reference height	h_0	550	m
Reference snow load	z_k	1.39	kN/m^2
Shape coeff	μ_1	0.8	
Snow load	$q_{k,snow}$	1.112	
Note: Reference SIA 261 § 5.2			
Snow load		**1.2**	**kN/m^2**

FACADE DEAD LOAD				
Index	Name	Thickness (mm)	Density (kN/m^3)	Surface load (kN/m^2)
1	Columns	-	5	-
2	Joists	95x200@700	5	0.14
3	Gypsum board	13	22	0.286
4	Vapor barrier	-	-	0.002
5	OSB	22	8	0.176
6	Insulation	240	0.8	0.192
7	Sub structure	30	-	0.1
8	Finishing	20	8	0.16
	Total			1.05
	Rounded total			**1.1**

The loads are summed up in the table below:

Table 18 Load summary

LOAD SUMMARY - ROOF			
Index	Name	Symbol	Surface load (kN/m^2)
0	Dead Load	$g_{k,roof}$	0.94
1	Snow load	$q_{k,snow}$	1.2
2	Maintenance	$q_{u,H}$	0.4
3	Wind load	$q_{k,wind}$	-0.6
LOAD SUMMARY - FLOOR			
Index	Name	Symbol	Surface load (kN/m^2)
0	Dead Load	$g_{k,floor}$	1.79
4	Service load	$q_{u,C}$	3

The loads are combined according to the following load coefficients:

Table 19 Load coefficients

LOAD COEFFICIENT						
Index	Name	ULS		SLS Ψ_0	SLS Ψ_1	SLS Ψ_2
0	Dead Load	γ_G	1	1	1	1
1	Snow load	γ_Q	2	0.8	0.55	0
2	Maintenance	γ_Q	2	0	0	0
3	Wind load	γ_Q	2	0.6	0.5	0
4	Service load School	γ_Q	2	0.7	0.7	0.6
5	Dead load favourable	$\gamma_{G,inf}$	1	-	-	-
6	Service load Residential	γ_Q	2	0.7	0.5	0.3
7	Service load Offices	γ_Q	2	0.7	0.5	0.3
	Source: SIA 261 table 2					

Finally, the following table lists the studied load cases.

Table 20 Load combination

LOAD COMBINATION ULS																
Index	Main load	Load coefficitents								$q_{roof,d}$ (kN/m^2)	$q_{floor,A,d}$ (kN/m^2)	$q_{floor,B,d}$ (kN/m^2)	$q_{floor,C,d}$ (kN/m^2)	$q_{hor,A,d}$ (kN/m^2)	$q_{hor,B,d}$ (kN/m^2)	$q_{fac,v,d}$ (kN/m^2)
		0	1	2	3	4	5	6	7							
0	Snow load roof	1.35	1.5	0	0	0.7	0	0.7	0.7	3.07	3.82	4.52	4.52	0	0	1.485
1	Wind load roof	0	0	0	1.5	0	0.9	0	0	-0.06	1.62	1.62	1.62	1.26	-0.45	0.99
2	Service load	1.35	0.8	0	0	1.5	0	1.5	2	2.23	5.42	6.92	6.92	0	0	1.485
3	Wind load stability	1.35	0.8	0	1.5	0.7	0	0.7	0.7	1.33	3.82	4.52	4.52	1.26	-0.45	1.485
LOAD COMBINATION SLS FREQUENT																
Index	Main load	0	1	2	3	4	5	6	7	$q_{roof,ser}$ (kN/m^2)	$q_{floor,A,ser}$ (kN/m^2)	$q_{floor,B,ser}$ (kN/m^2)	$q_{floor,C,ser}$ (kN/m^2)	$q_{hor,A,ser}$ (kN/m^2)	$q_{hor,B,ser}$ (kN/m^2)	$q_{fac,v,ser}$ (kN/m^2)
	Creep coefficient	0.6														
0	Snow load roof	1.6	0.55	0	0	0.96	0	0.48	0.48	2.17	3.83	4.31	5.75	0	0	1.76
1	Wind load roof	1.6	0	0	0.5	0	0	0	0	1.21	2.87	2.87	2.87	0.42	-0.15	1.76
2	Service load	1.6	0	0	0	1.06	0	0.68	0.68	1.51	4.23	4.91	6.05	0	0	1.76
3	Wind load sway	1.6	0	0	0.5	0.96	0	0.48	0.48	1.21	3.83	4.31	5.75	0.42	-0.15	1.76
	Source: SIA 261 equations: 17 & 21															

The table shows that the snow load is the main one when calculating the roof whereas the service load is used for the floors.

Note: the SLS load coefficient includes an increase in load to account for the creep related to the quasi-permanent part of the load.

Timber properties

The table below shows the timber properties used:

Table 21 Timber properties

Timber properties GL 24H				
Index	Description	Name	Value	Unit
0	Flexural strength characterisitc	$f_{m,k}$	24	N/mm^2
1	Mean young's modulus	$E_{m,mean}$	11000	N/mm^2
2	Flexural strenth	$f_{m,d}$	16	N/mm^2
3	Parallel tensile strength	$f_{t,0,d}$	12	N/mm^2
4	Parallel compressive strength	$f_{c,0,d}$	14.5	N/mm^2
5	Perpendicular tensile strength	$f_{t,90,d}$	0.15	N/mm^2
	Perpendicular compressive strength			
6	General	$f_{c,90,d}$	1.9	N/mm^2
7	In beam	$f_{c,90,d}$	2.5	N/mm^2
8	Shear modulus	G_{mean}	500	N/mm^2
9	Density	ρ_k	380	kg/m^3
10	Mean density	ρ_{mean}	460	kg/m^3
11	Shear strength	$f_{v,d}$	1.8	N/mm^2
	Note: Source SIA 265 table 7			

ANNEX F: Calculation procedures of timber members

For timber members, the following verifications are done:

$$\frac{N_{Ed}}{Ak_c f_{c,0,d}} + \frac{6M_{Ed}}{k_m f_{m,d} bh^2} \leq 1$$

$$\frac{V_{Ed}}{A} \leq f_{v,d}$$

With k_c and k_m the buckling and lateral buckling coefficient respectively. Their calculation procedures are detailed below.

Note: The strength of timber in compression, flexion, shear are taken with safety coefficients from the norm SIA 265 (SIA, 2003d) with the following hypothesis k_h=1, humidity class 1.

Buckling

The procedure used to calculate the buckling coefficients is presented hereafter:

Note: The procedure is shown for the y-axis but the same applies to the z-axis.

The buckling length: $l_{k,y}$ [mm] is taken as the length between two nodes

Note: $l_{k,z}$ is taken as the length between secondary beams

Slenderness: $\lambda_y = l_{k,y}\sqrt{\frac{A}{I_y}}$

Relative slenderness: $\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0.05}}}$

With $E_{0.05}$=0.85 E_{Mean}

Buckling coefficient in y-direction: $k_{c,y} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}}$

With: $k_y = 0.5(1 + \beta_c(\lambda_{rel,y} - 0.3) + {\lambda_{rel,y}}^2)$

With $\beta_c = 0.1$ for glue-laminated timber

Similarly, we can find $k_{c,z}$, the coefficient in the z-direction.

The buckling coefficient $\boldsymbol{k_c} = \mathbf{min}\,(\boldsymbol{k_{c,y}}; \boldsymbol{k_{c,z}})$

Source: SIA265 §4.2.8 (SIA, 2003d)

Lateral torsional buckling

For the bending of the top chord, the following formulas are used to calculate the lateral-torsional buckling coefficient:

The lateral-torsional buckling length: l_{lat} is taken as the distance between the secondary supports. This simplifying hypothesis ignores the fact that the moments are not equal at these points, however, this is a conservative hypothesis.

Relative slenderness: $\lambda_{rel,m} = 1.15\frac{\sqrt{hl_{lat}}}{b}\sqrt{\frac{f_{m,k}}{E_{0.05}}}$

Lateral buckling coefficient: $k_m = \begin{cases} 1 & if\ \lambda_{rel,m} \leq 0.75 \\ 1.56 - 0.75\lambda_{rel,m} & \text{if } 0.75 < \lambda_{rel,m} \leq 1.4 \\ \frac{1}{\lambda_{rel,m}{}^2} & if\ 1.4 < \lambda_{rel,m} \end{cases}$

Note: there is no moment in the z-direction.

Legacy use checks

The hypotheses are that the buckling length of the columns is equal to the height of one floor and, the beams are perfectly hinged. Moreover, no lateral buckling of the beams occurs.

The moment of the beam is found by: $M_{Ed} = \frac{q_{Ed}l^2}{8}$

The deformations of the beam: $w_{ser} = \frac{\frac{5}{384}q_{ser}l^4}{EI}$

with q_{ser} increased according to account for creep

The cross-section checks are the same as those of the truss.

ANNEX G: Results for timber members

The following table contains the results for the ULS of the origin structure

Table 22 ULS results for origin structure

ULS ORIGIN STRUCTURE

Top chord							
Forces				Cross section			
Normal force	N_{ED}	-1030	kN	Width	b	285	mm
Moment	M_{ed}	73	kNm	Height	h	500	mm
Shear force	V_{ED}	50	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	6.67	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	1	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.93		Bending stress	σ_M	6.14737	MPa
Buckling coeff z	$k_{c,z}$	1					
Buckling coeff	k_m	0.93					
Normal stress	σ_N	7.2	Mpa				
Bending & Normal force				Shear			
Unity check	0.920	<	1	Shear stress	τ	0.35	MPa
				Unity check	0.195	<	1

Bottom chord							
Forces				Cross section			
Normal force	N_{ED}	950	kN	Width	b	285	mm
Moment	M_{ed}	5	kNm	Height	h	500	mm
Shear force	V_{ED}	3	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	-	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	-	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	1		Bending stress	σ_M	0.42105	MPa
Buckling coeff z	$k_{c,z}$	1					
Buckling coeff	k_m	1					
Normal stress	σ_N	6.7	Mpa				
Bending & Normal force				Shear			
Unity check	0.582	<	1	Shear stress	τ	0.02	MPa
				Unity check	0.012	<	1

Edge Diagonals							
Forces				Cross section			
Normal force	N_{ED}	-490	kN	Width	b	285	mm
Moment	M_{ed}	18.3	kNm	Height	h	300	mm
Shear force	V_{ED}	11	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	7.13	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	1	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.55		Bending stress	σ_M	4.29	MPa
Buckling coeff z	$k_{c,z}$	1					
Buckling coeff	k_m	0.55					
Normal stress	σ_N	5.7	Mpa				
Bending & Normal force				Shear			
Unity check	0.984	<	1	Shear stress	τ	0.13	MPa
				Unity check	0.071	<	1

Other Diagonals							
Forces				Cross section			
Normal force	N_{ED}	-400	kN	Width	b	285	mm
Moment	M_{ed}	0.0	kNm	Height	h	300	mm
Shear force	V_{ED}	0	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	7.13	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	7.13	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.53		Bending stress	σ_M	0.00	MPa
Buckling coeff z	$k_{c,z}$	0.5					
Buckling coeff	k_m	0.50					
Normal stress	σ_N	4.7	Mpa				
Bending & Normal force				Shear			
Unity check	0.645	<	1	Shear stress	τ	0.00	MPa
				Unity check	0.000	<	1

Column elements							
Forces				Cross section			
Normal force	N_{ED}	-406	kN	Width	b	285	mm
Moment	M_{ed}	0	kNm	Height	h	300	mm
Shear force	V_{ED}	0	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	3.3	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	3.3	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.96		Bending stress	σ_M	0	MPa
Buckling coeff z	$k_{c,z}$	0.95					
Buckling coeff	k_m	0.95					
Normal stress	σ_N	4.7	Mpa				
Bending & Normal force				Shear			
Unity check	0.345	<	1	Shear stress	τ	0.00	MPa
				Unity check	0.000	<	1

Diagonal in tension							
Forces				Cross section			
Normal force	N_{ED}	400	kN	Width	b	285	mm
Moment	M_{ed}	0	kNm	Height	h	300	mm
Shear force	V_{ED}	0	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	-	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	-	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	1		Bending stress	σ_M	0	MPa
Buckling coeff z	$k_{c,z}$	1					
Buckling coeff	k_m	1					
Normal stress	σ_N	4.7	Mpa				
Bending & Normal force				Shear			
Unity check	0.390	<	1	Shear stress	τ	0.00	MPa
				Unity check	0.000	<	1

Secondary beams							
Forces				Cross section			
Normal force	N_{ED}	-10.3	kN	Width	b	125	mm
Moment	M_{ed}	6.14	kNm	Height	h	250	mm
Shear force	V_{ED}	6.14	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	4	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	4	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.87		Bending stress	σ_M	4.72	MPa
Buckling coeff z	$k_{c,z}$	0.32					
Buckling coeff	k_m	0.32					
Normal stress	σ_N	0.3	Mpa				
Bending & Normal force				Shear			
Unity check	0.366	<	1	Shear stress	τ	0.20	MPa
				Unity check	0.109	<	1
SLS							
Length	L	4	m	Deformations LC4	w_4	4.0	mm
Max deformations	L/350	11.4	mm				

Stability short edge							
Forces				Cross section			
Normal force	N_{ED}	300	kN	Width	b	285	mm
Moment	M_{ed}	0	kNm	Height	h	300	mm
Shear force	V_{ED}	0	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	3.3	m	LTB length	l_k	-	m
Buckling length z	l_{kz}	3.3	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.96		Bending stress	σ_M	0	MPa
Buckling coeff z	$k_{c,z}$	0.95					
Buckling coeff	k_m	0.95					
Normal stress	σ_N	3.5	Mpa				
Bending & Normal force				Shear			
Unity check	0.308	<	1	Shear stress	τ	0.00	MPa
				Unity check	0.000	<	1

The following table shows the results of SLS calculations for the origin structure

Table 23 SLS results for origin structure

SLS - Origin											
Vertical deformation				Horizontal deformations main direction				Horizontal deformations secondary direction			
Length	L	59.6	m	Height	H	13.3	m	Height	H	19.5	m
Max deformations	L/500	119.2	mm	Max deformations	H/500	26.6	mm	Max deformations	H/500	39	mm
Main load:snow	w_4	72.2	mm	Main load:snow	w_4	8.4	mm	Main load:snow	w_4	0	mm
Main load:wind	w_5	48.4	mm	Main load:wind	w_5	7.7	mm	Main load:wind	w_5	19.2	mm
Note: the deformations are higher in the snow load case because the vertical load pushes the columns outwards slightly											

The following table exposes the results for the ULS and SLS of the legacy structure:

Table 24 ULS and SLS results of the legacy structure

LEGACY STRUCTURES

Legacy beam 3.3m							
Forces				Cross section			
Normal force	N_{ED}	0	kN	Width	b	285	mm
Moment	M_{ed}	37.68	kNm	Height	h	300	mm
Shear force	V_{ED}	45.67	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	-	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	-	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	-		Bending stress	σ_M	8.81	MPa
Buckling coeff z	$k_{c,z}$	-					
Buckling coeff	k_m	1					
Normal stress	σ_N	0.0	Mpa				
Bending & Normal force				Shear			
Unity check	0.551	<	1	Shear stress	τ	0.53	MPa
				Unity check	0.297	<	1
SLS							
Length	L	3.3	m	Deformations LC4	w_4	5.3	mm
Max deformations	L/350	9.4	mm				

Legacy beam 6.66m							
Forces				Cross section			
Normal force	N_{ED}	0	kN	Width	b	285	mm
Moment	M_{ed}	153.61	kNm	Height	h	500	mm
Shear force	V_{ED}	92.22	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	-	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	-	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	-		Bending stress	σ_M	12.94	MPa
Buckling coeff z	$k_{c,z}$	-					
Buckling coeff	k_m	1					
Normal stress	σ_N	0.0	Mpa				
Bending & Normal force				Shear			
Unity check	0.808	<	1	Shear stress	τ	0.65	MPa
				Unity check	0.360	<	1
SLS							
Length	L	6.7	m	Deformations LC4	w_4	19.0	mm
Max deformations	L/350	19.1	mm				

Legacy Column 3.3m - 10 floors							
Forces				Cross section			
Normal force	N_{ED}	-913.44	kN	Width	b	285	mm
Moment	M_{ed}	0.00	kNm	Height	h	300	mm
Shear force	V_{ED}	0.00	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	3.36	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	3.36	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.96		Bending stress	σ_M	0.00	MPa
Buckling coeff z	$k_{c,z}$	0.95					
Buckling coeff	k_m	0.948					
Normal stress	σ_N	10.7	Mpa				
Bending & Normal force				Shear			
Unity check	0.777	<	1	Shear stress	τ	0.00	MPa
				Unity check	0.000	<	1

Legacy Column 6.6m - 6 floors							
Forces				Cross section			
Normal force	N_{ED}	-1106.6	kN	Width	b	285	mm
Moment	M_{ed}	0.00	kNm	Height	h	300	mm
Shear force	V_{ED}	0.00	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	3.36	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	3.36	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.96		Bending stress	σ_M	0.00	MPa
Buckling coeff z	$k_{c,z}$	0.95					
Buckling coeff	k_m	0.948					
Normal stress	σ_N	12.9	Mpa				
Bending & Normal force				Shear			
Unity check	0.942	<	1	Shear stress	τ	0.00	MPa
				Unity check	0.000	<	1

Legacy truss							
Forces				Cross section			
Normal force	N_{ED}	-606	kN	Width	b	285	mm
Moment	M_{ed}	18	kNm	Height	h	300	mm
Shear force	V_{ED}	22	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	3.4	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	3.4	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	0.95		Bending stress	σ_M	4.21	MPa
Buckling coeff z	$k_{c,z}$	1					
Buckling coeff	k_m	0.95					
Normal stress	σ_N	7.1	Mpa				
Bending & Normal force				Shear			
Unity check	0.778	<	1	Shear stress	τ	0.26	MPa
				Unity check	0.143	<	1
SLS							
Length	L	34	m	Deformations LC4	w_4	40	mm
Max deformations	L/500	68	mm				

Secondary beams							
Forces				Cross section			
Normal force	N_{ED}	0	kN	Width	b	125	mm
Moment	M_{ed}	9.04	kNm	Height	h	250	mm
Shear force	V_{ED}	9.04	kN	Material	GL24h		
Normal force				Bending			
Buckling length y	l_{ky}	-	m	LTB length	l_k	1	m
Buckling length z	l_{kz}	-	m	LTB coefficient	k_m	1	
Buckling coeff y	$k_{c,y}$	-		Bending stress	σ_M	6.94	MPa
Buckling coeff z	$k_{c,z}$	-					
Buckling coeff	k_m	1					
Normal stress	σ_N	0.0	Mpa				
Bending & Normal force				Shear			
Unity check	0.434	<	1	Shear stress	τ	0.29	MPa
				Unity check	0.161	<	1
SLS							
Length	L	4	m	Deformations LC4	w_4	11.3	mm
Max deformations	L/350	11.4	mm				

ANNEX H: Calculation procedures of built-up elements

Built-up beams

In the part exploring truss alternatives, built-up beams are used. This applies to the top chord where two elements are stacked on top of each other. Additionally, two elements are connected longitudinally to create the 6m chord. This part explains their calculation.

To calculate the built-up beams, I used a reduction factor on the inertia and the moment resistance. They were calculated in the following way:

Note: since by design, only square elements are used which simplifies some formulas.

First, we need to find the efficient stiffness: EI_{Eff}. There are two different values depending if we look at ULS or SLS. This is because the rigidity of the bolt-timber connection K_i is different:

$K_{i,ser} = \frac{1}{23}\rho_{mean}^{1.5}d$ With d the diameter of the connector

$K_{i,ult} = \frac{2}{3}K_{i,ser}$

The rest of the calculation process is the same for both ULS and SLS with $K_{i,ult}$ instead of $K_{i,ser}$ for conciseness the generic procedure is shown.

The cooperation factor: $\gamma_i = \frac{1}{1+p}$

With: $p = \frac{\pi^2 E_i A_i s_i}{K_i l^2}$ With s_i the spacing between connectors, l the length of the beam

With 2 elements, we take, arbitrarily, the element 2 as the reference element.

Thus, $\gamma_2 = 1$

The distance from the n.a of element 2 and the built-up beam: $a_2 = \frac{\gamma_1 E_1 A_1 (h_1 + h_2)}{2\sum_{i=1}^{2}\gamma_i E_i A_i}$

The efficient stiffness: $EI_{ef} = \sum_{i=1}^{2} E_i I_i + \gamma_i E_i A_i a_i^2$

With $I_i = \frac{b_i h_i^3}{12}$ & $a_1 = \frac{h_1 + h_2}{2} - a_2$

Thus the reduction factor for inertia in SLS is $\chi = \frac{EI_{ef,SLS}}{EI_{th}}$ With $EI_{th} = E_{m,mean}\frac{b(2h)^3}{12}$

Using $K_{i,ult}$, we can find the bending stresses in ULS (note: since we are searching for a reduction factor, we can take any value for M as long as it is consistent):

$\sigma_i = \frac{ME_{m,mean}}{EI_{ef,ULS}}(\gamma_i a_i + 0.5h_i)$

And the solid cross-section stresses: $\sigma_{1,th} = \sigma_{2,th} = \frac{ME_{m,mean}}{EI_{th}}(h_1)$

Finally, the reduction factor for resistance: $\phi = \frac{\sigma_{1,th}}{\max(\sigma_i)}$

Normal forces on the built-up beams

For normal forces, I used a simplified, conservative, way of calculating the buckling coefficient. I supposed no increase in inertia due to the connectors. Therefore, we need to check $k_{c,1}$ the buckling coefficient of one element only on one unit length and $k_{c,2}$ the buckling coefficient of two elements, linked in the middle of the chord by a rigid connection, with the buckling length taken as the distance between two nodes.

To calculate $k_{c,2}$, we need to use the same formula as for k_c, but with effective slenderness:

$$\lambda_{ef} = \sqrt{\frac{l_{tot}^2 A_{tot}}{I_{tot}} + \frac{\eta n 6 l_1}{h}}$$

with: n=2 the number of elements; l1 the length of 1 element

In the end, $k_c=\min(k_{c,1};k_{c,2})$

Source: EC5

ANNEX I: Calculation of the connections

I will start by checking the thickness of the plates for the connecting elements. This is a pre-design to prove the feasibility of the concept. It is possible in a later stage to do optimization of these elements using FEM software; however, it is outside the scope of this project.

All pieces are in S355.

Central piece

The flow of forces in the central piece is complicated and should be analyzed in a FEM software. However, relatively simple calculations can be done to give good hindsight into the required plates.

The piece is composed by an H beam part and two endplates. The endplates need to be checked mainly for the transmissions of the forces from the bolts and will be addressed in the bolt section.

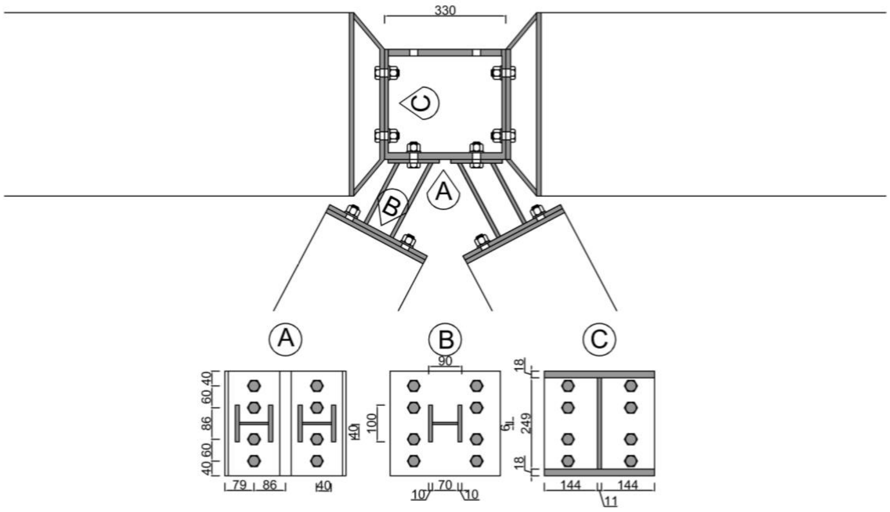


Figure 85 Truss connection, not to scale

Concerning the H part, plate buckling problems can be avoided by having a class I or II cross-section. For this reason, I will start by checking this.

Cross-section classification

$$\varepsilon = \sqrt{\frac{235}{f_y}} = 1$$

Web: $\frac{h_0}{t_w} = 25.3 < 30.9 = 38\varepsilon$ (note: hypothesis of pure compression)

Flanges: $\frac{b-t_w}{2t_f} = 7.5 < 8.1 = 38\varepsilon$ (note: hypothesis of pure compression)

Therefore, the cross-section is CLASS II.

Cross-section resistances

We can now do simple cross-section calculations. The hypothesis is that the force between the truss members is transferred via a normal force and the force between the diagonals is transferred trough shear of the web.

Normal force: $N_{Rd} = \frac{f_y A}{\gamma_{M1}} = 4442\ kN$

Shear force: $V_{Rd} = \frac{f_y A_v}{\gamma_{M1} 3^{0.5}} = 676\ kN$ With A_v the area of the web

Resistance of the net cross-section

Additionally, in the tensile chord, we need to verify that the bolt holes did not reduce the tensile resistance too much.

The resistance of the net cross-section: $N_{Rd} = \frac{0.9 f_u A_{net}}{\gamma_{M2}} = 3661kN$

With $A_{net} = A - 8d_0 t_f = 9970mm^2$

Resistance to buckling

Although the buckling should not happen, we can check that the elements will not buckle under compression for the top chord.

The buckling length is taken, conservatively, as the length of the assembly in both y and z directions.

l_{ky}=330mm l_{kz}=330mm

4The calculation methodology is shown for the y-direction, the same applies for z

The relative slenderness: $\bar{\lambda}_{K,y} = \frac{f_y l_{k,y}^2 A}{\pi^2 E I_y} = 0.03$

Buckling factor: $\chi_{k,y} = \frac{1}{\phi_k + \left(\phi_k^2 - \bar{\lambda}_{K,y}^2\right)^{0.5}}$=1

With: $\phi_k = 0.5(1 + \alpha\left(\bar{\lambda}_{K,y} - 0.2\right) + \bar{\lambda}_{K,y}^2)$ and α the imperfection factor

Similarly, $\chi_{k,z} = 1$

Introduction of forces

Finally, on the support, there is an important force applied transversally to the profile. For this reason, we need to check the stability of the web according to §4.6.3 of SIA263 (SIA, 2003c).

The resistance for an element subject to a force acting on both sides and at the end of the beam is given as:

$$F_{Rd} = \frac{1}{2\gamma_{M1}} 3 t_w^2 f_y \sqrt{\frac{E}{f_y}\frac{t_f}{t_w}} \beta_1 \beta_3 \beta_4 = 631\ \text{kN}$$

With: $\beta_1 = \left(\frac{b}{2}\frac{1}{5t_f}\right)^{\frac{1}{4}} = 1.12 \leq 1.25$ the flange slenderness

$\beta_3 = 1 + \frac{s_s}{h - t_f} = 1.5 \leq 1.5$ depending on s_s the force introduction length taken as 300mm

$\beta_4 = 1.5 - \frac{\sigma_{x,Ed}\gamma_{M1}}{f_y} = 1 \leq 1$ to account for potential axial forces. Here, it is taken as 1

The calculations are summed up in the following table:

Table 25 Resistance of the middle assembly

Middle assembly							
Geometric parameters							
Width	b	280	mm	Height	h	300	mm
Thick. Flanges	t_f	18	mm	Thick. Web	t_w	11	mm
				Height web	h_0	278	mm
Area	A	13138	mm^2	Area for shear	A_v	3300	mm^2
Inertia in y	I_y	2.20E+08	mm^4	Inertia in z	Iz	6.59E+07	mm^4
γ_{M1}	1.05			γ_{M2}	1.25		
Material properties							
Steel class		S355		Young's Mod.	E	210000	MPa
Yield strength	f_y	355	Mpa	Shear modulus	G	81000	Mpa
Ultimate strength	f_u	510	MPa	Poisson coeff	v	0.3	
Cross section classification							
Eps	ε	1					
Web classification	h_0/t_w	25.27	<	30.92	=	38ε	CLASS II
Flanges	b_0/t_f	7.47	<	8.1	=	10ε	CLASS II
Cross section resistance							
Normal force	N_{Rd}	4442	kN	Shear force	V_{Rd}	676.37	kN
Buckling							
Buckling length y	$l_{k,y}$	330	mm	Buckling length z	$l_{k,z}$	330	mm
Buckling curve	b	α	0.34	Buckling curve	c	α	0.49
Relative slendern.	$\bar{\lambda}_{K,y}$	0.03		Relative slendern.	$\bar{\lambda}_{K,y}$	0.06	
	$\Theta_{k,y}$	0.47			$\Theta_{k,z}$	0.47	
Buckling coeff	$\chi_{k,y}$	1.00			$\chi_{k,z}$	1.00	
Normal resistance	$N_{Rd,K}$	4442	kN	Normal resistance	$N_{Rd,K}$	4442	kN
Introduction of foces							
Flange slendern.	β_1	1.12		Axial force coeff	β_4	1	
Contact length	s_s	300.00	mm	Contact coeff	β_4	1.5	
Resistance	F_{Rd}	631.66	kN				
Net cross section							
Diameter hole	d0	22.00	mm	nbe holes	8		
Net cross section	A_v	9970	mm	Resistance	N_{Rd}	3661.0	kN

Unity check

The highest shear load is present at the edges of the truss, the max load for the introduction of forces, and the max compressive and tensile loads in the middle of the truss at the top and bottom, respectively. The U.C. are given in the table below:

Table 26 U.C for middle assembly

Middle assembly							
U.C.							
Compressive force	N_{ed}	1030	kN	Compressive strength	$N_{k,Rd}$	4442	kN
Tensile force	N_{ed}	1050	kN	Tensile strength	N_{Rd}	3661	kN
Shear force	V_{ed}	450	kN	Shear strength	V_{Rd}	676.37	kN
Introduction	F_{ed}	440	kN	Resistance	F_{Rd}	632	kN

Diagonal connectors

The diagonal elements are connected to the central piece with the help of a small H steel element.

It needs to be checked for normal forces, shear force, and buckling.

Normal & shear forces

Similarly to the central element: N_{Rd}=834kN V_{Rd}=110kN

Buckling resistance

Similarly to the central element, with a buckling length of 200mm, we find the following buckling coefficient: $\chi_k = 1$

Results

The calculations are summed up in the table below:

Table 27 Resistance of the diagonal connectors

Diagonal connectors							
Geometric parameters							
Width	b	100	mm	Height	h	90	mm
Thick. Flanges	t_f	10	mm	Thick. Web	t_w	6	mm
				Height web	h_0	78	mm
Area	A	2468	mm^2	Area for shear	A_v	540	mm^2
Inertia in y	I_y	3.45E+06	mm^4	Inertia in z	Iz	1.67E+06	mm^4
γ_{M1}	1.05			γ_{M2}	1.25		
Material properties							
Steel class		S355		Young's Mod.	E	210000	MPa
Yield strength	f_y	355	Mpa	Shear modulus	G	81000	Mpa
Ultimate strength	f_u	510	MPa	Poisson coeff	v	0.3	
Cross section classification							
Eps	ε	1					
Web classification	h_0/t_w	13.00	<	30.92	=	38ε	CLASS II
Flanges	b_0/t_f	4.70	<	8.1	=	10ε	CLASS II
Cross section resistance							
Normal force	N_{Rd}	834	kN	Shear force	V_{Rd}	110.68	kN
Buckling							
Buckling length y	$l_{k,y}$	300	mm	Buckling length z	$l_{k,z}$	300	mm
Buckling curve	b	α	0.34	Buckling curve	c	α	0.49
Relative slendern.	$\bar{\lambda}_{K,y}$	0.10		Relative slendern.	$\bar{\lambda}_{K,y}$	0.15	
	$\Theta_{k,y}$	0.49			$\Theta_{k,z}$	0.50	
Buckling coeff	$\chi_{k,y}$	1.00			$\chi_{k,z}$	1.00	
Normal resistance	$N_{Rd,K}$	834	kN	Normal resistance	$N_{Rd,K}$	834	kN

The most normal force and shear are on the outermost diagonals and give the following checks:

Table 28 U.C. diagonal connectors

Diagonal connectors							
U.C.							
Compressive force	N_{ed}	450	kN	Compressive streng	$N_{k,Rd}$	834	kN
Shear force	V_{ed}	15	kN	Shear strength	V_{Rd}	111	kN

Bolts

For the bolts, I calculated the resistance in shear and tension and then compare the various forces with this. In the entirety of the project, M20 bolts in 10.9 grade are used.

Geometric constraints

The spacings, named according to figure AAA, must be larger than the following minimum values:

For M20 bolts: p_1,p_2>45mm; e_1>30mm; e_2>25mm.

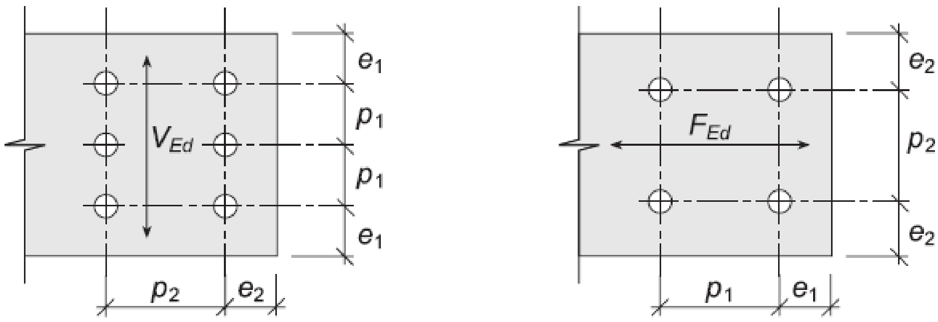


Figure 86 Spacing names (SIA, 2003c)

Resistance of a bolt

The resistance of a bolt in shear is: $F_{v,Rd} = \frac{0.6 f_{ub} A}{\gamma_{M2}}$=150kN

The resistance of a bolt in tension is: $F_{t,Rd} = \frac{0.9 f_{ub} As}{\gamma_{M2}} = 174kN$

With A_s the efficient cross section

Additionally, we need to check the combination of forces:

$$\left(\frac{F_{t,Ed,bolts}}{F_{t,Rd}}\right)^2 + \left(\frac{F_{v,Ed,bolts}}{F_{v,Rd}}\right)^2 \leq 1$$

Bearing of the plate

In addition to the resistance of the bolts, we need to check that the forces on the plates do not cause ovalization of the holes:

Because the spacing of the bolts corresponds to standard spacing according to SIA 265 (SIA, 2003d), we can use the following formula:

$$F_{b,Rd} = \min\left(\frac{0.85 e_1 f_u d t}{d_0 \gamma_{M2}}; \frac{2.4 f_u d t}{\gamma_{M2}}\right) = \min(126{,}195) = 126\text{kN}$$

With d_0 the diameter of the hole,
t the thickness of the plate taken as 10mm (min value)
f_u the ultimate strength of the plates

The calculations for M20 bolts are summed up below:

Table 29 Resistance of the bolts

Bolts							
Geometric parameters							
Spacing edge	e1	40	mm	Spacing bolts	p1	30	mm
Thick. Plate/flange	t	10	mm	Ult. Strength plate	fup	510	mm
Bolt parameters							
Bolts:	M20			Class	10.9		
Yield strength	f_{yB}	900	Mpa	Ult. Strength bolt	f_{uB}	1000	MPa
Hole diameter	d_0	22	mm	Diameter bolt	d	20	mm
Area	A	314	mm^2	Eff. Area	A_s	245	mm^2
Resistance							
Bolt in shear	$F_{v,Rd}$	150.72	kN	Bolt in tension	$F_{t,Rd}$	176.4	kN
Bearing of the plate	$F_{b,Rd}$	126.11	kN				

Unity check

The value of the unity check is the highest of the three values:

$$UC_1 = \left(\frac{F_{t,Ed,bolts}}{F_{t,Rd}}\right)^2 + \left(\frac{F_{v,Ed,bolts}}{F_{v,Rd}}\right)^2 \qquad UC_2 = \frac{F_{t,Ed,bolts}}{F_{t,Rd}}$$

$$UC_3 = \frac{F_{V,Ed,bolts}}{\min\left(F_{v,Rd};F_{b,Rd}\right)} \qquad UC = \min\left(UC_1; UC_2; UC_3\right)$$

For the three most heavily loaded connections, the following unity checks are performed:

Table 30 U.C. for bolts

Origin truss								
Mid-truss top								
Zone A			Zone B			Zone C		
Load case	Snow on roof		Load case	Snow on roof		Load case	Snow on roof	
N	50	kN	N	50	kN	N	-1030	kN
V	0	kN	V	0	kN	V	45	kN
Angle	62	deg	Angle	0	deg	Angle	0	deg
F_{ax}	44.1	kN	F_{ax}	50.0	kN	F_{ax}	-1030.0	kN
F_v	23.5	kN	F_v	0.0	kN	F_v	45.0	kN
n_{bolts}	4		n_{bolts}	8		n_{bolts}	8	
U.C	0.06		U.C	0.04		U.C	0.73	
Mid-truss bottom								
Zone A			Zone B			Zone C		
Load case	Snow on roof		Load case	Snow on roof		Load case	Snow on roof	
N	-60	kN	N	-60	kN	N	1060	kN
V	0	kN	V	0	kN	V	0	kN
Angle	62	deg	Angle	0	deg	Angle	0	deg
F_{ax}	-53.0	kN	F_{ax}	-60.0	kN	F_{ax}	1060.0	kN
F_v	-28.2	kN	F_v	0.0	kN	F_v	0.0	kN
n_{bolts}	4		n_{bolts}	8		n_{bolts}	8	
U.C	0.08		U.C	0.04		U.C	0.75	
On support								
Zone A			Zone B			Zone C		
Load case	Snow on roof		Load case	Snow on roof		Load case	Snow on roof	
N	-490	kN	N	-490	kN	N	220	kN
V	11	kN	V	11	kN	V	0	kN
Angle	62	deg	Angle	0	deg	Angle	0	deg
F_{ax}	-427.5	kN	F_{ax}	-490.0	kN	F_{ax}	220.0	kN
F_v	-220.3	kN	F_v	11.0	kN	F_v	0.0	kN
n_{bolts}	4		n_{bolts}	8		n_{bolts}	8	
U.C	0.61		U.C	0.35		U.C	0.16	

Legacy scenario

In the legacy use, the bolts must transmit the shear force but also take on the eccentricity from the connection to the center of the column.

The eccentricity will result in the following normal force in the bolts:

$F_{t,Ed,ecc} = \frac{V_{Ed}e}{h}$ with e the eccentricity and h the spacing between the bolts

The bolts are also subject to a shear force:

$F_{t,Ed,ecc} = \frac{V_{Ed}}{n_{bolt}}$

The checks are then the same as exposed earlier.

Table 31 U.C. bolts in legacy use

Legacy					
V_{Ed}	92.22	kN	e	150	mm
h	170	mm	$F_{t,Ed,Ecc}$	81.4	kN
$n_{bolts,shear}$	8		$n_{bolts,tension}$	4	
U.C.	0.12				

Glued in rods

The glued-in rods are subject to normal force and shear. I will first explain the process for finding these resistances, then give them for the two elements, i.e. diagonals and chords. Finally, I will compare the strength with the forces.

In normal force

The calculation for glued-in rods, as well as the interface strength, are taken from (Sandhaas & Blass, 2017).

The rods need to respect rules about spacing to avoid premature failure:

Minimum spacing: Between rods: a=5d
Between rod and loaded end: a=2.5d
Between rods and unloaded end: a=4d

The resistance of a rod is taken as

Resistance of the rod: $F_{ax,rod,Rd} = A_{ef} f_{yd}$

With A_{ef} the effective area of the rod, f_{yd} the yield strength of the rod

Resistance of the interface: $F_{ax,int,Rd} = \pi d l_{ad} f_{ki,RD}$

With: l_{ad} the penetration length and

the interface strength: $f_{ki,RD} \begin{cases} 4 \; if \; l_{ad} < 250 \\ 5.25 - 0.0005 l_{ad} \; if \; 250 \leq l_{ad} \leq 500 \\ 3.5 - 0.0015 l_{ad} \; if \; l_{ad} > 500 \end{cases}$

Resistance of one connector: $F_{ax,Rd} = \min(F_{ax,int,Rd}; F_{ax,rod,Rd})$

Note: there is a minimum penetration length: $l_{ad,min} = \max(0.5d^2; 10d)$

The resistance of the assembly with n rods depends on:

Resistance of timber member: $R_{mem,d} = (A - nA_{hole})f_{t,0,d}$

Resistance of the group of rods: $R_{gr,d} = n^{0.9}F_{ax}$

Resistance of the assembly: $\boldsymbol{R_d} = \mathbf{min}\ (\boldsymbol{R_{gr,d}}; \boldsymbol{R_{mem,d}})$

In shear

We can treat the lateral strength of rods similarly to dowels with the Johansen equations. Additionally, given the strength and stiffness of the glue line, we can take the rope effect to be to the maximum of what is allowed for a dowel (Sandhaas & Blass, 2017).

First, we need the embedment strength at 90 degrees from the grain

$f_{h,90,k} = \frac{0.082(1-0.01d)\rho_k}{1.35+0.015d}$ With the hypothesis of soft-wood GLT

We also need the resistance of the rod in bending:

$M_{y,Rk} = 0.3 f_{u,k} d^{2.6}$ With $f_{u,k}$ the ultimate strength of the bolt

We can now use the Johansen model with the hypothesis of a thick plate since the bolts are welded to it which will prevent the rotation, with t1 the length of the rod.

Resistance of one rod in shear: $$F_{v,Rk} = min\begin{cases} f_{h,k}t_1 d \\ f_{h,k}t_1 d(\sqrt{2+4\frac{M_{y,Rk}}{f_{h,k}dt_1^2}} - 1 + \frac{F_{ax,Rk}}{4} \\ 2.3\sqrt{M_{y,Rk}f_{h,k}d} + \frac{F_{ax,Rk}}{4} \end{cases}$$

For the axial component and the rope effect, the pullout strength is great because of the glue line. However, it is recommended to use the limit related to a bolt which means an increase of the resistance by 25% (Sandhaas & Blass, 2017). Therefore, we have the following formulas:

Resistance of one rod in shear: $$F_{v,Rk} = min\begin{cases} f_{h,k}t_1 d \\ (f_{h,k}t_1 d\left(\sqrt{2+4\frac{M_{y,Rk}}{f_{h,k}dt_1^2}} - 1\right)1.25 \\ \left(2.3\sqrt{M_{y,Rk}f_{h,k}d}\right)1.25 \end{cases}$$

Because force and wood fibers are perpendiculars, there is no need for an effective resistance. The total shear resistance is: $F_{v,Rd} = \frac{nF_{v,Rk}}{1.3}$

Shear normal force interaction

I supposed the following formula to check both shear and normal forces:

$$U.C. = \frac{V_{Ed}}{F_{v,Rd}} + \frac{N_{Ed}}{F_{ax;Rd}}$$

Resistance of the glued-in rods

The resistance for the assemblies are given in the following tables:

Table 32 Resistance of the glued-in rods

Gluled in assembly - Diagonals						
Inputs						
Timber cross section:	b	285	mm	h	300	mm
Steel:	d	16	mm	A_{ef}	245	mm^2
	$f_{u,k}$	570	MPa			
	$f_{y,d}$	438	Mpa	A_{hole}	314	mm^2
Timber properties	ρ_k	380	kg/m^3	γ_M	1.3	
Interface strength	$f_{i,Rd}$	2.85	MPa	$f_{t,0,d}$	12	MPa
Minimum spacing:						
Between bolts	a	80	mm			
To loaded end	a	64	mm			
To unloaded end	a	40	mm			
Minimum/selected length	l_{min}	160	mm	l	480	mm
Calculations of one bolt						
Embeddment strength	$f_{h,0,k}$	26.2	MPa			
Resistance rod	$R_{rod,d}$	107.3	kN			
Resistance interface	$f_{h,0,k}$	68.8	kN			
Resistance one	$F_{V,r,k}$	68.8	kN			
Calculations of assembly						
Possible number	n_v	3		n_h	3	
Chosen number	n_v	3		n_h	3	
Resistance assembly	R_d	496.8	kN			
Resistance cross section	A_{eff}	82672.57	mm^2	$R_{eff,d}$	992	kN
Resistance axial	$F_{V,Rd}$	**496**	**kN**			
Shear resistance						
Embeddment strength	fh,90,k	16	MPa			
Bending of the bolt	My,Rk	2.31E+05	Nmm			
Resistance 1 rod	Fv,Rk	22.43	kN			
Resistance shear	**Fv,Rd**	**155.27**	**kN**			

Gluled in assembly - Diagonals						
Inputs						
Timber cross section:	b	285	mm	h	500	mm
Steel:	d	16	mm	A_{ef}	245	mm^2
	$f_{u,k}$	570	MPa			
	$f_{y,d}$	438	Mpa	A_{hole}	314	mm^2
Timber properties	ρ_k	380	kg/m^3	γ_M	1.3	
Interface strength	$f_{i,Rd}$	2.525	MPa	$f_{t,0,d}$	12	MPa
Minimum spacing:						
Between bolts	a	80	mm			
To loaded end	a	64	mm			
To unloaded end	a	40	mm			
Minimum/selected length	l_{min}	160	mm	l	650	mm
Calculations of one bolt						
Embeddment strength	$f_{h,0,k}$	26.2	MPa			
Resistance rod	$R_{rod,d}$	107.3	kN			
Resistance interface	$f_{h,0,k}$	82.5	kN			
Resistance one	$F_{V,r,k}$	82.5	kN			
Calculations of assembly						
Possible number	n_v	6		n_h	3	
Chosen number	n_v	6		n_h	3	
Resistance assembly	R_d	1112.2	kN			
Resistance cross section	A_{eff}	136845.1	mm^2	$R_{eff,d}$	1642	kN
Resistance axial	$F_{V,Rd}$	**1112**	**kN**			
Shear resistance						
Embeddment strength	fh,90,k	16	MPa			
Bending of the bolt	My,Rk	2.31E+05	Nmm			
Resistance 1 rod	Fv,Rk	22.43	kN			
Resistance shear	**Fv,Rd**	**310.54**	**kN**			

Unity checks:

The unity checks for the most heavily loaded elements are given below.

Table 33 U.C for the glued-in rods

Unitiy checks					
Origin structure					
Chord elements					
Ned	1050	kN	Ved	0	kN
Unitiy checks	0.94				
Diagonal elements					
Ned	450	kN	Ved	11	kN
Unitiy checks	0.98				
Lagacy structure					
Chord elements					
Ned	0	kN	Ved	92.22	kN
Unitiy checks	0.30				
Diagonal elements (as beam)					
Ned	46	kN	Ved	11	kN
Unitiy checks	0.30				

Joist to beam

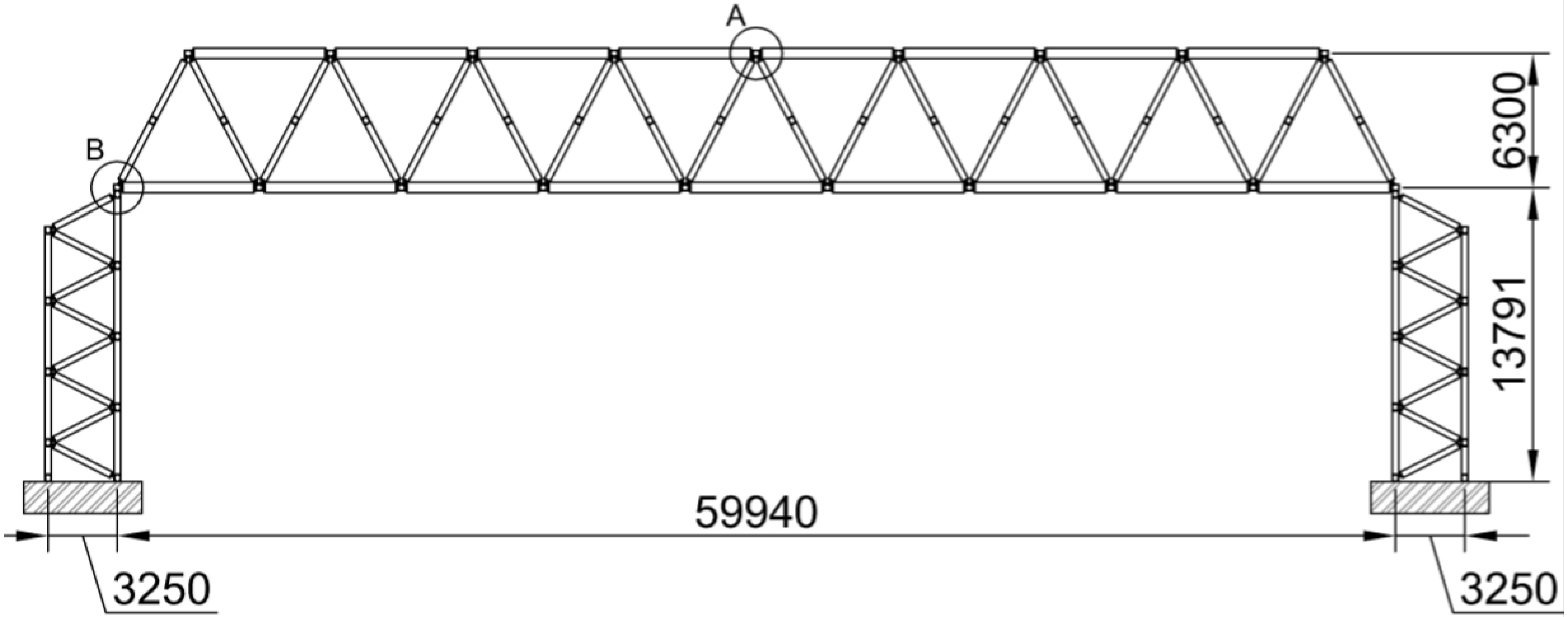
Because it is a low force connection that needs to be put in place in difficult conditions (on the roof), metal hangers screwed in the beam are a good solution.

Because it is a very standard solution, the bearing is taken from the chosen manufacturer. For example JH 95x165 by lumberlok (MiTek, 2018)

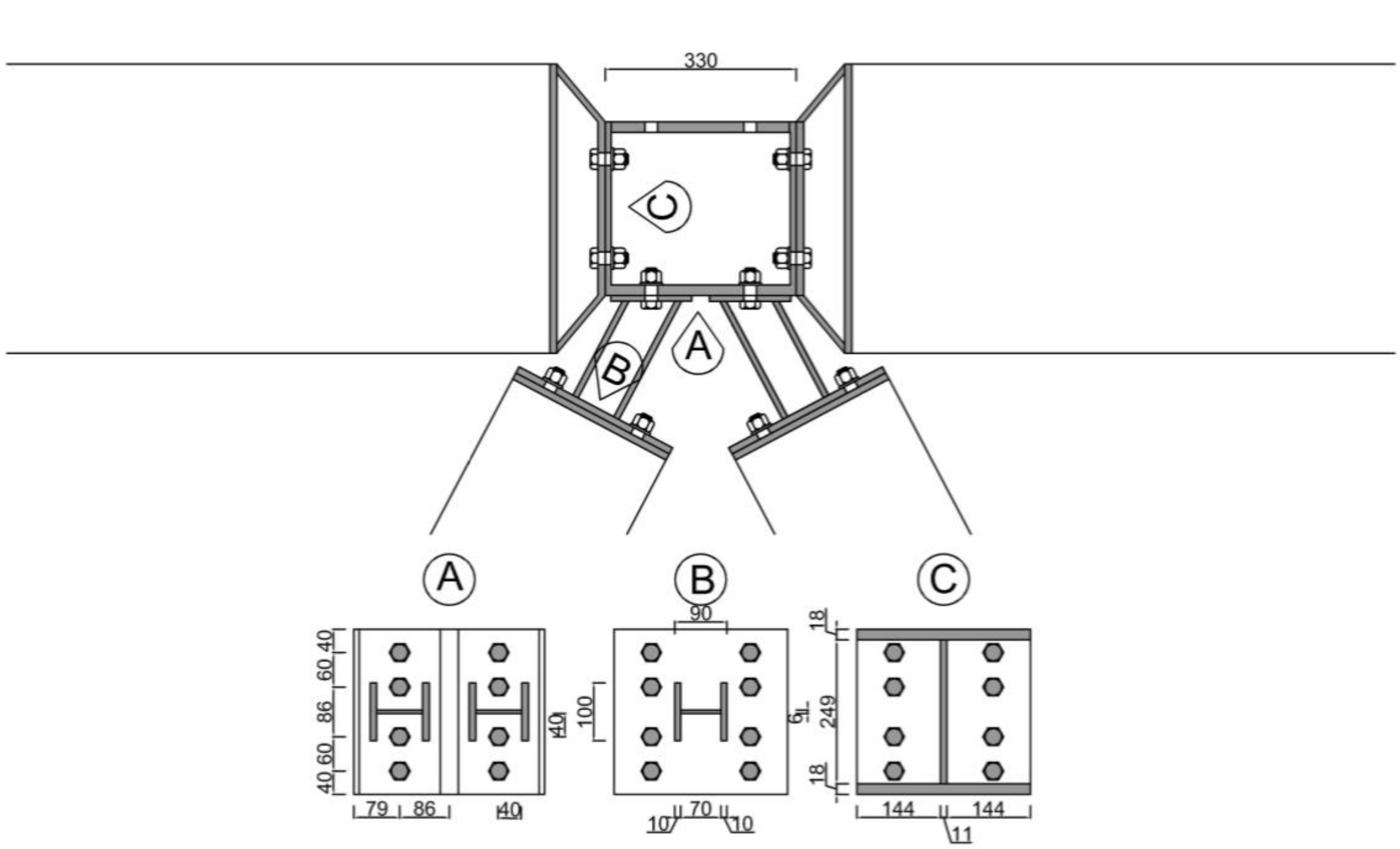
ANNEX J: Detailed drawings of the structure

The following pages contains drawing of the structure:

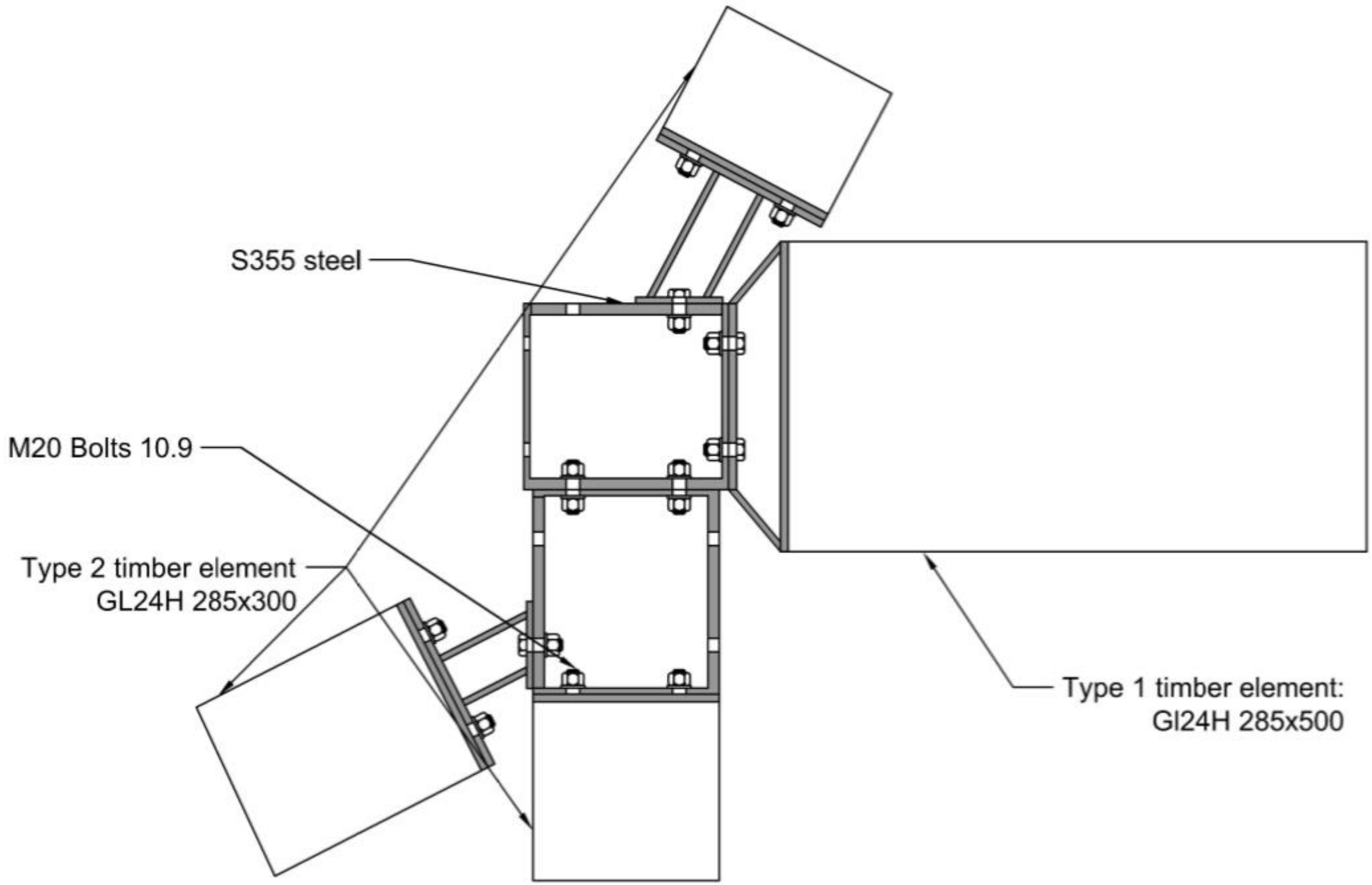
- The first is a cut of the origin structure showing the main dimensions and the locations of details A & B which are in the following pages
- The third shows the connection between the longitudinal stability elements and the structure
- Finally, a cut of the legacy structure with the relevant details is presented



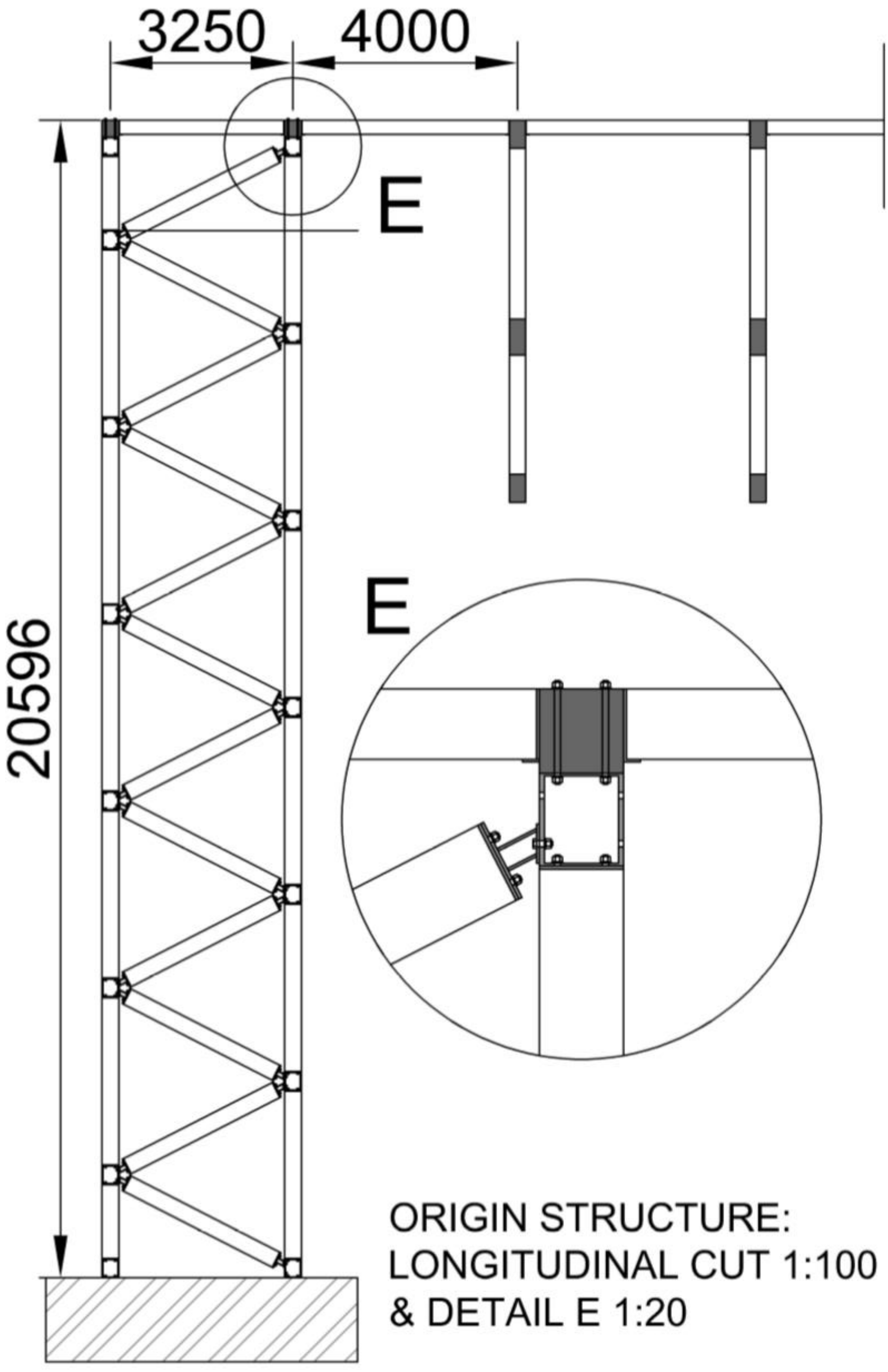
ORIGIN STRUCTURE: TRANSVERSE CUT 1:300



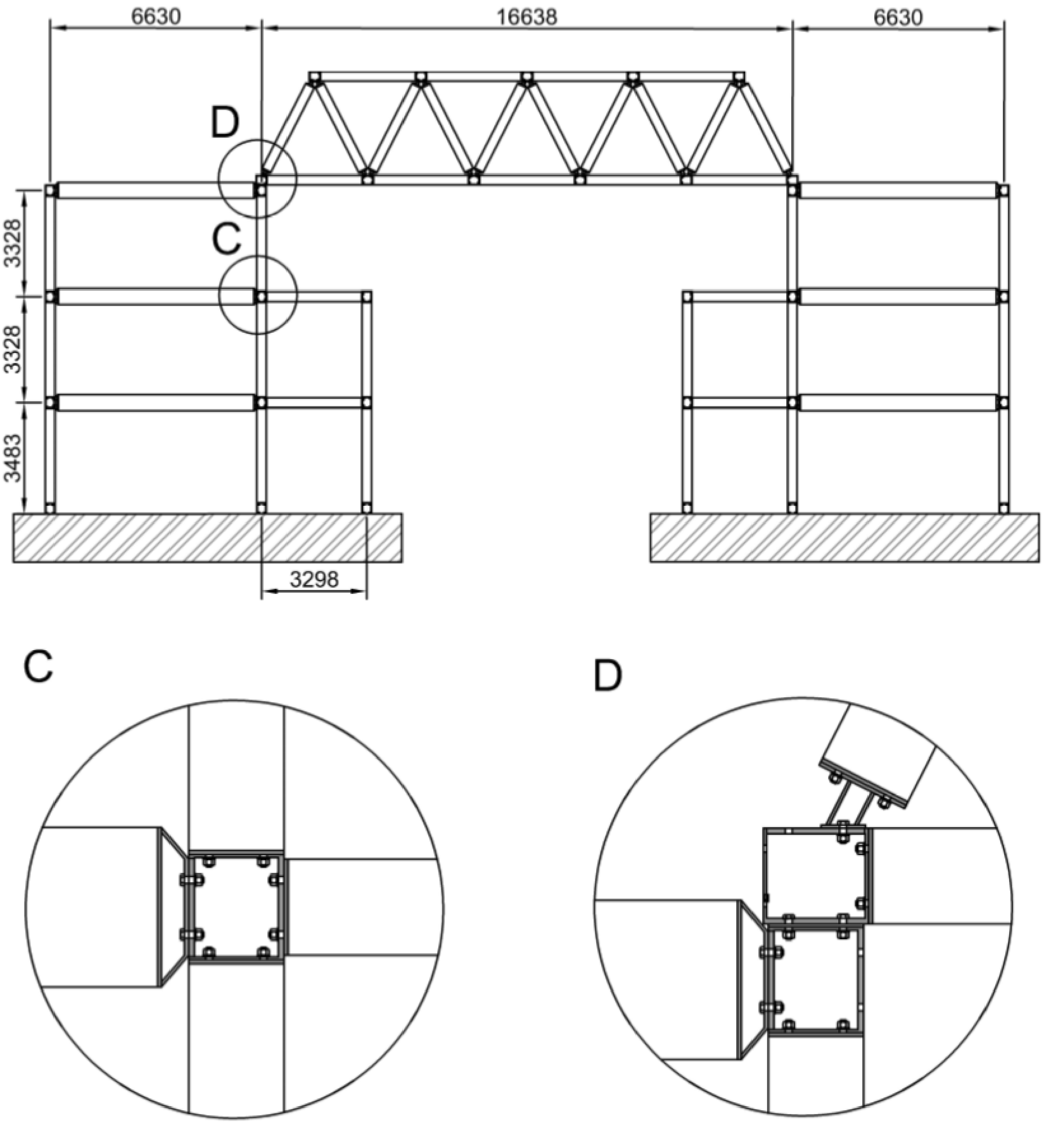
ORIGIN STRUCTURE: DETAIL A 1:10



ORIGIN STRUCTURE: DETAIL B 1:10



ORIGIN STRUCTURE:
LONGITUDINAL CUT 1:100
& DETAIL E 1:20



LEGACY STRUCTURE:
TRANVERSE CUT 1:200
& DETAIL C&D 1:20

References

2024 Olympics: Hamburg says "No" to hosting Games. (2015). *BBC News*. Retrieved from https://www.bbc.com/news/world-europe-34960208

Addis, B. (2012). *Building with Reclaimed Components and Materials: A Design Handbook for Reuse and Recycling*. Retrieved from https://books.google.com/books?id=U-3iFNZYbpYC&pgis=1

Airbus. (n.d.). Airbus Corporate Answer To Disseminate Environmental Management System.

Akinade, O. O., Oyedele, L. O., Ajayi, S. O., Bilal, M., Alaka, H. A., Owolabi, H. A., … Kadiri, K. O. (2017). Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*, *60*, 3–13. https://doi.org/10.1016/j.wasman.2016.08.017

Angsts, V. (2008). *Handbook 1 Timber structures*.

Asdrubali, F., Baldassarri, C., & Fthenakis, V. (2013). Life cycle analysis in the construction sector: Guiding the optimization of conventional Italian buildings. *Energy and Buildings*, *64*, 73–89. https://doi.org/10.1016/j.enbuild.2013.04.018

Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. (2012). Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, *47*, 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049

Azzali, S. (2019). Mega sporting events and their impact on the built environment: Lessons learned from the past. *A/Z ITU Journal of the Faculty of Architecture*, *16*(2), 25–37. https://doi.org/10.5505/itujfa.2019.12499

BAMB. (n.d.). Build reversible in conception. Retrieved January 16, 2020, from http://www.constructionmanagermagazine.com/insight/circular-economy-world-keeps-turning/

Bergman, R. D., & Bowe, S. A. (2012). Life-cycle inventory of manufacturing hardwood lumber in southeastern US. *Wood and Fiber Science*, *44*(1), 71–84.

BWF. (n.d.). OLYMPIC GAMES STATEMENT OF BADMINTON ' S REQUIREMENT.

Byers, T., Slack, T. & Parent, M. M. (2012). Mega Events. In *Key Concepts in Sport Management* (pp. 103–106). 1 Oliver's Yard, 55 City Road, London EC1Y 1SP United Kingdom: SAGE Publications Ltd. https://doi.org/10.4135/9781473914599.n23

Capelle, T., Mantell, S., Steinlage, M., Henrotay, C., Farnetani, M., Lowres, F., … Heinrich, M. (2020). BUILDINGS AS MATERIAL BANKS-TESTING BAMB RESULTS THROUGH PROTOTYPING AND PILOT PROJECTS, (642384).

CE100. (2016). Circularity in the Built Environment: Case Studies, (April), 1–72.

Chen, C. X., Pierobon, F., & Ganguly, I. (2019). Life Cycle Assessment (LCA) of Cross-Laminated Timber (CLT) produced in Western Washington: The role of logistics and wood species mix. *Sustainability (Switzerland)*, *11*(5). https://doi.org/10.3390/su11051278

CIOB. (2014). Circular economy: the world keeps turning. Retrieved January 16, 2020, from http://www.constructionmanagermagazine.com/insight/circular-economy-world-keeps-turning/

Crowther, P. (2005). Design for disassembly - themes and principles. *RAIA/BDP Environment Design Guide*, (August), Australia. https://doi.org/10.1115/1.2991134

Crowther, P. (2009). Designing for disassembly. *Technology, Design and Process Innovation in the Built Environment*, *9780203928*, 224–237. https://doi.org/10.4324/9780203928325

Crowther, P. (2016). *Technology, Design and Process Innovation in the Built Environment*.

Danatzko, J. M., & Sezen, H. (2011). Sustainable structural design methodologies. *Practice Periodical on Structural Design and Construction*, *16*(4), 186–190. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000095

Divisare. (2015). Nelson Mandela High School. Retrieved from https://divisare.com/projects/295049-francois-leclercq-cyrille-weiner-takuji-shimmura-lycee-international-nelson-mandela

Divisare. (2017). Le déjeuner sur l'herbe. Retrieved from https://divisare.com/projects/350051-carlana-mezzalira-pentimalli-le-dejeuner-sur-l-herbe

Divisare. (2019). Bunq. Retrieved from https://divisare.com/projects/414518-bunq-david-gagnebin-de-bons-cedric-widmer-45ce

Durmisevic, E., Beurskens, P. R., Adrosevic, R., & Westerdijk, R. (2017). Systemic View on Reuse Potential of Building Elements, Components and Systems: Comprehensive Framework for Assessing Reuse Potential of Building Elements. *International HISER Conference on Advances in Recycling and Management of Construction and Demolition Waste*, (June), 275–280.

EFP. (2019). Bric Poster 2019.

Ehrbar, H., & Kellenberger, J. (2003). Risk Management During Construction of the Gotthard Base Tunnel. *Proceedings GTMM, Karlsruhe*, 1–5. Retrieved from http://www.heinzehrbarpartners.com/files/2503-2003-Ehrbar-Kellenberger-Karlsruhe_Risk_Management.pdf

Erman, E. (2002). Demountable timber joints for timber construction systems. *Architectural Science Review*, *45*(2), 133–143. https://doi.org/10.1080/00038628.2002.9697501

Erten, S., & Özfiliz, S. (2012). Stadium Construction and Sustainability : the Review of Mega-Event Stadiums (1990-2012). *Built Environment*, 525–541.

Essex, S., & Chalkley, B. (2004). *Mega-sporting events in urban and regional policy: A history of the Winter Olympics*. *Planning Perspectives* (Vol. 19). https://doi.org/10.1080/0266543042000192475

Fadai, A., & Stephan, D. (2019). Ecological performance and recycling options of primary structures. *IOP Conference Series: Earth and Environmental Science*, *323*(1). https://doi.org/10.1088/1755-1315/323/1/012133

Ferrari, S., & Guala, C. (2017). Mega-events and their legacy: Image and tourism in Genoa, Turin and Milan. *Leisure Studies*, *36*(1), 119–137. https://doi.org/10.1080/02614367.2015.1037788

Gibson, O. (2016). West Ham stadium faces losses for years due to retractable-seating problems. *The Guardian*. Retrieved from https://www.theguardian.com/sport/2016/nov/02/west-ham-stadium-losses-retractable-seating-problems

Giulianotti, R., Armstrong, G., Hales, G., & Hobbs, D. (2015). Sport Mega-Events and Public Opposition: A Sociological Study of the London 2012 Olympics. *Journal of Sport and Social Issues*, *39*(2), 99–119. https://doi.org/10.1177/0193723514530565

Goens, H. (2017). Building reversible in conception (BRIC) Presentation 10/2017, 1–25.

Gustavsson, L., Joelsson, A., & Sathre, R. (2010). Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy and Buildings*, *42*(2), 230–242. https://doi.org/10.1016/j.enbuild.2009.08.018

Guy, Brad, & Ciarimboli, N. (2005). DfD Design for Disassembly in the built environment: a guide to closed-loop design and building Foreword and Acknowledgements. Retrieved from http://www.lifecyclebuilding.org/docs/DfDseattle.pdf

Guy, Bradley. (2002). Design for Deconstruction and Materials Reuse. *Proceedings of the CIB Task Group 39 – Deconstruction Meeting*, *272*(April), 244. Retrieved from www.cce.ufl.edu/affiliations/cib

Hafner, A., Ott, S., & Winter, S. (2014). Recycling and End-of-Life Scenarios for Timber Structures. In *Materials and Joints in Timber Structures* (pp. 89–98). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-7811-5_8

Herzog, T., & Natterer, J. (2004). *Timber Construction Manual*. https://doi.org/10.1201/b15320-186

Hill, C. A. S. (2019). The Environmental Consequences Concerning the Use of Timber in the Built Environment. *Frontiers in Built Environment*, *5*(October), 1–10. https://doi.org/10.3389/fbuil.2019.00129

Hoffstetter, M. (2018). Le non des Valaisans devrait enterrer les JO de Sion. *Bilan*. Retrieved from https://www.bilan.ch/tv-bilan/le_non_des_valaisans_devrait_enterrer_les_jo_de_sion

Hradil, P. (2015). Barriers and opportunities of structural elements re-use.

Hradil, P., Talja, A., Wahlstr, M., Huuhka, S., Lahdensivu, J., & Pikkuvirta, J. (2014). *Re-use of structural elements Environmentally efficient recovery of building components*. Retrieved from http://www.vtt.fi/publications/index.jsp

Iimura, Y., Kurita, S., & Ohtsuka, T. (2006). Reticulated timber dome structural system using glulam with a low specific gravity and its scalability. *9th World Conference on Timber Engineering 2006, WCTE 2006*, *1*, 64–71.

INJEP. (2018). Tableaux statistiques relatifs au recensement des licences sportives de 2018. Retrieved February 13, 2020, from Tableaux statistiques relatifs au recensement des licences sportives de 2018

Institut Bauen und Umwelt e.V. (IBU). (2013). *Glued laminated timber (Glulam) Studiengemeinschaft Holzleimbau e.V.*

Institut Bauen und Umwelt e.V. (IBU). (2015). Reactive resins based on polyurethane or SMP, filled or aqueous, solvent-free FEICA - Association of the European Adhesive and Sealant Industry.

Institut Bauen und Umwelt e.V. (IBU). (2018). Structural Steel : Sections and Plates bauforumstahl e . V .

International Energy Agency. (2017). *Global Status Report 2017. Global Status Report 2017*.

IOC. (2005). Technical Manual on Venues - Design Standards for Competition Venues.

Italy withdraws Rome 2024 Olympic Games bid. (2016). *BBC News*. Retrieved from https://www.bbc.com/news/world-europe-37624948

Jung, K., Kitamori, A., & Komatsu, K. (2008). Evaluation on structural performance of compressed wood as shear dowel. *Holzforschung*, *62*(4), 461–467. https://doi.org/10.1515/HF.2008.073

Khasreen, M. M., Banfill, P. F. G., & Menzies, G. F. (2009). Life-cycle assessment and the environmental impact of buildings: A review. *Sustainability*, *1*(3), 674–701. https://doi.org/10.3390/su1030674

Kibert, C. J. (2007). The next generation of sustainable construction. *Building Research and Information*, *35*(6), 595–601. https://doi.org/10.1080/09613210701467040

Lennartz, M. W., & Freitag, S. J. (2015). *New Architecture in Wood: Forms and Structures*.

Lim, L. (2012). China post-olympic woe, how to fill an empty nest. *Npr.Org*. Retrieved from https://www.npr.org/2012/07/10/156368611/chinas-post-olympic-woe-how-to-fill-an-empty-nest

Luscuere, L. M. (2017). Materials Passports: Optimising value recovery from materials. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*, *170*(1), 25–28. https://doi.org/10.1680/jwarm.16.00016

Lyon, A. (2002). Directives Et Recommandations Concernant Les Constructions Scolaires.

Mehr, J., Vadenbo, C., Steubing, B., & Hellweg, S. (2018). Environmentally optimal wood use in Switzerland—Investigating the relevance of material cascades. *Resources, Conservation and Recycling*, *131*(December 2017), 181–191. https://doi.org/10.1016/j.resconrec.2017.12.026

MiTek. (2018). Structural fixings on-site guide.

Müller, M. (2015). What makes an event a mega-event? Definitions and sizes. *Leisure Studies*, *34*(6), 627–642. https://doi.org/10.1080/02614367.2014.993333

Neufert, E. (1998). *Architect's data Second (international) English Edition.*

Norm Nederlanse. (2020). Nen-en 15978, *15978*(november 2011).

Nussli. (2016). NUSSLI builds a temporary arena with 52,016 Seats for the Federal Wrestling and Alpine Festival in Estavayer. Retrieved November 27, 2019, from https://www.nussli.com/en/news-pr-and-media/current-news-and-media-releases/nussli-builds-a-temporary-arena-with-52016-seats-for-the-federal-wrestling-and-alpine-festival-in-estavayer/

O'Brien, E., Guy, B., & Lindner, A. S. (2006). Life cycle analysis of the deconstruction of military barracks: Ft. McClellan, Anniston, AL. *Journal of Green Building*, *1*(4), 166–183. https://doi.org/10.3992/jgb.1.4.166

Ortiz, O., Castells, F., & Sonnemann, G. (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, *23*(1), 28–39. https://doi.org/10.1016/j.conbuildmat.2007.11.012

Oxford dictionary. (2019). White elephants. Retrieved November 27, 2019, from https://www.lexico.com/en/definition/white_elephant

Panagiotopoulou, R. (2014). The legacies of the Athens 2004 Olympic Games: A bitter-sweet burden. *Contemporary Social Science*, *9*(2), 173–195. https://doi.org/10.1080/21582041.2013.838297

Passarelli, R. N., & Koshihara, M. (2017). CLT panels in Japan from cradle to construction site gate: global warming potential and freight costs impact of three supply options. *International Wood Products Journal*, *8*(2), 127–136. https://doi.org/10.1080/20426445.2017.1317471

Petit levage SA. (2020). Grue 100 tonnes télescopique automotrice rapide GMK 4100.

Porter, B. (2002). *Carpentry and joinery I.*

ProBas. (2000). Prozessdetails: Lkw (int). Retrieved May 20, 2020, from https://www.probas.umweltbundesamt.de/php/prozessdetails.php?id=%7BB11C6A80-A5B4-11D3-B42D-FED95173DC12%7D

Probos. (2017). The Netherlands National Market Report. *Institute for Forestry, Forest Products and Services.*

Puettmann, M. E., & Wilson, J. B. (2005). Gate-to-gate life-cycle inventory of glued-laminated timbers production. *Wood and Fiber Science*, *37*(Corrim 2001), 99–113.

Puettmann, M. E., & Wilson, J. B. (2014). Life-cycle analysis of wood products : Cradle-to-gate LCI of residential wood building materials LIFE-CYCLE ANALYSIS OF WOOD PRODUCTS : CRADLE-TO-GATE LCI OF RESIDENTIAL WOOD BUILDING MATERIALS, (July).

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., … Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, *68*(October 2015), 333–359. https://doi.org/10.1016/j.rser.2016.09.107

Sahoo, K., Bergman, R., Alanya-Rosenbaum, S., Gu, H., & Liang, S. (2019). Life cycle assessment of forest-based products: A review. *Sustainability (Switzerland).* https://doi.org/10.3390/su11174722

Sandhaas, C., & Blass, H. J. (2017). *Timber Engineering Principles for design*. KIT Scientific Publishing.

Sathre, R., & Gustavsson, L. (2009). Using wood products to mitigate climate change: External costs and structural change. *Applied Energy*, *86*(2), 251–257. https://doi.org/10.1016/j.apenergy.2008.04.007

Sathre, R., & O'Connor, J. (2010). Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environmental Science and Policy*, *13*(2), 104–114. https://doi.org/10.1016/j.envsci.2009.12.005

Seelye, K. (2015). Boston's Bid for Summer Olympics Is Terminated. *The New York Times*. Retrieved from https://www.nytimes.com/2015/07/28/sports/olympics/boston-2024-summer-olympics-bid-terminated.html

Shen, L. Y., Li Hao, J., Tam, V. W. Y., & Yao, H. (2007). A checklist for assessing sustainability performance of construction projects. *Journal of Civil Engineering and Management*, *13*(4), 273–281. https://doi.org/10.1080/13923730.2007.9636447

SIA. (2003a). SIA 260:2003 Bases pour l'élaboration des projets de structures porteuses, 1–44. Retrieved from papers3://publication/uuid/D78E4637-9475-4B90-8520-1A09D47D77EA

SIA. (2003b). SIA 261 2003 Actions sur les structures porteuses, *4*, 1–94.

SIA. (2003c). SIA 263:2003 Construction en acier, 1–40.

SIA. (2003d). SIA 265:2003 Construction en bois, 1463–1482.

Sotayo, A., Bradley, D., Bather, M., Sareh, P., Oudjene, M., El-Houjeyri, I., … Guan, Z. (2019). Review of State of the Art of Dowel Laminated Timber Members and Densified Wood Materials as Sustainable Engineered Wood Products for Construction and Building Applications. *Developments in the Built Environment*, 100004. https://doi.org/10.1016/j.dibe.2019.100004

Stahlbau Zentrum Schweiz. (2005). Tables de construction C5/05.

Steward, J. (2002). Adaptable design in Olympic Construction. *Nrl.Northumbria.Ac.Uk*, *24*(August), 23–35. https://doi.org/10.1108/17410391111097438

Summer, J. (2016). Building a circular future.

Teigland, J. (1999). Mega-events and impacts on Tourism; The predictions and realities of the lillehammer olympics. *Impact Assessment and Project Appraisal*, *17*(4), 305–317. https://doi.org/10.3152/147154699781767738

Tlustochowicz, G., Serrano, E., & Steiger, R. (2011). State-of-the-art review on timber connections with glued-in steel rods. *Materials and Structures/Materiaux et Constructions*, *44*(5), 997–1020. https://doi.org/10.1617/s11527-010-9682-9

Totaro, A. I. (2017). Closing the Circle is Just One Option. *Renewable Matter*.

TRADA. (2007). Wide-Span Wood Sports Structures, 47.

Trebilock, P. (2004). *Architectural Design in Steel*. https://doi.org/0203641655

Treloar, G., Fay, R., Ilozor, B., & Love, P. (2001). Building materials selection: greenhouse strategies for built facilities. *Facilities*, *19*(3), 139–150. https://doi.org/10.1108/02632770110381694

Turuban, P. (2019). Le canton de Vaud manque de gymnases, selon une commission. *RTS*. Retrieved from https://www.rts.ch/info/regions/vaud/10402754-le-canton-de-vaud-manque-de-gymnases-selon-une-commission.html

UBC. (2019). C-K Choi building. Retrieved December 13, 2019, from https://ies.ubc.ca/about-us/c-k-choi-building/sustainability-features/

Vallée, T., Tannert, T., & Fecht, S. (2017). Adhesively bonded connections in the context of timber engineering–A Review. *Journal of Adhesion*, *93*(4), 257–287. https://doi.org/10.1080/00218464.2015.1071255

Vogtlander, J. (2014). *A Practical Guide to LCA for Students, Designers and Business Managers: Cradle-to-grave and Cradle-to-cradle*.

Vollichard, P. (1986). *Constructions en bois. Réalisations récentes en Suiss*.

Webster, M. D., & Costello, D. T. (2005). Designing Structural Systems for Deconstruction: How to extend a new building's useful life and prevent it from going to waste when the end finally comes. *Greenbuild Conference*, 1–14.

Wikipedia. (2019a). London Stadium. Retrieved November 27, 2019, from https://en.wikipedia.org/wiki/London_Stadium#London_2012

Wikipedia. (2019b). Torino Palavela. Retrieved November 21, 2019, from https://en.wikipedia.org/wiki/Torino_Palavela

Woodard, A. C., & Milner, H. R. (2016). *Sustainability of timber and wood in construction. Sustainability of Construction Materials* (Second Edi). Elsevier Ltd. https://doi.org/10.1016/b978-0-08-100370-1.00007-x

Ximenes, F. A., & Grant, T. (2013). Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia. *International Journal of Life Cycle Assessment*, *18*(4), 891–908. https://doi.org/10.1007/s11367-012-0533-5

Figures

Cover image, Richmond Olympic oval, Retrieved nov. 27 2019 from: https://structurecraft.com/projects/richmond-olympic-oval

Figure 1 Davos ice rink, Retrieved jan. 27 2020 from http://www.eduardoperez.de/architecture/design/artek-hc-davos/

Figure 2 Dutch fans at the women football WC, Retrieved nov. 27 2020 from: https://cdn-europe1.lanmedia.fr/var/europe1/storage/images/europe1/sport/videos-coupe-du-monde-feminine-deferlante-de-supporters-neerlandais-a-valenciennes-3904737/53162093-1-fre-FR/VIDEOS-Coupe-du-monde-feminine-deferlante-de-supporters-neerlandais-a-Valenciennes.gif

Figure 3 Hamar viking ship, Retrieved nov. 27 2019 from: https://vikingskipet.com/vare-anlegg/vikingskipet/beliggenhet/

Figure 4 Brummel city hall and the globe, Retrieved nov. 27 2019 from: http://www.constructionmanagermagazine.com/insight/circular-economy-world-keeps-turning/ & http://www.jpf-ducret.ch/fr/references/terrasse-du-paleo.html

Figure 5 Flags of the represented nations in London, Retrieved nov. 27 2019 from: https://news.cision.com/sister/i/world-comes-together-on-regent-street-4,c1221538

Figure 6 World cup stadium under construction, Retrieved nov. 27 2019 from: https://edition.cnn.com/2013/03/04/opinion/brazil-world-cup-and-olympics-opinion/index.html

Figure 7.1 London stadium in football mode, Retrieved nov. 27 2019 from: https://www.thestadiumbusiness.com/2019/04/15/london-stadium-goes-claret-west-ham-agreement/

Figure 7.2 London stadium in athletics mode, Retrieved nov. 27 2019 from: https://www.express.co.uk/sport/othersport/838058/World-Athletics-Championships-2017-Day-4-results-Laura-Muir-1500m-Wayde-van-Niekerk

Figure 8.1 London aquatic center in Olympic mode, Retrieved nov. 27 2019 from: https://swimswam.com/zaha-hadid-designer-london-olympic-aquatics-centre-dies-65/

Figure 8.2 London aquatic center in Legacy mode, Retrieved nov. 27 2019 from: https://www.dezeen.com/2014/02/25/zaha-hadids-olympic-aquatics-centre-due-to-open-as/

Figure 9 Arena in Zoug, Retrieved nov. 27 2020 from: https://www.rts.ch/sport/lutte/10655352-lutte-la-federale-prend-ses-quartiers-a-zoug-pour-un-weekend-de-folie.html

Figure 10 A timber connection , Retrieved jan. 20 2020 from: https://structurecraft.com/materials/connectors/timber-connections

Figure 11 Dimensions of sustainability, Icon made by Freepik, Good Ware, Smash icon, Retrieved jan.12 2020 from: www.flaticon.com

Figure 12 Quality structures have a seemingly infinite lifespan, Retrieved nov. 27 2019 from: https://www.flickr.com/photos/22746515@N02/8082864097

Figure 13 LCA process

Figure 14 Timber harvesting, Retrieved nov. 27 2019 from: https://www.flickr.com/photos/oregondepartmentofforestry/15457609889

Figure 15 Timber house under construction, Retrieved jan. 20 2020 from: https://www.homebuilding.co.uk/timber-frame-guide/

Figure 16 Timber logs, Retrieved dec. 27 2019 from: https://unsplash.com/s/photos/timber

Figure 17 Building under demolition, Retrieved dec. 13 2019 from: https://www.cordilleralodge.com/construction-waste-management-handling-different-types-of-waste/

Figure 18 Workers demounting a timber roof, Retrieved dec. 13 2019 from: https://www.angieslist.com/articles/old-house-salvage-home-deconstruction-methods.htm

Figure 19 Left: Facade of the building, Right: Reclaimed timber structure , Retrieved dec. 13 2019 from: https://ies.ubc.ca/about-us/c-k-choi-building/sustainability-features/ & https://sppga.ubc.ca/wp-content/uploads/sites/5/2017/08/lounge_2-1024x680.jpg

Figure 20 DfD categories, Icon made by Those; Freepik & Monkik from www.flaticon.com, Retrieved dec. 13 2019 from: www.flaticon.com

Figure 21 House made with reclaimed timber in chile, Retrieved Feb. 12 2020 from: https://www.archdaily.com/887654/casa-pollo-ortuzar-gebauer-arquitectos

Figure 22 BRIC 1, Retrieved Jan. 16 2020 from: https://www.bamb2020.eu/topics/pilot-cases-in-bamb/bric/Figure 23 BRIC 1 construction

Figure 23 BRIC 1 construction, Retrieved Jan. 16 2020 from: https://www.bamb2020.eu/topics/pilot-cases-in-bamb/bric/Figure 23 BRIC 1 construction

Figure 24 Comparison of re-use vs traditional (Capelle et al., 2020)

Figure 25 Brummen city hall, Retrieved Jan. 16 2020 from: https://www.rau.eu/portfolio/gemeentehuis-brummen/Figure 26 Examples of connections (Summer, 2016)

Figure 26 Examples of connections (Summer, 2016)

Figure 27 Brummen city hall floorplans, Retrieved Jan. 16 2020 from: https://www.rau.eu/portfolio/gemeentehuis-brummen/

Figure 28 Paleo's terrace, Retrieved Jan. 16 2020 https://www.lacote.ch/dossiers/paleo/articles/terrasse-essentielle-a-l-assise-financiere-684645

Figure 29 Timber construction, Retrieved Feb 11 2020 from: https://decor10blog.com/design-decorate/decorating-ideas/wooden-pavilions-by-lake-flato-create-a-farming-school-in-the-texas-landscape.html

Figure 30 Badminton at the 2012 London Olympics , Retrieved May 27 2020 from: https://ichef.bbci.co.uk/images/ic/640x360/p00ws82h.jpg

Figure 31 Left: Frauenfeld's governmental building; Top: Bunq; Bottom Nelson Mandela high school, , Retrieved May 27 2020 from: https://divisare.com/projects/350051-carlana-mezzalira pentimalli-le-dejeuner-sur-l-herbe; https://divisare.com/projects/414518-bunq-david-gagnebin-de-bons-cedric-widmer-45ce; https://divisare.com/projects/295049-francois-leclercq-cyrille-weiner-takuji-shimmura-lycee-international-nelson-mandela

Figure 32 Mortise tenon assembly, Retrieved Feb. 16 2020 from: https://www.papavoine-menuiserie.com/escalier-merisier.php

Figure 33 Dowelled connection with slotted-in plate, Retrieved Feb. 16 2020 from: https://www.archdaily.com/519304/long-sutton-studio-cassion-castle-architects/53a85eabc07a80b48b000107_long-sutton-studio-cassion-castle-architects-_kilo-0119-0026-jpg/

Figure 86 Spacing names (SIA, 2003c)

Tables