Master Thesis – **Sustainable Sport venue design**

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A design proposal for a demountable temporary Olympic arena, optimized for a post-event use in steel construction.

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Report P5

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1 Introduction

Large sport events are often characterized by what they leave behind, which can be both successful and unsuccessful. Countries and cities are awarded to host events such as the Olympics or the FIFA World cup. For a relatively short period of time there is a large influx of people and events, which requires a suitable large amount of accommodations. History has shown that more often than not the city or country has difficulty or even fails completely to create a lasting legacy for the venues and accommodations (Alm J., 2012).

Such events are held around the globe and therefore likely to be located in completely different environments. FIFA for example even set this as a requirement, by introducing the policy of a rotating system. It states that the World Cup tournament should rotate between continents (Alm, 2012). The expected legacy therefore is highly dependent on culture, financial state, environmental influences and popularity of a certain sport (Pitts A., 2009). To find a single solution for the problem of creating a lasting positive legacy is hard, since every event has a different context.

Even when organizations have good intentions and plans for a post use of a sports venue it is no guarantee for a good legacy. Take for example of the swimming arena used for the Rio Olympics 2016 (Figure 1.1). The designers took into account the post event use of the venue, but the arena is currently unused and abandoned. In other cases (ex. basketball, London Olympics 2012) only part of the structure is reused, while the rest has no real use in the current market.

Figure 1.1. *Handball arena Rio Olympics 2016 before and after.* retrieved from *https://upload.wikimedia.org/wikipedia/commons/thumb/8/8f/Esportes_Aqu%C3%A1ticos_Rio_2016.jpg/1200px-Esportes_Aqu%C3%A1ticos_Rio_2016.jpg on 16 June 2017*

Temporary structures are more frequently used for these events, which can be concluded from the number of temporary seats during the Olympics (figure 1.2). It gives an opportunity to host large events without the disadvantages of permanent buildings (Bulley & Cardwell, 2015). These reusable structures are ideally demounted relatively easy, and can be transported somewhere else (partially or whole) to be rebuild.

Even though temporary structures do not leave a visible legacy after a sports event, its materials often do leave one. Although temporary structures are more sustainable than leaving an actual structure behind without purpose, the material use should be considered.

Many different materials are used in temporary sport venues in different quantities, the largest amount in mass determined by the material choice of the load bearing construction. Almost exclusively stainless steel is used for these constructions, because of its weight to strength ratio and its versatility. Also, roughly 95% the steel used in the current steel construction industry is recycled, which means there is currently a large market for used steel. However that market is particularly aimed at recycling opposed to other forms of reuse that have a lower impact on the environment.

The goal of this research is to find a sustainable design strategy for a demountable steel construction for a temporary Olympic venue. Aiming for an improvement of a reuse strategy towards a post-event use compared to previous designs with a similar intent.

For the purpose of the design requirements a case study has been chosen for which the design strategy is made, namely the temporary volleyball arena of the Olympic games of Paris in 2024.

The research question in this report is as follows: *How can a design proposal for a demountable temporary Olympic sports arena be optimized towards a post-event use in steel construction?*

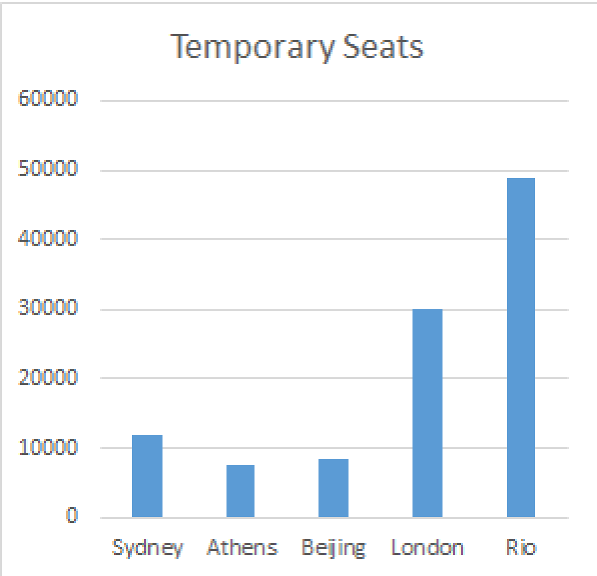


Figure 1.2. Amount of temporary seating during the Olympics since 2000.[1] *(Bulley, 2015)*

[1] *The amount of temporary seats in Rio is an approximation, the event occurred recently and it is still unclear how many seats were actually temporary. Also, seats reused in other Olympics are lower than expected when compared to the claims of the IOC.*

2 Methodology

To answer the research question this thesis is divided in three parts, a literature research, a description of requirements and a design proposal. The literature will form the background of the research. This includes several case studies, which are documented throughout the chapter. Rather than having a chapter dedicated on these case studies, the case studies will be documented alongside the research. Below a list can be found referencing to each case study in the document.

The second chapter of the report describes the requirements for a design proposal. The chapter acts as a link where the previously discussed findings in the literature research are compared to requirements for a sports arena. This information is gained from literature, case studies (see below) and other documentation that is not necessarily scientific literature.

Sydney Olympics 2000

- National stadium [pg. 17]

London Olympics 2012

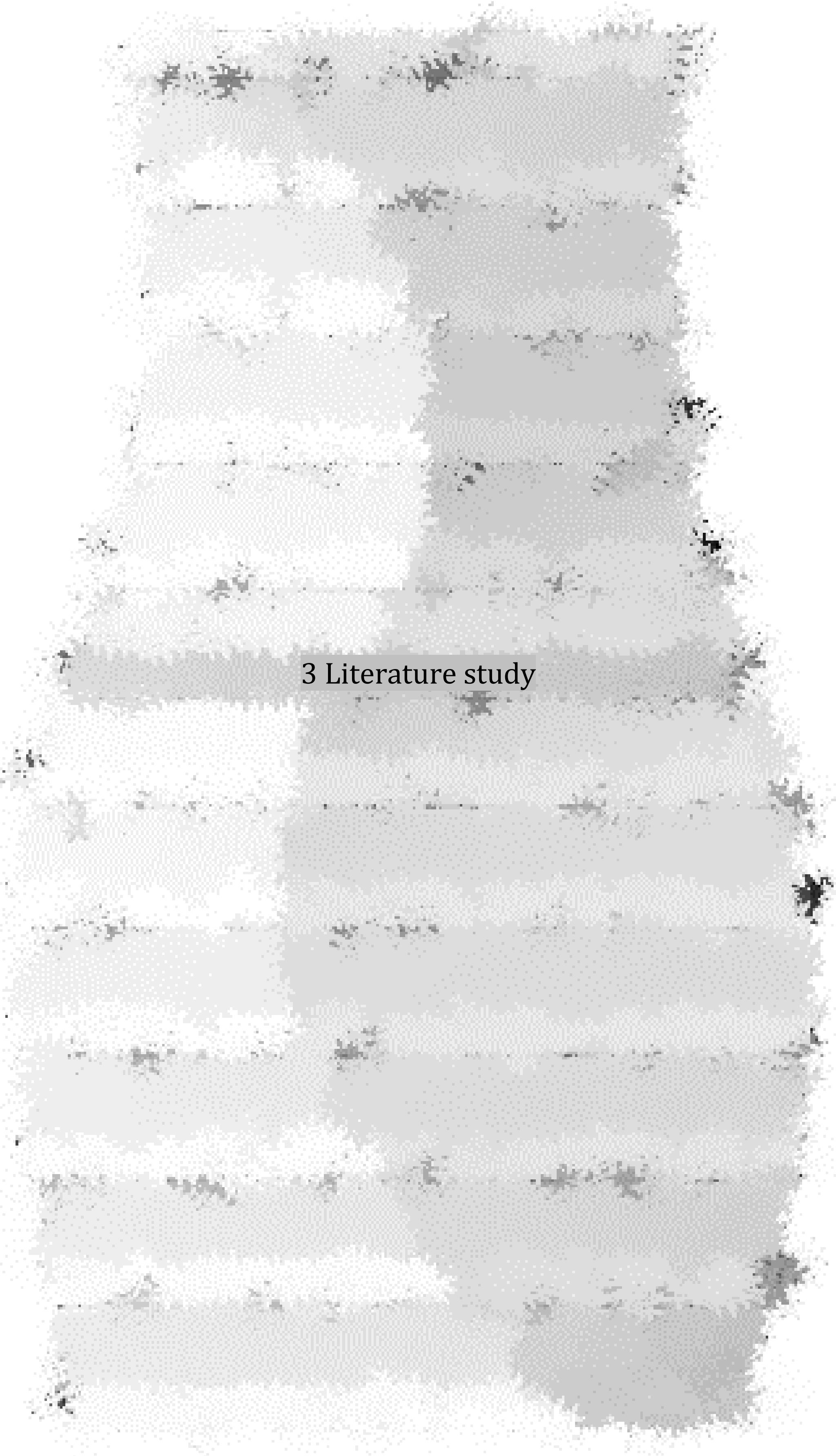
- Basketball Arena [pg. 15]
- Handball arena, Copper box
- Water Polo Arena
- Aqua centre [pg. 18]
- Olympic Stadium
- Shooting Range

Rio de Janeiro Olympics 2016

- Handball Arena
- Aqua centre

The third chapter will contain a design proposal for a reusable Olympic Arena. The goal is to conform to the requirements stated in the previous chapter, while it is also based on a *research by design*. This method can be described as follows: design implications are tested and reviewed, after which conclusions can be drawn regarding these design implications. These design implications are not necessarily based on scientific research but result from a creative design process, for example sketching.

To assess multiple designs a parametric model is used. A parametric model is a tool in the design process where the geometry is computed by a program (Rhinoceros, grasshopper) instead of being drawn by hand. By adjusting parameters several designs can be made relatively quickly. Although preliminary in nature, much information can be retrieved from these designs. Based on this information and literature research on reusable construction designs can be rated and compared in terms of reusability. This can then serve as feedback for the final design proposal.



3 Literature study

3.1 Legacy of the Olympics

The legacy of a large sport event can be described in numerous ways, and it depends on source and point of view which kind is referred to (Gratton, Preuss, 2008). Organizations and committees often refer to a legacy in a vague and immeasurable manner, creating the impression a legacy is always beneficial.

According to Cashman (2005) there are six fields of legacies: economics, infrastructure, information and education, public life, politics and culture. The legacies of structures and venues fall mainly in the category of infrastructure, although other fields may also be involved. Within those fields Cashman recognizes three dimensions: planned & unplanned, tangible & intangible and negative and positive. To place an existing or intended legacy in one of these sub cubes (figure 3.1) is useful to objectively define the outcome of that legacy.

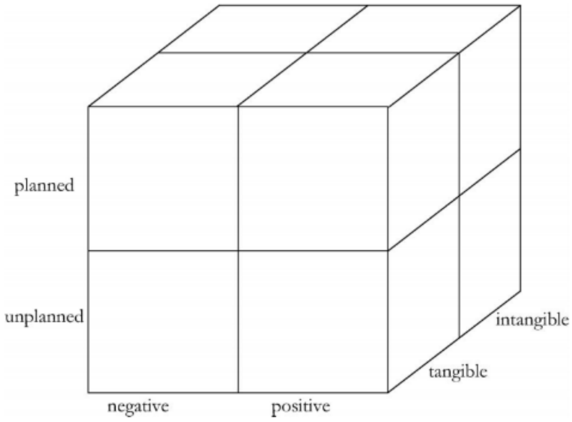


Figure 3.1. Legacy cube *(Cashman, 2005)*

The sub cube 'positive, planned and tangible' in the field of infrastructure is where sport venues are placed. Of course the influence of sport venues goes beyond these categories and fields of legacies.

In this research specifically an Olympic venue is considered. Unique in many ways from other large sport events because of scale, diversity and publicity. Similarly its legacy is unique in many ways, on top of the notoriously reputation of preceding hosting cities. The IOC sets certain requirements to the business plan regarding the legacy of Olympic infrastructure and venues (International Olympic Committee, 2015).

- *the expected benefits at Games-time;*
- *the post-Games use of key Olympic venues and infrastructure;*
- *how the Olympic Games fit into the city/region's long-term planning strategy;*
- *financial planning; and*
- *pre-Games and post-Games ownership and responsibility for operations of the venues and infrastructure built for the Games (as determined by the OCOG in collaboration with the delivery partners)* (Host city contract IOC, page 77, IOC, 2015)

Although the IOC takes the legacy into account, these requirements are still not measurable and leave room for interpretation. It also does not guarantee a positive outcome, as it simply requires the hosting city to have a long-term planning strategy.
On October the 6st 2016 the Paris bid committee submitted their phase 2 of the candidature file. On the matter of legacy the organization has proposed a new entity named 'Legacy Paris 2024' to add to the structure of the organization (see Figure 3.2) (Paris Bid Committee, 2016).

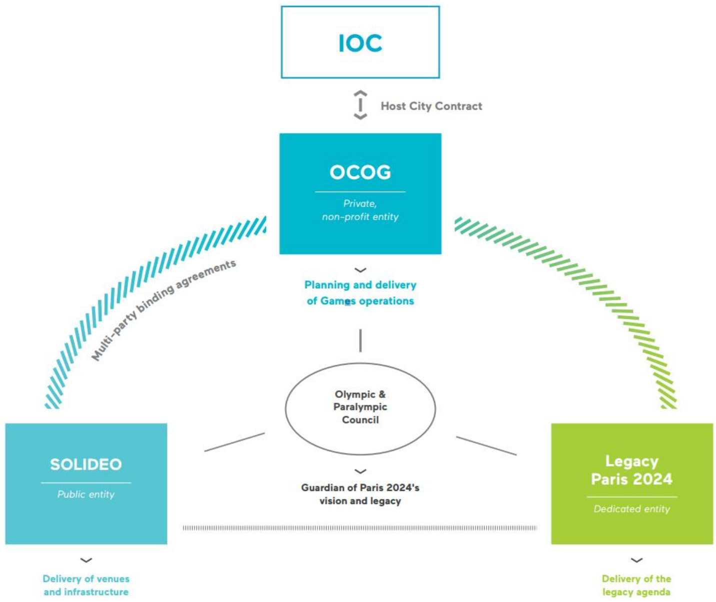


Figure 3.2. Structure of the organization of Paris 2024 *(Paris Bid Committee, 2016)*

This committee will act as an initiator of connections which will be made between the Le Comité National Olympique et Sportif Français (CNOSF), sports federations, public authorities and other partners (Paris Bid Committee, 2016). It shows that the importance of legacy is acknowledged by the hosting city, and is willing to let it play a role in the development of the games.

The location of the Olympic games according to the organization has been chosen deliberately, and has similarities with the London 2012 Olympics. Although the Olympics will be planned throughout the city, many key events will be situated in the youngest population center in the city (north-east, see Figure 3.3). It creates an incentive for rapid urban development in this area (Paris Bid Committee, 2016).

Figure 3.3. Olympic masterplan Paris 2024 *Retrieved from http://www.paris2024.org/medias/styles/thumb_1440/public/cartes/carte_en.png?itok=RIUuvl27 on 14 June 2017*

Much of the urban development was already planned in 2013, and has a vision for 2030. The Paris candidature file states that this urban development will only be accelerated (Paris Bid Committee, 2016). The venues and acquisition of land will be temporary through an agreement of covering rental fees , which is why the Volleyball Arena, Badminton Arena and shooting range will be temporary venues.

3.2 Post-event uses

There are many aspects to the building process of temporary sport venues, including structure, management, infrastructure and logistics to name a few. In this paper the physical structure of the venue and building technologies will be the focus of this research.
In the field of architecture short term structures are not the norm, and a definition of the term temporary in architecture varies. The most fitting definition of temporary structures is described by the Institute of structural Engineers (2007); *Structures used in a wide variety of ways for a relatively short period of time, generally lightweight, easily built up and easily taken apart*.

Although temporary structures are often related to sustainable concepts, this is not necessarily so in terms of material use and carbon footprint. Logically, if the material of the structure is used for a limited time and has no following purpose the negative impact on the environment is significant. When referred to temporary structures it is often assumed the structure is also *demountable*. Demountable structures are designed for easy disassembly and often have a predetermined use after disassembly. Although similar, demountable structures can have a much longer lifespan than temporary structures (Richard, 2006). It means that there are three different life cycles in terms of temporality and demountability. In figure 3.4 the three life cycles of structures described above are visualized.

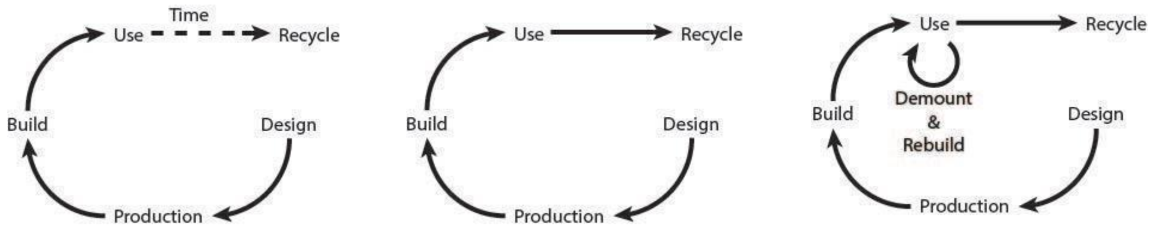


Figure 3.4. Life cycles of structures 1. Conventional structures 2. Temporary structures 3. Temporary demountable structures

Venues for large temporary sport events are built for a temporary time span more frequently, because its function is only required for a short period of time. With few exceptions (Olympic stadium Sydney 2000) these temporary venues are built to be demountable. Three recurring characteristics of these venues can be described as follows: *1 Predetermined post-event strategy 2 Designed for disassembly 3 Building with elements and components for further use.*

What becomes of temporary demountable structures for large sport events after the initial use is crucial for the sustainability of the project. It is the single most important asset that separates temporary structures from permanent ones. All structures can be considered temporary when the expected life cycle ends, but the difference in time scale is key for different post-event strategies.

Recently the concept of a circular economy has become much more popular and used widespread in design. It stands for a sustainable economy where the post-use is included in a design. A focal point for circular design in architecture is to consider the material use after the demolition phase of the building. Quite similar conceptually compared to the *post-event use* strategies described above it has been decided to not use circular design as a term.

Four categories of post-event strategies are distinguished. First, a structure can be recycled. The materials are separated and turned into building materials of lesser quality , effectively closing (and ending) the life cycle of the structure (Guy, 2006). Secondly, a variation is upcycling, where the material is turned into building material of higher quality. Thirdly, a structure can be relocated and used for the same function. Lastly, a structure can be adapted after the initial use, where one of the categories above is used for the temporary part. In many large projects a combination of these are used. Because of the number of different elements and materials it is not commonplace to fit them all in a single category.

1 Recycle
2 Up-cycle
3 Relocating
4 Adapting

3.2.1 Recycling

A form of sustainable reuse that can be considered when building a temporary demountable structure. After the intended use and demounting of the structure, building materials are separated and recycled. That means that they are reduced to building materials of lesser quality. In terms of the lifecycle of the structure it means the cycle ends and continues in another product or form. The energy and effort required to recycle these building materials often exceeds the positive effects of the reduced material used. In short it comes down to selecting materials which can be recycled and preventing permanent bonds in the design (McDonough, 2010). In the current economy where the majority of materials can be recycled in some shape or form this strategy is probably the easiest to achieve, and many projects for longer term are using this strategy (Guy, 2006).

3.2.2 Up-cycling

Similar to recycling, the life cycle of the construction also ends and continues in another product or form after demounting the structure. The difference is that the building material gains quality when used in its new form. In case of temporary structures it usually means that the intended use after the event has a permanent function. The term that often coincides with up-cycling is cradle to cradle. It means that all building materials have a predetermined use after the initial function (McDonough, 2010).

Examples where this has been used for sport venues are the London 2012 Olympic stadium, where sewer pipes were used as construction elements (Hartman, 2012). In case the stadium needed to be demounted these elements could be used as sewer pipes. It must be noted that the intended use has not been realized as the stadium has become a permanent venue.

3.1.3 Relocating

A demountable structure requires the structure able to be rebuild after demounting. This is not necessarily always the case as sometimes connections are designed to be taken apart by breaking or shearing. Some relocating structures are meant to be built in the same configuration each time, others can be flexible. In case of relocation the demountable structure undergoes a life cycle multiple times.

Relocating (part of) a construction is not commonplace in the field of architecture. Although many examples can be found of scaffolding that form the basis of a temporary structure, which can be relocated and reconfigured. Also festivals make use of this typology extensively. All these constructions have in common to have lightweight elements.

[**Case study 1.** A good example of a venue where the strategy of relocation was used is the basketball arena of the London Olympics 2012. This venue was built between October 2009 and June 2011. It has a capacity of around 12.000 visitors and was designed to be completely temporary. A half year after the Olympic Games and the Paralympics it was demounted in under 5 weeks (Gibson, 2013). Ever since it has been disassembled it has been stored and up for sale by *GL events Slick Seating*, the company that provided the construction and seats for all grandstands of the Olympics (Gibson, 2013).

The inside (grandstands) and outer shell can be purchased or rented separately, but clearly these elements are meant to stay together. Since its disassembly the stadium has seen no use, although hopes were that it would see a use in the Rio 2016 Olympics. It can be assumed that the market for these complete stadiums is small, and the initial idea of a moving stadium has not been realized.

It remains speculation of why this strategy has been chosen, it seems the organization reached an agreement with the provider of the stadium (GL events Slick Seating). Because a private party has ownership the legacy of the stadium is no longer responsibility of the organization. It means there was no risk for the IOC in experimenting with a new concept.

The demounting time of the arena was particularly short (under five weeks), for a structure that size. A detailed look of the techniques and tools used has not been possible. An assumption is that because of the layered structure (see figure 3.5) each layer is independent of the other in terms of stability. That way the structure can be demounted in multiple places simultaneously.]

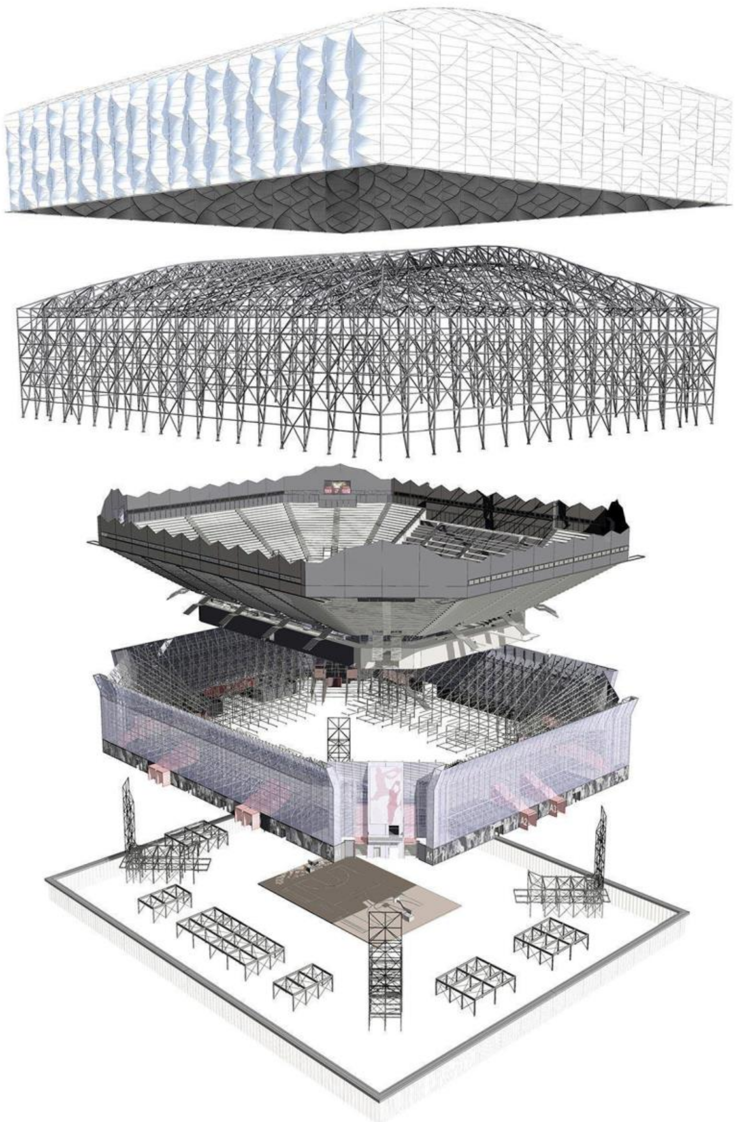


Figure 3.5. Olympic Basketball Arena 2012 - *A layered structure allows for efficient demountability and flexible reuse. Retrieved from http://www.wilkinsoneyre.com/assets/images/439_439X012_h.jpg on 16 June 2017*

3.2.4 Adapting

A demountable structure is applicable when the purpose of the structure is similar to the post use purpose but needs adjustment to fit the exact needs. This can be an adjustment of scale, shape or orientation for example. An example of an adapting demountable structure is the Aquatics centre of the London 2012 Olympics. The grand stands used for the venue allowed a large amount of spectators, but after the games these were removed. The amount of spectator seats lowered dramatically as did the size of the venue and facade surface, doing so the organisers anticipated for the post-use of the aquatic centre.
When adapting a demountable structure it is rare for the complete demountable structure to be used again. This is due to specific building components which work in only one configuration, which is typical for traditional construction. Also sections of the structure often remain untouched during the demounting phase. This part of the construction then complies to both configurations, before and after demounting.

[Case study 2. A great example of such a venue is the Sydney ANZ stadium, used for the Olympics 2000. The venue was designed in 1993 and finished in 1999. Intended to be the largest Olympic stadium ever built with a capacity of over 100.000 spectators, it was designed to be transformed after the games (official website ANZ Stadium, 2017). The three most popular sports in Australia all use different pitches for their games, namely football, rugby and Australian rugby, which uses an oval field. The intended design for the stadium was to create a stadium which could host all these sports, which required flexible seating stands (see figure 3.6).

Figure 3.6. ANZ Stadium, Sydney - *On the right the flexible seating can be seen. Retrieved from https://i.ytimg.com/vi/4mbBJlFp6q0/maxresdefault.jpg*

After the games the capacity was reduced from 105.000 to 85.000 by the removal of the north and south grandstands (see figure 3.6). They were replaced by two smaller grandstands, and completed the continuous roof. The post-event of this stadium was clearly to *adapt* the structure to fulfil new requirements. This adaptation took place between 2000 and 2003.

The demounting of the grandstands was quite an undertaking, because they were not built for disassembly. Portions of the structure were made of concrete, which had to be hacked away and recycled or dumped.

As of 2017 the stadium is very well used since the games, though recently it has been announced the stadium will undergo a second transformation. The transformation will turn the stadium in a so called rectangular stadium, with spectators being able to be much closer to the action. It does mean the flexibility of the stadium for multiple sports is lost. Also, a new closable roof will be added.]

Figure 3.7. ANZ Stadium, Sydney, before and after reconfiguration in 2003 - *The stadium was transformed by the removal of two grandstands. Retrieved from http://s138.photobucket.com/user/duongLe_/media/stadiumaustralia2.jpg.html & https://s-media-cache-ak0.pinimg.com/736x/2b/af/1f/2baf1f3fa18a2888720e64fe89bb567f.jpg*

[Case study 3]. Another such a venue is the aquatic Centre for the London Olympics 2012. This famous building has been designed by the architecture firm of Zaha Hadid. Designed in 2003 and finished in 2011, it turned out to be one of the most iconic venues of the Olympic games of 2012. The most outstanding piece of the venue is the huge wave-like roof structure, measuring over a thousand square meters. During the Olympic games the capacity of the venue was over 17.500, which was lowered to 2800 after reconfiguration. The intended post-event use of the Centre was to become a new public swimming accommodation, and occasionally host large competitions.

Two very large grandstands were used during the Olympic games, which allowed for approximately 14.500 visitors. First work on the removal of these structures started in early December of 2012, and the final part was removed in May 2013 (Gibson, 2012), a bit under six months of demounting (see figure 3.7). In place of the grandstands a new glass facade has been placed, while the grandstands were *designed for disassembly.*

Similar to the ANZ stadium there were permanent and temporary elements to this venue, the post-use strategy of this venue was *adapting*. Unfortunately it remains unclear what happened to the temporary construction elements, and whether they found a similar use in a different construction.]

Figure 3.8. Olympic Aquatic Centre 2012 - *Two removable grandstands allowed for a high capacity for a brief time. Retrieved from http://i.dailymail.co.uk/i/pix/2012/11/28/article-0-0D2C0B6E00000578-663_634x402.jpg & http://www.detail-online.com/fileadmin/_processed_/csm_ZH_Aquatic_Centre_70_8d88a5b20a.jpg on 16 June 2017*

A combination of the categories above is often used for a larger project. Some structures can both be relocated and adapted in its configuration. Scaffolding is a good example of this. Also, in some cases it might be difficult to determine in what category a reuse strategy falls, as it contains characteristics of both.

3.3 Design for disassembly

Permanently assembling structures reduces financial costs, building time and complexity for most architectural purposes (Guy, Shell & Esherick, 2006). Structures are permanent until the expected lifespan is reached, thus this type of assembling is very common. Since the awareness and necessity of sustainable design has grown recently, designers are looking at alternative strategies. Design for deconstruction (DfD) is a good example of such a strategy, its foundation lying in the end of the 20th century by the work of N. J. Habraken and Stewart Brand (Guy, 2006). According to Guy the intended goal of DfD is to "reduce pollution impacts and increase recourse and economic efficiency in the adaptation and eventual removal of buildings, and recovery of components and materials for reuse, remanufacturing and recycling."

It must be noted that the DfD movement is mainly intended for constructions with a permanent location, and not for temporary constructions. Guy (2006) even comments on the fact that hardly ever demountable components can be reused for the same purpose without maintenance or adaptation after the average lifetime of a structure.

According to Guy (2006) the *characteristics of DfD* include the disentanglement of building and climate systems and a reduction of chemically bonded building elements (coatings, adhesives). A structure will need a construction manual as well as a *de*construction manual, where the accessibility and difficulty of deconstruction will be taken into account. Most importantly, selection of material and construction method must be conforming with the DfD concept. This includes high quality and recyclable materials and systems that allow for a closed loop waste management.

To achieve this, knowledge about the end of life cycle of a product is needed to accurately manage the deconstruction of a building (Rose, 1999). Two critical factors influencing the life cycle described by Rose (1999) are *wear out life* and *technology cycle*. Wearing of product determines at what stage a product cannot fulfil its task any longer, and how it will progress to that stage. The *technology cycle* depicts what technical actions a product undergoes in its life cycle, which includes assembly, maintenance and disassembly.
To insure a successful disassembly stage, which is part of the technology cycle, time is known to be the most important factor (Otto & Wood, 2003). A short disassembly phase can be achieved by three factors: *number of tasks, number of tools* and *time or degree of difficulty.* This is especially the case with temporary venues, because of the ratio between the phases of use and disassembly.

More specifically for steel construction, the connection method of steel members play a central role in the disassembly phase of a (temporary) structure (Silverstein, 2009). Güngör (2006) identifies six parameters which influence the allowance for disassembly of a connection.

1 Allowance to non-destructive disassembly
2 Complexity of disassembly motion
3 Tool complexity
4 Reusability
5 Allowance for automated non-destructive disassembly
6 Time to disassemble

Without specific order of importance, these parameters should be referred to in a final design. Silverstein (2009) describes that *internal accessory connections* are most commonly used for structures designed for disassembly. In this category a variety of bolted connections are possible. Other categories such as *filled connections* (welding), *integral connection interlocking* (LEGO bricks), *integral connection overlapping* (facade plating) and external *accessory connections* (clamps) are found to be unsafe or cumbersome for disassembly. Connections in steel construction are either *shear connections* or *moment connections*. The difference can be found in the name, a connection can either transfer shear forces, or both shear and a moment.

Three common types of bolted shear connections are fin-plates, flexible end-plates and angle cleat connections which are shown in figure 3.9. Fin plates are welded to a continues part of a column, while the beam is only drilled. A flexible end plate connection is the opposite of a fin plate connection, where the beam has a welded connection and the column is drilled. Angle cleat connections have no welded connections but contain more bolted connections, it is therefore less influential to the beam and column.

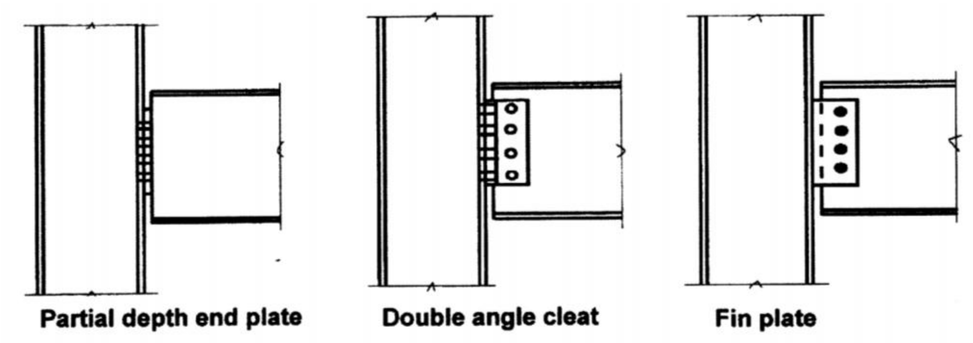


Figure 3.9. *Three types of bolted shear connection of column and beam* (Silverstein, 2009)

Regarding the six parameters given by Gungor (2006) the fin plate and flexible end plate connections score quite similar as both welded and bolted connections are made. Because bolts are very common both the complexity of the disassembly motion and the reusability are rated good. Bolted connections are usually regarded as labour intensive, so time to disassemble can be considered average. A cleat connection is rated differently as it is less destructive for the elements because there are no welded connections. This does the amount of bolts in each connection though, which influences time to disassemble negatively.

Two common types of bolted moment connections are full depth end-plate connections and extended end-plate connections (Figure 3.10). Which are similar to flexible end-plate connections only that the end-plate is larger and can contain more bolts if a stiffer connection is needed.

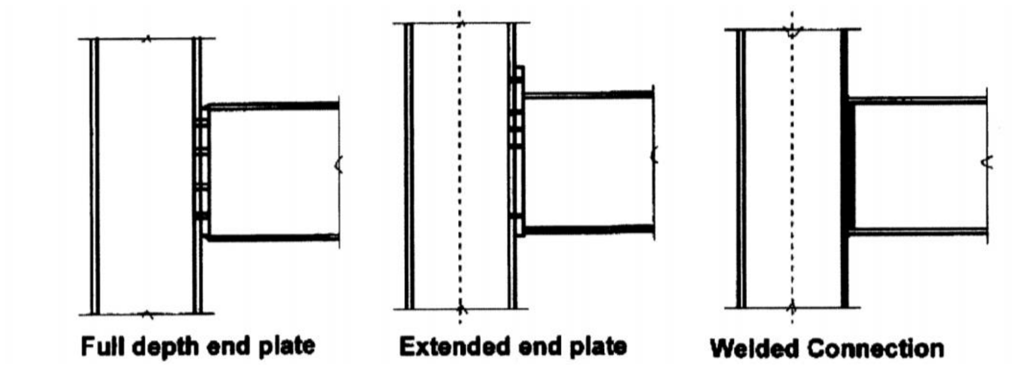


Figure 3.10. *Three types of moment connection of column and beam,* (Silverstein, 2009)

It is difficult to generalize differences between these connection when taken into account the six parameters. The number of bolts in bolted moment connections are mainly dependent on the forces involved and the stiffness required. generally speaking, a moment connection requires more bolts than a shear connection, and scores lower on the six parameters of disassembly.

3.3.1 Prefabrication

Building on site is more expensive and more labour intensive than prefabricated building elements that have been built in a more controlled environment. To guarantee acceptable assembling and assembling time of the arena, prefabrication of building parts and elements is critical.

Also, the controlled environment in which prefabricated elements are built is preferred even more so when demountable elements are considered. High precision fabrication reduces the chances of errors, which in turn increases the demountability of the arena.

What this primarily means for the building process is that all prefabricated elements of the arena need to be transported to the location. This affects the maximum dimensions of each element. Secondly it increases the chances of damaging the element, as more proceedings and handling is needed.

3.4 Transportation

For any potential reuse of a temporary venue, transportation is needed. For all types of transportation there are restrictions on the dimensions of transported objects. These need to be taken in consideration when designing elements of the arena. It necessary to comply to the restrictions of the intended means of transport.

It should be noted that all forms of transportation in this case starts with transportation on road. Considering the location of the arena, many types of transport after that are available, including transport by road, water, railroad or by aviation. Presumably a building element that will comply to many of these restrictions, will be easier to reuse than an element that violates many of those restrictions.

All four of these means of transportation have restrictions in terms of dimensions and weight limits listed in the tables below. Except for road transport, there is hardly any standardisation in these dimensions. In the tables below all values numbered with a *'v*'* are variable, depending on location, company and other factors. Values marked with a *'v*'* should therefore not be taken literally but more as guides. The first table is focussed on restrictions in France, the second table is orientated more on European and international standards.

	max. Length (m)	max. Width (m)	max. Height (m)	max. Weight (t)
Road	12 - 18.75	2.55	not defined	40
Maritime	90(v*)	12(v*)	6 - 10(v*)	3000(v*)
Railroad	22,6 (v*)	2.8 (v*)	2.8 (v*)	60 (v*)

Table 3.1. *restrictions in different types of transport in France road (Wideberg, 2009) , Maritime (PIANC, 1990), railroad (DB Schenker, 2011).*

	max. Length (m)	max. Width (m)	max. Height (m)	max. Weight (t)
Road (Eur.)	12 - (v*)	2.55	4m	44(v*)
Maritime (int) **container (int)**	(v*) 12.19	(v*) 2.44	(v*) 2,59	(v*) 30.4
Railroad (Eur.)	22,6 (v*)	2.8 (v*)	2.8 (v*)	60 (v*)
Aviation (int.)	3,2(v*)	2,6(v*)	2,6(v*)	(v*)

Table 3.2. restrictions in different types of transport by international & European standards aviation, (retrieved on 6th of December 2017 from http://www.profreight.co.nz/Useful+Info/Airline+Pallet+Dimensions.html), container (retrieved on 6th of December 2017 https://www.containercontainer.com/shipping-container-dimensions).

As can be seen in both tables, many values are marked as variable. The most restrictive means of transport is aviation, with road transport second. Although it's not the most restrictive, road transport is presumably the most common means of transport when building materials are considered. Therefore we can conclude that building elements of the project should maintain the restrictive dimensions of road transport.

3.5 Reuse of steel

Reuse of building component has a correlation with the material of the component. When load bearing construction are considered, there are three materials that represent the big majority of all construction in Europe (BCSA, n.d.). All three can be seen in figure 3.13, concrete, timber and steel. The amount of concrete that is reused can be neglected, while timber is reused the most often relatively.

Steel is mostly recycled in construction, and rarely reused (or thrown away for that matter). Surprisingly, many studies suggest that steel is most qualified to be reused, although reuse is not increasing nowadays (Fujita, 2008). This is further confirmed by the British Constructional Steel Association, who state that reuse is less common in the UK (BCSA, 2008). This contradiction can be explained because there are currently a couple of barriers in the steel industry which will be discussed later.

The reason steel is suitable for reuse is because is a very durable product, and certain steel elements have been standardized. Steel will not have greatly reduced mechanical properties after use, even after longer periods of time. Because of the strength/weight ratio is quite hard to damage steel elements as well. On top of it many profiles have been standardized.

3.5.1 Steel market development

When looking at figure 3.11 it can be seen that the demand for steel is going up in the year 2016 (Carvalho, 2017). According to a research by the European Union this is a trend that will continue until 2030 which can be seen in figure 3.12 (Pardo, 2012), which is the timeframe in which our design is situated. The growing demand for steel could be an opportunity for the reuse of steel, as prices of new steel presumably increases with higher demand and stock decreases due to less material available. Although a higher demand than production is predicted, note that they are converging towards 2030. According to the research export of steel products are decreasing down to zero in 2030. This means that whatever advantage reusing steel products there is due to a higher demand, it will presumably last until 2030.

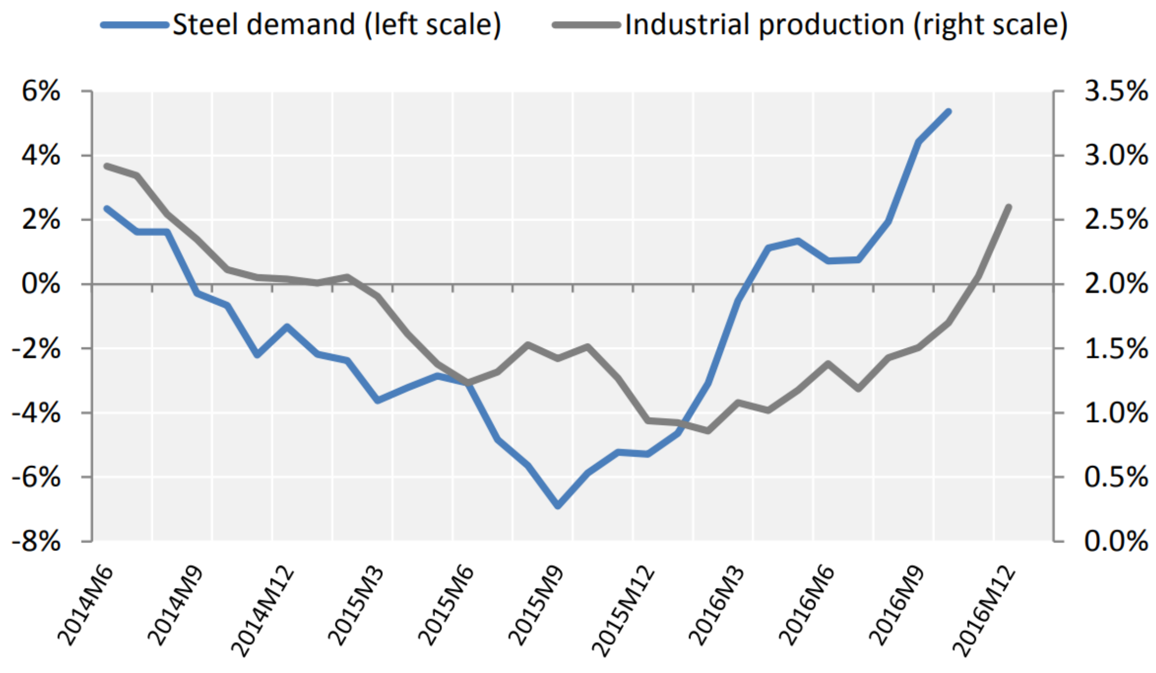


Figure 3.11. Consumption of hot-rolled steel products, major economies, and world industrial production growth. (Carvalho, 2017)

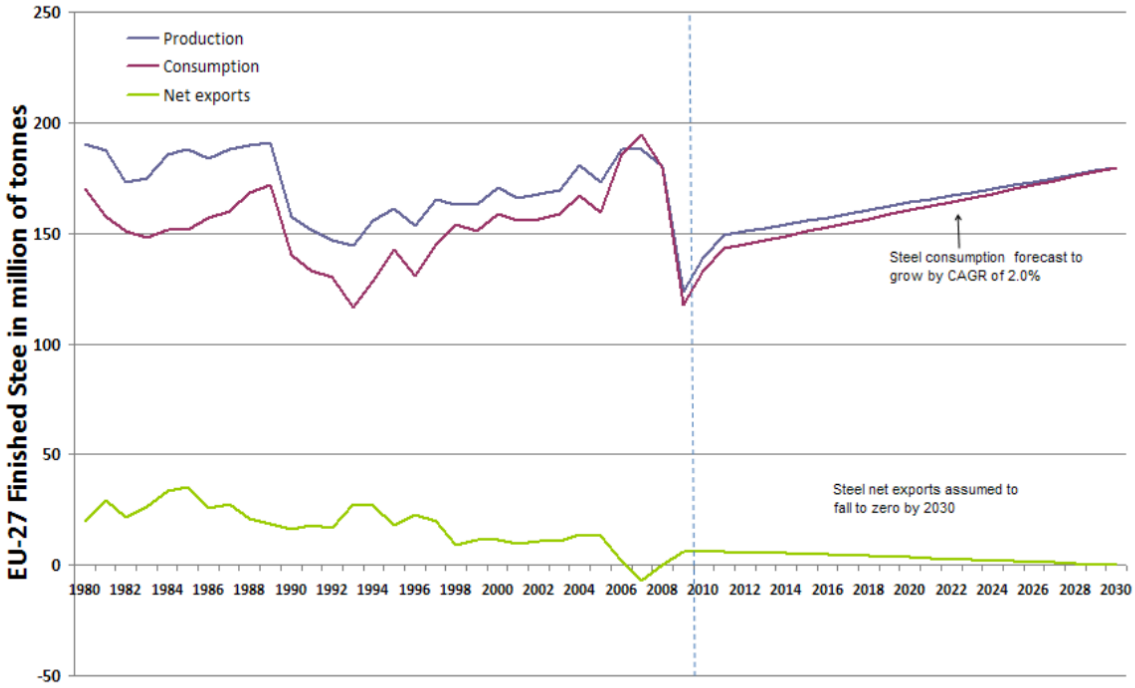


Figure 3.12. Iron & Steel production, demand and net export for EU27 up to 2030 (Pardo, 2012)

Likely to be even more influential on the reuse industry, the availability and demand of scrap steel will change considerably according to the EU research. Simply stated, the demand for scrap steel is predicted to increase, while the availability will decrease (figure 3.13). This will influence reuse in a negative way, as it increases the incentive to sell used steel as scrap rather than to reuse it.

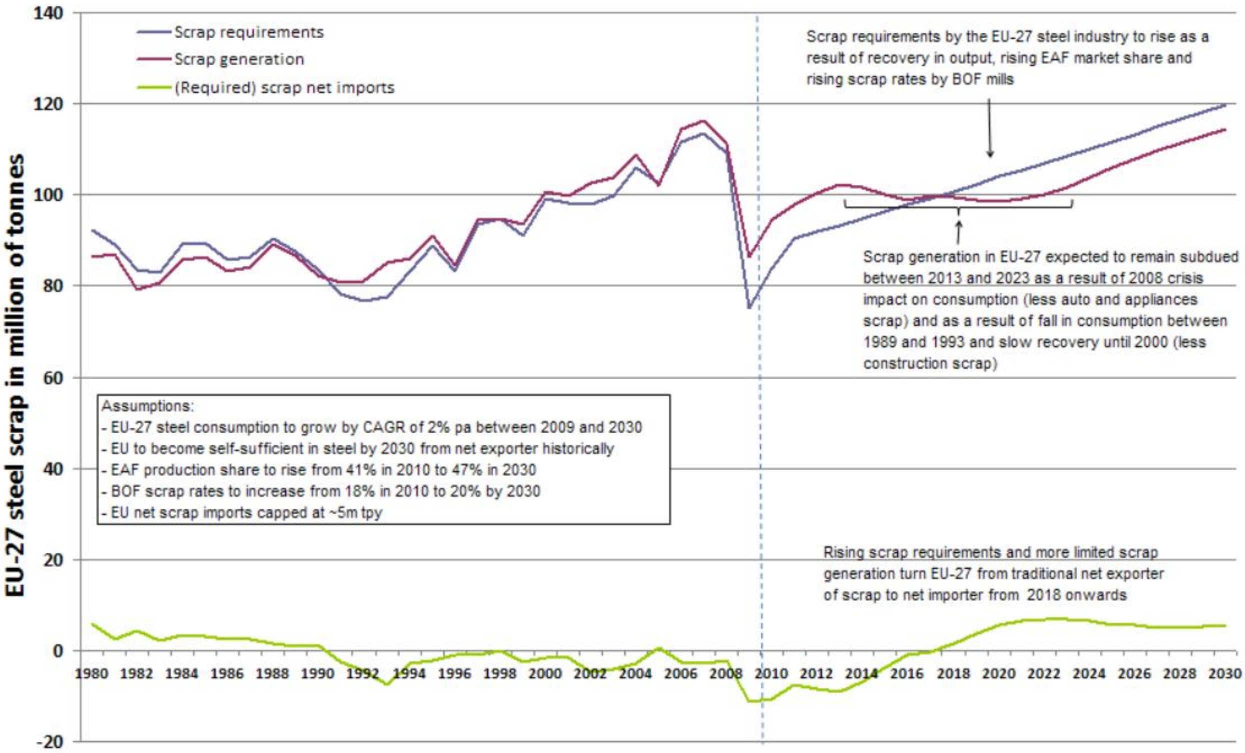


Figure 3.13. Scrap requirements, scrap generation and scrap net import for the EU-27 (Pardo, 2012)

3.5.2 Barriers of reusing steel

As noted previously, one of the disadvantages of using steel in the current and future economy is controversially the excellent recycling abilities of steel in the demolishing industry, as further shown in figure 3.14. In fact there is quite a market for used steel and scrap steel, as it is needed to produce new steel (BCSA, n.d.)

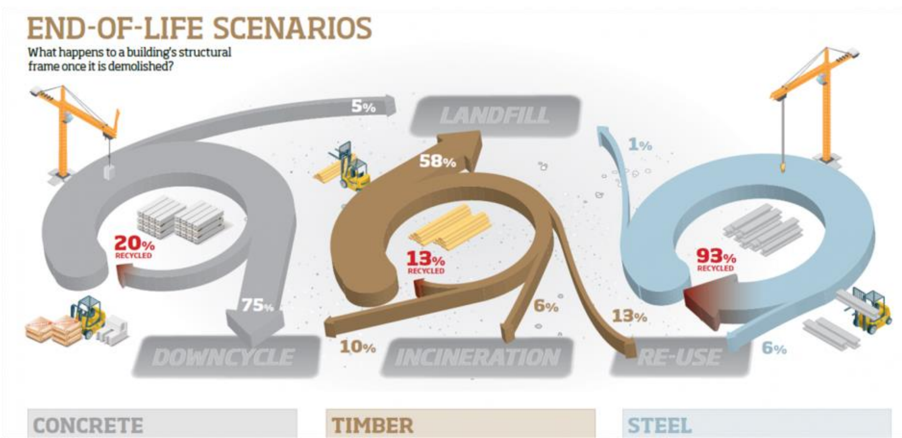


Figure 3.14. Three end of life scenarios in the demolition industry of buildings in the UK. (BCSA, n.d.)

Because the steel forging industry needs scrap metal, value needs to be added to steel construction components that have been used if the goal is to reuse instead of to recycle. Value can be added in multiple ways, considering environmental, financial, technical and logistical reasons.

First of all reused steel has a lower environmental impact when compared to recycling steel. It is often overlooked that recycling will cost energy, in the case of steel almost 30% of the primary production (figure 3.15). Opting for reuse can be the key to obtain the highest ratings in BREEAM and LEED).

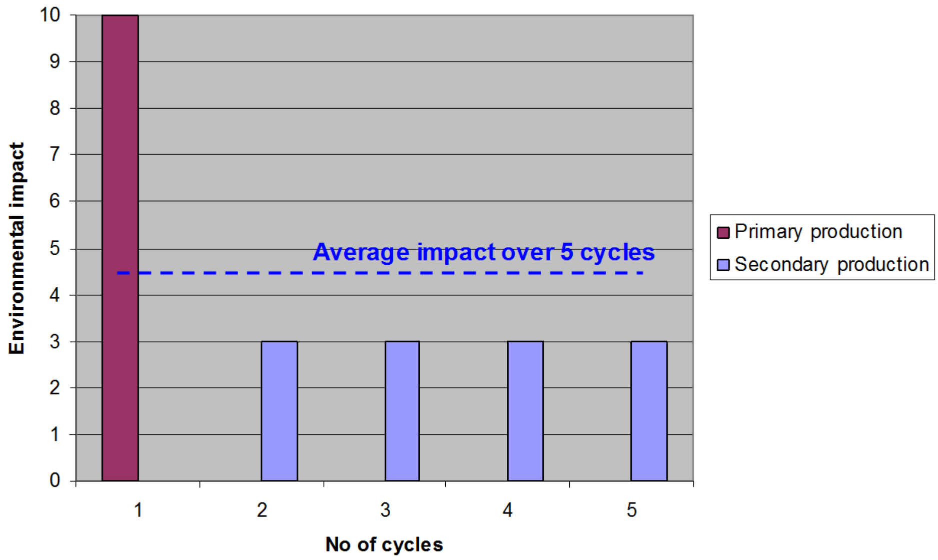


Figure 3.15. Environmental impact of recycling steel in the UK. (BCSA, n.d.)

In financial terms reusing steel elements can increase the cost of a project. To research and design with already used components often takes more time and could potentially delay construction. On the other hand, used steel is often much cheaper as it is sold as scrap material. Roughly speaking, reusing steel components becomes financially viable when costs made through research and design are balanced out by material expenses. This can be positively influenced for example by flexible usability of the component, or when the component needs very little adjustment.

Logistically there are a few barriers which prevent a more widespread market for reusing steel construction components. According to the website of *steelconstruction* there are four barriers worth of mentioning (BCSA, n.d.):

- Assured availability of supply
- Demolition programmes are too short to enable contractors to deconstruct buildings
- Sufficient storage space for recovered products
- Deconstruction as opposed to demolition has significant impacts on the health and safety precautions required

It shows that the demolition phase of the project is critical for successful reuse of steel structural components. These barriers can be overcome when a clear and safe strategy is in place, with quick and clear demountable structures. Also, it should be considered in what time span the components will be reused, and consequently how long they need to be stored.

When it comes to the technical aspect of reusing steel components, *steelconstruction* identifies six barriers (BCSA, n.d.):

- Lack of standardization of components
- Ensuring and warranting the performance of reused components
- Lack of detailed knowledge of the product's properties and in-use history (this may be important, for example, if the component has been subject to fatigue loading)
- Quality assurance of reused products
- Robustness of products in the deconstruction process, i.e. many lighter products do not survive the deconstruction process intact
- Practicalities of economic deconstruction including deconstructing composite components

First of all, in the current economy many buildings are uniquely designed and built for optimization and use unique constructions to do so. A lack of standardization is one of the drawbacks of this. To overcome that barrier, a good reuse strategy must allow for flexibility or adaptation in its components.

Secondly, it is quite difficult to determine what the exact mechanical properties of used steel components are. Due to lack of in-use history, missing documentation, damage during construction and deconstruction insurance companies find it hard to warrant used steel components. One way of dealing with this is to properly document the use of components.

3.6 Reuse of steel in other industries

Although reuse might be relatively uncommon in modern architecture, in many other industries reuse is much more common. For example the crane industry, where tower cranes are used in all types of construction. These cranes are made of standardized elements and can be stacked to variable height in a relatively short time span. After its use it can be disassembled, transported to another location for storage, or to be used again in another project.

More examples of standardized (steel) elements in engineering can be found in infrastructure. Structural portals over roads and railways for example. Although many of these cannot be considered temporary as the arena, reuse is still common.

Note that these examples are always reused in the same manner and for the same purpose, they are effectively relocated. The reuse strategy of relocation for a large sport venue was considered for the basketball arena for the London Olympics 2012. Unfortunately the arena never found a purpose beyond the London Olympics.

Also, many examples of reuse can be found in civil engineering. Temporary supports are often used steel elements, and sometimes even reused after. Examples of such elements can be found in large projects like stadiums such as the Gwagmyeong Velodrome in South Korea (Figure 3.16). It is common that these elements remain the property of the contractor. Because the construction does not change owner it is easier to document the specifics of the structure.

Figure 3.16. *Gwagmyeong Velodrome under construction, the roof construction is supported by a temporary steel construction*. Retrieved on 6 December 2017 from http://www.lusas.com/case/civil/images/velodrome_roof_10_350.jpg

3.7 Conclusion

The legacy of a large sport event often has a relatively large impact on the hosting city. The Olympic games are notoriously hard to deal with, as history shows. Many factors influence this legacy, and one of the most visible legacies is left by the Olympic infrastructure, which includes the venues. Images of 'white elephants' (abandoned buildings) come to mind in former Olympic cities as Beijing, Rio de Janeiro and Athens.

Paris will host the 2024 Olympics and is keen on leaving a positive and tangible legacy,. To achieve this the Bid Committee (2016) has published candidature files which describes their strategy. A combination of temporary, existing and permanent venues and infrastructure.

Temporary venues are more frequently used as a means to prevent a negative legacy of the event, which is the case with the Paris Olympic Games 2024. Four strategies of reuse are distinguished: recycling, upcycling, relocating & adapting. A combination of any of these strategies is possible, and common with large venues.

Temporary venues are not necessarily 'designed for disassembly', as described by Guy (2006). Design for disassembly(or dismounting) can be done in different ways, and certain factors are essential for the success of a disassembling phase of the building. Otto (2003) describes three factors: number of tasks, number of tools and time or degree of difficulty.

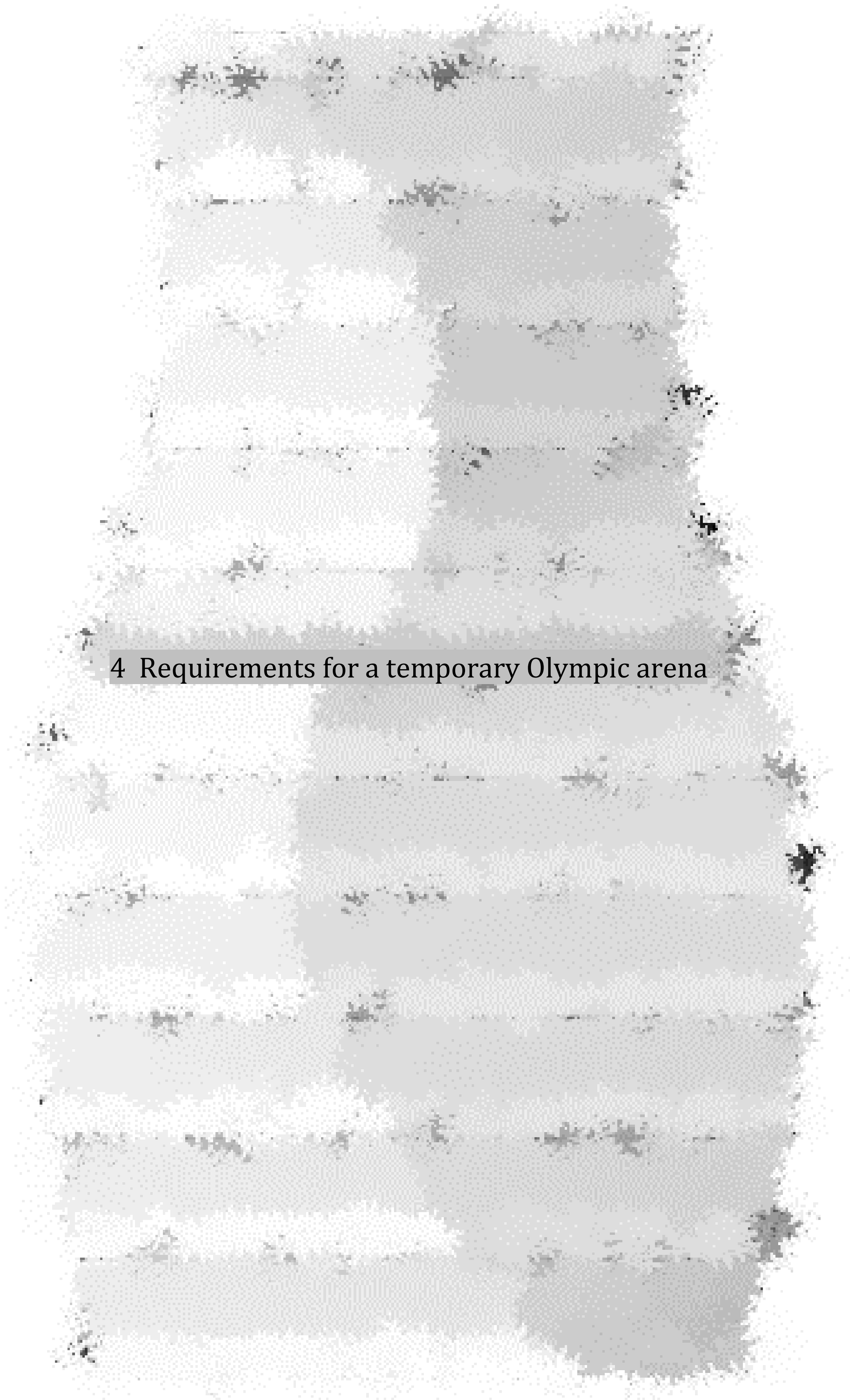
But, disassembling structures will not necessarily lead to reuse in temporary architecture. In order for (steel) elements to be reused in architecture, there are several barriers to be overcome.

Furthermore, for a demountable structure to be successfully reused designers need to take into account transportation. Restrictions on dimensions and weight determine whether building elements can be transported. Presumably a building element that will comply to many of these restrictions, will be easier to reuse than an element that violates many of those restrictions.

In reusing construction materials from buildings which are either temporary or permanent steel there are three main material flows: steel, timber and concrete. Especially in steel construction there is potential to reuse more material than currently happens. In other industries reusing steel construction is more common, and coincidentally it is often temporary construction as well. Lessons from does industries should be drawn in future research.

Currently there are several reasons why steel structures aren't reused more often in architecture. It can be concluded that steel elements are nowadays not valuable enough to reuse. New is often financially more viable, and the highest bidders on the current scrap steel market are the industries that recycle steel. For steel to be reused more often, value needs to be added in some way. Figure 3.17 shows the conclusions of the literature research in an infographic.

Figure 3.17. Infographic*. Conclusions drawn from the literature research*



4 Requirements for a temporary Olympic arena

4.1 Design focus

This preliminary design of the temporary volleyball arena for the Paris Olympics 2024 will be limited in detail, focussing primarily on the reusability of the arena . Not all aspects will be present in the design, because it is assumed that aspects are either not possible to reuse, or already are widely reused. An example would be the seating of the arena, which can be rented and thereby reused. Analysing similar arena designs (Figure 4.1) all technical aspects of the venue have been roughly separated. Following are a few aspects which will not be integrated in the design.

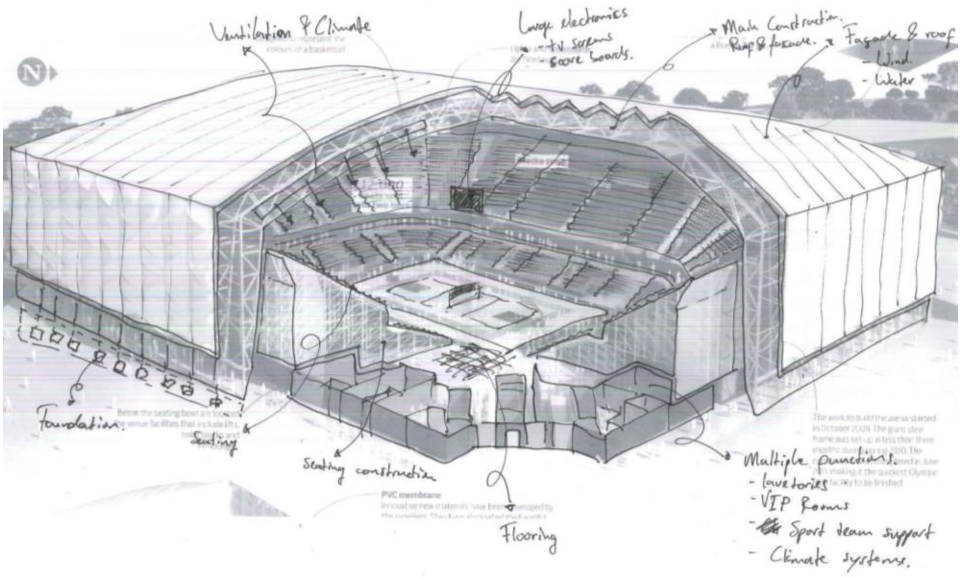


Figure 4.1. Basketball arena of the London Olympics 2012 analysed

Grandstands and associated seating can be rented and installed by designated companies. Many temporary events, mostly outdoors, have many visitors for a short period of time. A healthy market exists to provide seating for these crowds, a good example would be World Champions for field hockey in the Hague (figure 4.2).

Figure 4.2. *Temporary grandstands and seating during the world championships Field hockey in The Hague, and temporary seating of the beach volleyball arena in Rio 2016*. Retrieved 6 December 2017 from http://medias.photodeck.com/cccad746-41e3-4288-8f9c-e2fd818a3bfd/79540_xgaplus.jpg & http://cdn.newsapi.com.au/image/v1/380127bfa842c79caa6eee3d9c6f6018

There are also many examples of other grandstands which are specifically designed for a unique occasion. The Aquatics Centre of the London Olympics 2012 is a good example where uniquely designed grandstands have been designed to account for the large number of visitors. In the case of Le Bourget the visitor count (13.010 seats) is moderately large for such an occasion. It is therefore assumed the seating can be rented, built and demounted by a private company.

Infrastructure in and around the venue will not be part of this design. The study of escape routes, sightlines and such is extensive and hardly influences the roof and façade design. Also, temporary infrastructure is very widely used an just like the grandstands, can be rented.

The playing field has some very strict demands made by the organization of the international volleyball board. Often layers are permanently attached to each other, although there are examples of other playing fields which could be reused. Whether the field will be reused will not influence much of the design, except maybe the size of the field.

The focus for this project will mainly be the roof and facades of the arena. Volleyball on world class level requires a well-controlled climate indoors, and that means the arena needs a temporary structure to shield it. The greatest challenge is posed by the scale of the arena. Inevitably the structure will be quite large and bulky, unlike the most common structures in architecture.

To design a load bearing structure of the roof and facades is therefore the main focus of this research. That is because the load bearing structure has the largest footprint on the environment compared to other elements in an Olympic arena, if not used to its full potential. This area of expertise is where the most potential for a more sustainable design is.

Also, apart from requirements of weatherproofing the arena, the façade requires to be temporary as well. This influences material choice, building techniques and appearance of the arena. It is therefore part of the design focus.

4.2 General requirements Olympic Arena

A generalization of requirements regarding Olympic arenas is researched and discussed below. Including capacity & size, indoor air quality, light & acoustics and program requirements. As a guide, a case study has been chosen to base several requirements. This case study is the future Volleyball arena for the Olympic games of 2024, held in Paris.

4.2.1 Paris Olympics 2024

The following information is taken from the candidature bid books (1,2 & 3) written by the organizing city (NOC, 2015). Currently Paris has been awarded to organise 2024 Olympic Games. The bid books contain the basic and important information regarding the organization of the games, which includes the venues.

It is the intention of this design project to research the reusability of a large temporary sport facility, such as a volleyball arena. It must be noted that the Paris Olympics of 2024 provide a framework to the project and a sense of realism. It is intended to take the reuse strategy to the limit and explore such a 'what if' scenario, and how that influences the design. The planned venue of the temporary volleyball arena 'Le Bourget' is a very good match for this purpose.

First of all a proposal of a design has not been made public yet, which leaves all possibilities open. It also means that the organization has not set the sustainable strategy in stone. Except for the fact that the venue must be temporary, as can be seen in table 4.1.

Olympic Sport	Paralympic sport	Name of venue	Venue status	Venue owner	Venue operator	Venue use	User groups
Volleyball (preliminary)	Boccia	Le Bourget b	new temporary	private owners	-	-	-
Volleyball (Final)	Volleyball (sitting)	Le Bourget a	new temporary	private owners	-	-	-

Table 4.1. *Venue owners of the temporary venues of le Bourget (NOC, 2017 February)*

4.2.2 Capacity & Volume(s)

The National Olympic Committee (NOC) published *bidbook, phase 3* (2017, February), and it gives a little more insight in the requirements of all venues. The organization plans on a relatively large arena, compared to other Olympic games. As can be seen in Table 4.2, there are two venues requested. The largest venue will host the finals and semi-finals and will need a capacity of 13.010 visitors. The second and also smaller venue will host most other matches and requires a capacity of 5560 visitors.

Olympic Sport	Name of venue	Name of cluster	Seating bowl capacity	Total gross capacity	Legacy capacity
Volleyball (preliminary)	Le Bourget b	Grand Paris Zone	5560	5560	-
Volleyball (Final)	Le Bourget a	Grand Paris Zone	13.010	13.010	-

Table 4.2. *Taken from Paris 2024 (NOC, 2017 February)*

Without further detailed information about demands or requirements for the shape and size of the arena, the fastest way of determining proportions is by comparing arenas of similar capacity requirements. Three similar arenas in size are: the Basketball arena London 2012, the Copper Box London 2012 and the Handball arena Rio 2016. In the table below are the number of visitors and proportions of the arenas. Below are the sections of the corresponding arenas.

	Capacity	Length	Width	Height
Basketball London 2012	12.000	114	96	30
Copper Box London 2012	6000	-	-	±20
Handball Rio 2016	12.000	±120	±90	±30
Water Polo London 2012	5000	-	50m	±30
Le Bourget Paris 2024	13.010	no restrictions	no restrictions	no restrictions

table 4.3. *Similar arenas to Le Bourget and their dimensions*

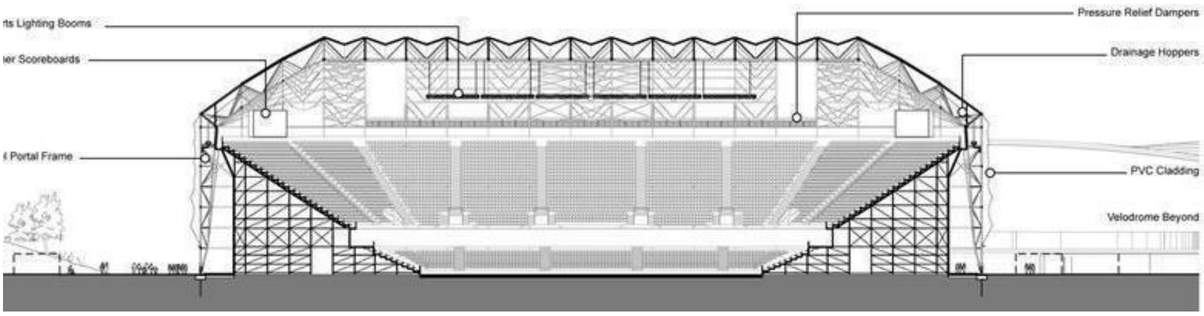


Figure 4.3. Section, temporary basketball arena London 2012, scale unknown. Retrieved on 6 December 2017 from https://images.adsttc.com/media/images/5031/a982/28ba/0d18/3000/0bc6/large_jpg/stringio.jpg?1360958476

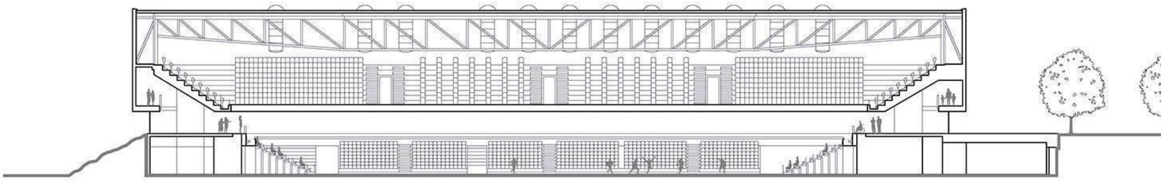


Figure 4.4. Section, permanent Copper Box London 2012, scale unknown. Retrieved on 6 December 2017 from http://www.queenelizabetholympicpark.co.uk/the-park/venues/copper-box-arena

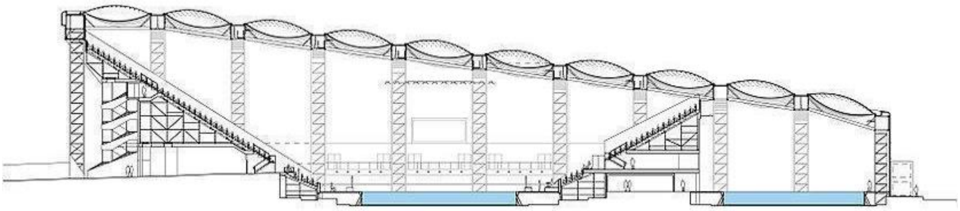


Figure 4.5. Section, temporary Water Polo arena London 2012, scale unknown. Retrieved on 6 December 2017 from http://davidmorleyarchitects.co.uk/assets/components/phpthumbof/cache/494-LongSection-500-2.2d00336dbe4dbbbe4eb34d10e73d575d.jpg

Based on these figures it is obvious that the shape of the arena is dictated by the spectators seating design. In this project there is no exact design to work with, and frankly it is not very relevant because these structures are independent. For calculations regarding structure, loads, climate and other decisions based on dimensions the used values can be found in table 4.4.

	Capacity	**Length**	**Width**	**Height** (top of grandstand)
Le Bourget (a) Paris 2024	13.010	125m	95m	22m
Le Bourget (b) Paris 2024	5560	90m	65m	12m

table 4.4. *Assumed dimensions for Le Bourget (a & b)*

It should be noted that in this table both venues are shown separately. Both venues will be included in the design. Whether the venues must be represented by two separated volumes or a single volume containing both is not stated by the IOC.

In figure 4.6 the seating bowls can be seen as stated in table 4.4. Note that these dimensions only contain the seating capacity, and do not include any information about further construction.

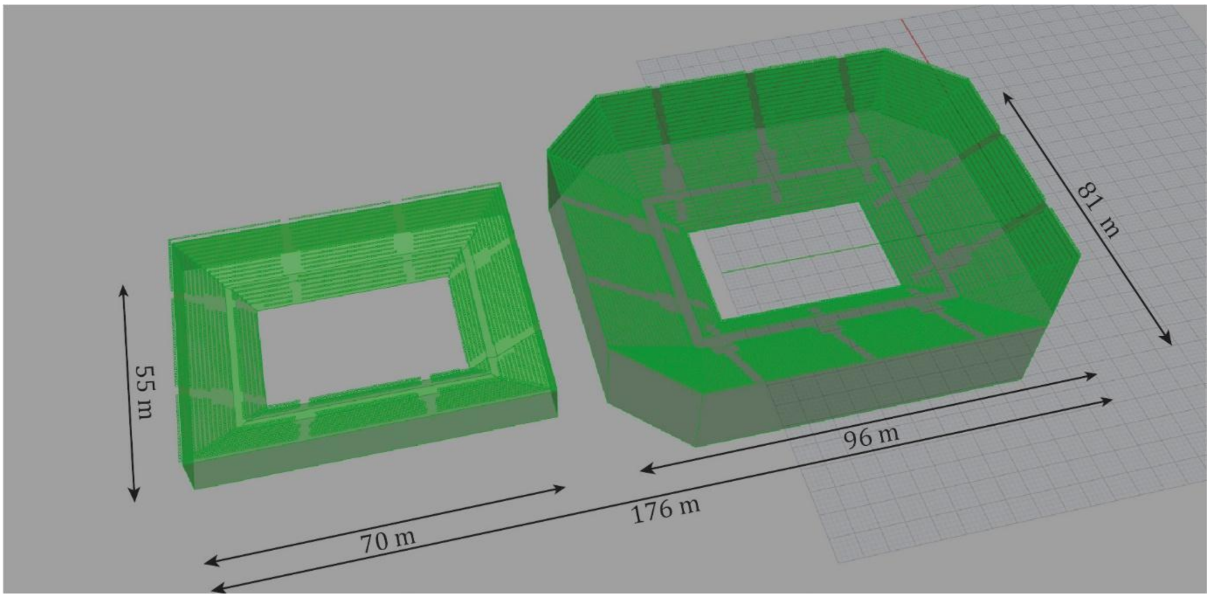


Figure 4.6. Proposed seating bowl for a double arena with respective capacities of 13.010 and 5560 visitors.

4.2.3 Climate & program requirements

The Fédération Internationale de Volleyball (FIVB) is the authority on regulations at large volleyball events. Those regulations include all sorts of game related rules and regulations, but also technical demands about the venue where the event is taking place (FIVB, 2017).

This includes dimensions of the playing field, program requirements, light demand, acoustic and air quality demands. Besides the demands by the FIVB, the arena also needs to comply to European and/or national legislation. Lastly, there are design requirements that might influence the eventual design.

The intended purpose is to come up with a conceptual climate design strategy. This strategy will comply to the requirements stated by the FIVB, European and/or national legislation, while also be demountable and reusable.

The program requirements stated by the FIVB can be found in table 4.5 below. These are the volumes that need to be present in the venue. In practise they will almost always be located below the spectator stands.

Function	Surface Area	Amount

Changing rooms (teams)	30m²	2
Changing rooms (referees)	20m²	2
Medical rooms	50m²	1
Technical room	50m²	1
Total	**200m²**	-

table 4.5. The program requirements stated by the FIVB that need to be in the venue.

Requirements regarding the indoor climate of any building normally includes two scenarios: summer situation and winter situation. For this temporary venue the summer situation is the only scenario required. Below are the maximum and minimum temperatures, average humidity and solar intensity.

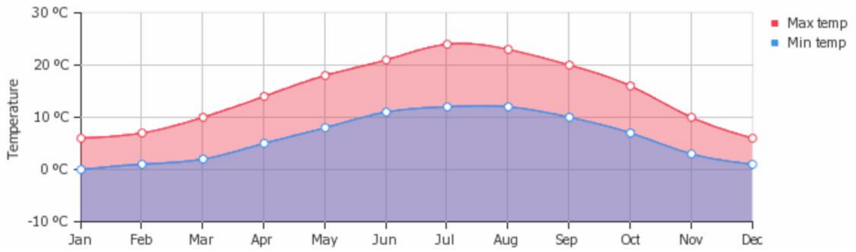


Figure 4.7. The monthly max/min temperatures in Paris. *Retrieved from https://weather-and-climate.com/average-monthly-min-max-Temperature-fahrenheit,Paris,France*

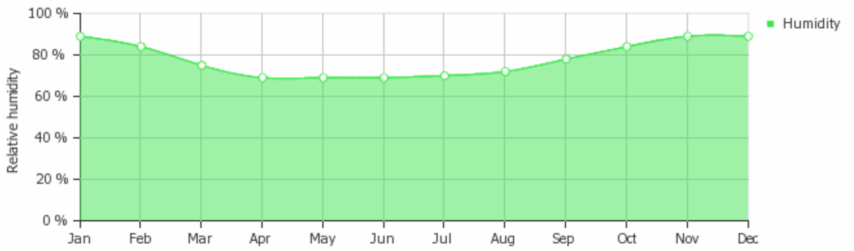


Figure 4.8. The monthly average humidity in Paris *Retrieved from https://weather-and-climate.com/average-monthly-min-max-Temperature-fahrenheit,Paris,France*

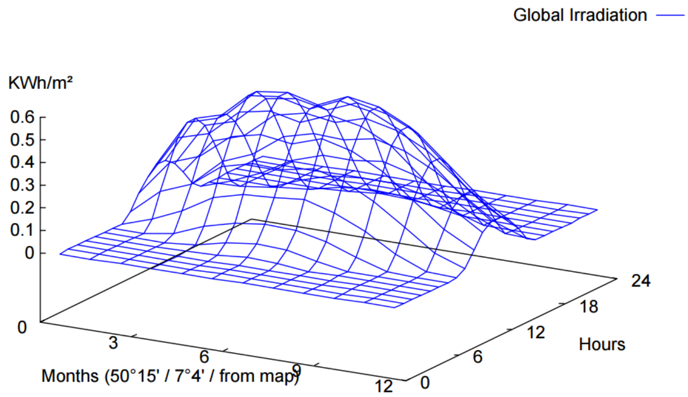


Figure 4.9. The monthly average irradiation per hour (Uccle, Belgium). (Scharmer, 2000)

In figure 4.7 the average temperatures are presented, note that only the months of the Olympic Games matter, which are June and July. The average minimum temperature in those months is 12 degrees Celsius, the maximum temperature is 24 degrees Celsius. The humidity in this period of time is 70% on average, which is shown in figure 4.8. Maximum solar irradiation is shown in figure 4.9. Note that the location of this measurement is not Paris, but roughly 200 km above it. The maximum solar irradiation is 450 kWh/m^2.

4.2.4 Light

Requirements of two authorities are distinguished, FIVB requirements and European legislation. Also, there are requirements that have been derived from the design strategy. Each of them will be stated below. The *FIVB* states four requirements regarding light in the arena (FIVB, 2017):

1. Lamps must not dazzle the players in any way, be too bright nor be placed over the centre line of the court;
2. Light intensity must be no less than **1500 lux measured at 1 m** from the floor;
3. Light beams should eliminate shadows on the floor; and
4. Spectator stands should be adequately and consistently lit.

In practise, the first and fourth demands are the most limiting, as it dictates how the playing field and spectator stands are illuminated. Although limiting, the first demand is not necessarily problematic. In some observed examples of volleyball arenas it means the light sources are bundled up close to the middle of the arena. Preferably the light sources a moveable and arranged on the long sides of the free zone, like in the arena seen in figure 4.10.

Figure 4.10. Stark Arena, Serbia. The optimal light source distribution according to the FIVB, arranged on the long sides of the 'free zone'. *Retrieved on 30 November 2017 from https://www.total-croatia-news.com*

The fourth demand is quite limiting as natural daylight is not consistent during the day, which means that artificial light is always required. It does not necessarily exclude natural daylight, but its application is challenging.

EU legislation states no requirements in terms of illumination for event venues like arenas. Of course the arena must be able to be adequately lit for visitors to manoeuvre to their seats. Once the sport event starts there is not a minimum of light stated.

The *design strategy* states that the arena needs to be reused and demountable. Light installations in many modern arenas are adjustable to account for different events. This is not necessary for the temporary Volleyball arena (le Bourget), as it will host only a single type of event. Due to its temporary nature, light installations in le Bourget must be demountable and reusable. This is common practice in the entertainment industry, for example concerts. It is assumed that all lights and required rigging can be hired from an external party.

4.2.5 Air quality

On air quality there are two authorities which state the requirements on indoor qualities. Again the FIVB regarding the playing field, and European and/or national legislation regarding spectators. The FIVB states that the temperature on the volleyball pitch should be anywhere between 16°C and 25°C. For spectators there are no regulations stated by the FIVB. On any other variables (air velocity, humidity, CO2 concentration) regarding the playing field nothing is stated.

By France regulations there is only a minimum temperature stated for indoor spaces, which is 18°C (Brelih, 2013). The value for maximum air velocity is not stated, most European countries set their limit between 0.15m/s and 0.3m/s which can vary according to the season. Also, maximum humidity was not found in the research by Brelih (2013), in other countries it varies wildly due to different climates.

The European Committee for Standardization (CEN) has published a document combining many European indoor air quality standards, which will be consulted regarding ventilation requirements (CEN, 2006). Two types of ventilation are distinguished: the first is based on the amount of people in the volume, the second is based on the surface area of the building, according to the pollution it produces. In case of a stadium the first type is more demanding because of the high visitor count. This type of ventilation *requires 7l/s/p* [litres fresh air/second/person].

[Case study x. Note that the requirements for the athletes differ from those of the visitors, which can conflict in the space where those two volumes meet. For sport facilities this is not unique, take for example the water polo arena from the London 2012 Olympic games.

The field of play was air conditioned to the strict requirements of Olympic Water Polo standards. The Olympic Family seating areas were cooled and heated and the general spectator seating was entirely naturally ventilated. The three zones were separated environmentally using air movement alone. This separation was achieved by air blades that acted as invisible thermal walls. By using this strategy they were able to halve the amount of heating, ventilation and cooling plant required by a traditional venue (figure 4.11).

Interestingly, the venue is ventilated from the ground floor up, as can be seen by the high air velocity near the pool. The higher velocity near the roof of the arena can be explained because of the natural ventilation. This reduces the need of ducts, assuming the climate systems are located at ground level as well.]

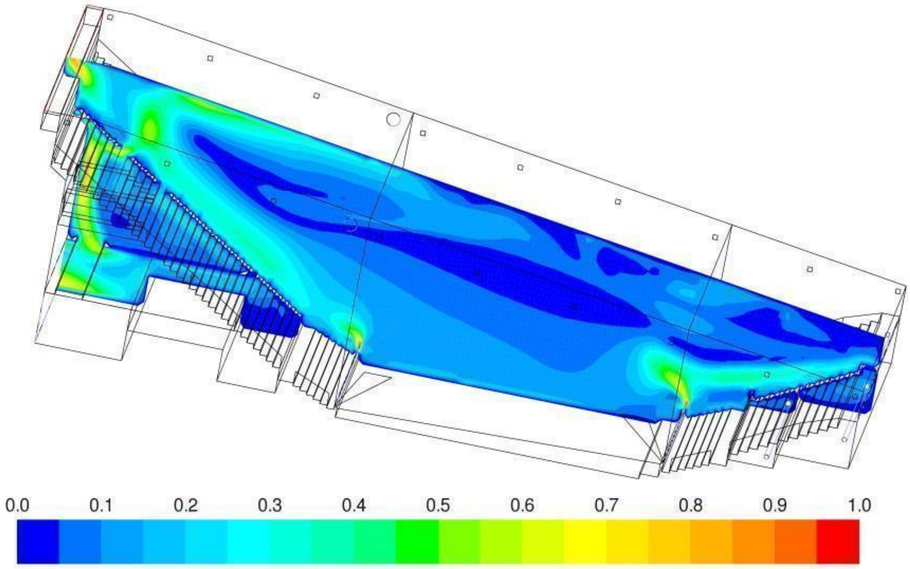


Figure 4.11. Water Polo London 2012. *Research done early in the design phase to test the ventilation plan, this image shows air velocity. Retrieved 6 December 2017 from http://www.maxfordham.com/assets/media/images/Services/Light%20and%20Air/Waterpolo1.jpg*

The temporary nature of the arena has large influence on the type of ventilation systems in the arena. Where a permanent structure can reduce much of its carbon footprint by an efficient climate system, this does not necessarily apply to a temporary structure. The sustainable qualities of the building are measured by its material use and reuse. It might be a sustainable strategy to use temporary HVAC installations. Also, the usefulness of natural ventilation should be considered. Its efficiency lies in the material reduction if applicable, not the energy reduction during that short period of time.

For systems that would need ducts it would be more sustainable to look beyond the conventional aluminium profiles. Fabrics that could be easily be recycled or profiles that would be more robust would better fit this temporary venue (figure 4.12).

Figure 4.12. Fabric ductwork in a swimming pool. Retrieved on 6 December 2017 from https://www.ke-fibertec.com/ImageGen.ashx?image=/media/431382/swimming_ol_700x415px.jpg&width=560&compression=95

4.2.6 Acoustics

Acoustics in a closed arena such as the volleyball arena are complicated and require extensive simulations to test design implications. Those kind of acoustic simulations will not be part of this research, and therefore it will not influence the design.

4.4 Structural requirements

In order to decide on a structural design multiple construction principles will be considered. The construction is divided into the roof structure and column structure. In some cases these will overlap, in which case they will fall into the category *roof structure.*

The most important parameters in this construction are dictated by two factors: 1. demountability and 2. reusability. The demountability of the structure will increase when structures are lightweight and not overly complex. Lightweight structures are easier to handle and require less effort to lift, adjust and therefore less prone to damage. Complexity of a structure will increase the construction time (and disassembly) of a structure, which makes it harder to become financially viable.

The reusability of a structure is described in the previous chapter. The requirement can be met in multiple ways, although there are limits as described previously. The structure could be either complex or simple as long as there is a practical approach to reusing.

4.4.1 Roof structure

In figure 4.13 an overview of roof structures for stadiums can be seen, taken from *Stadium Atlas* (Nixdorf, 2008). It showcases possible strategies, and notes the maximum span. There are multiple steel strategies that are able to span the required distance (90m). Although it should be noted that examples can be found where this overview conflicts with reality.

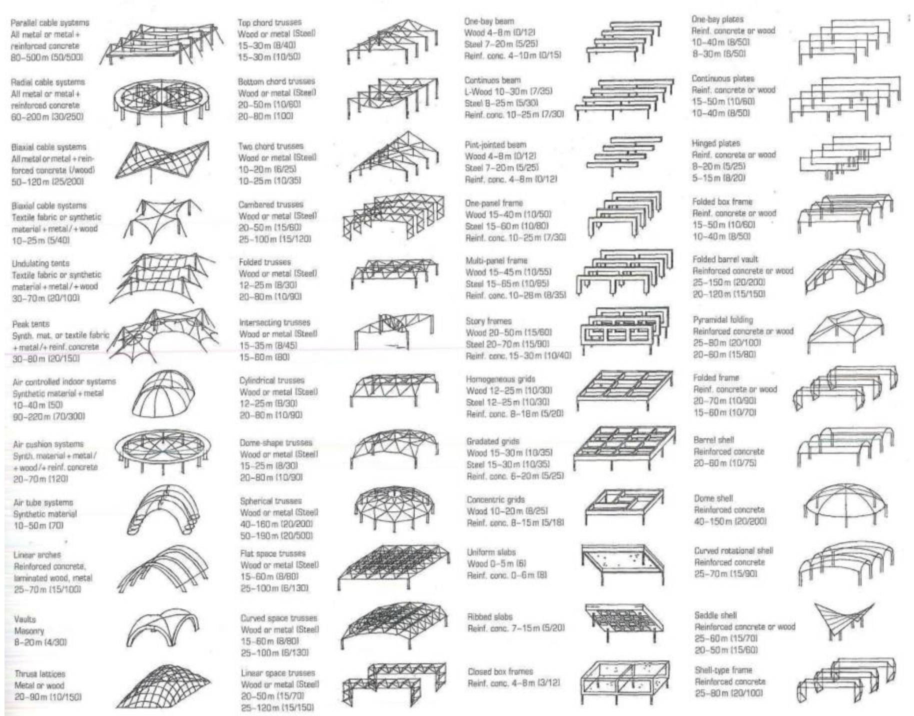


Figure 4.13. An overview of several roof structure strategies. *Taken from Stadium Atlas (Nixdorf, 2008).*

Apart from the overview from figure 4.13, the roof structure of several case studies have been analysed. Namely the Handball Arena (London Olympics 2012), Water Polo centre (London Olympics 2012), Basketball Arena (London Olympics 2012), Velodrome (London Olympics 2012) and the Handball Arena (Rio Olympics 2016). Combining the analysis of the case studies and the overview from figure 4.13, four categories of viable roof constructions were distinguished. These categories are: *1. Horizontal truss system 2. Arched truss system 3. Slanted truss system 4. Cable roof system.*

In table 4.6 an overview can be found where these categories and case studies are rated on four parameters, which make up a rating on reusability and demountability.

Roof principles	*Weight*	*Time to assemble*	*Practicality*	*Complexity*	*Reusability*	*Demountability*	*Average Ranking*
Horizontal truss system	+/-	++	+/-	++	+/-	+	+
Handball London 2012	+/-	+/-	+	+	*permanent*	*permanent*	
Water Polo London 2012	+	+	+	+/-	++	++	
Handball Rio 2016	-	+	++	+	+/-	--	
Arched Truss	+	+	-	+/-	+/-	+	+
Basketball London 2012	++	++	+/-	+/-	-	++	
Slanted truss	+	++	+/-	+	+	+/-	+
Cable roof	++	--	--	--	+/-	--	-
Velodrome London 2012	++	-	+/-	+/-	-	--	

table 4.6. *A comparison between four roof construction principles.*

The horizontal truss system is the least complex structure from the four categories. Due to its orthogonal nature and repeating structure it is a common structure for many large spans. The scale of the truss systems vary quite a lot, depending on the length of the span. For example, the water polo arena (London

Olympics 2012) roof height is 1 meter while it spans 50 meters. The handball arena (Rio Olympics 2016) roof has an estimated height of 5 meters, with a span of 95 meters.

An advantage to this system is its simplicity. It can be designed for disassembly, and takes relatively little time to build. Elements of the truss can be reused individually and segments can be reused as a whole if engineered correctly. Drawback is the weight of this system, which increases exponentially when the span increases. Individual elements can become large and cumbersome and hard to reuse as there is not great market for such elements.

The arched truss is a lighter construction in terms of weight compared to the horizontal truss. More economical in transport and in the assembling phase of construction. The basketball arena (London Olympics 2012) used such a construction. The height of the profile is approximately 2m, while the span of the arena is 90m, similar to the handball arena (Rio Olympics 2016). The individual elements of the basketball arena roof construction were not meant to be reused individually. The added complexity to the structure due to its curvature could be justified by its reuse strategy, which was relocation. If the strategy is to reuse individual elements an arched truss is probably not feasible construction.

The slanted truss is a common construction method for warehouses and other light constructions with a minimal amount of columns. It is slightly more efficient in its force distribution than a horizontal truss, and can therefore be lighter in weight. It does add complexity to the overall structure by the addition to an angled surface. An additional coincidence is that rainwater is more easily transported over such constructions.

A cable roof is a very light weight construction, held up by tensile forces. It requires a very strong ring shaped construction around the cable roof, able to withstand those forces, similar to spokes in a bicycle wheel. These constructions are very complex and are difficult to assemble and disassemble, and also hard to reuse.

4.4.2 Columns

The columns of the arena are loaded by the roof and all installations hanging from it. There is a strong correlation between the structure of the roof and that of the columns, and they cannot be looked at in complete isolation in an actual design. Nevertheless it is useful to compare variations of columns to get better insight on the possibilities for this project.

Based on three case studies three different column strategies have been recognized: 1. vertical truss systems 2. solid profiles 3. element built columns. The case studies are the Water Polo centre (London Olympics 2012), Basketball Arena (London Olympics 2012) and the Handball Arena (Rio 2016).

	Weight	*Time to assemble*	*Practicality*	*Complexity*	*Reusability*	*Demountability*	*Average Ranking*
Vertical Truss	+	+	++	+	+	+/-	+
Basketball London 2012	++	++	+	+/-	-	+	
Handball Rio 2016	++	+	+	+/-	+/-	-	
Solid steel profile	-	+	-	++	+/-	+/-	-
Element built	+	+	+/-	+/-	+	++	+
Water Polo London 2012	+	+	++	+	++	++	

table 4.7. *A comparison between three column construction principles.*

Both the basketball arena (London 2012) and the handball arena (Rio 2016) were supported on vertical truss columns. In Rio a three-dimensional truss was used, opposed to a two dimensional truss in the basketball arena. A much higher density of steel beams was used in the basketball arena. What both arenas have in common is that the columns are single elements, meaning they have to be assembled, disassembled and transported as a whole. This reduces the reusability of the element.

Alternatively, these elements can be built in elements, such as the construction of the water polo arena (London 2012). These elements can be assembled an disassembled on site in a relative short period of time. It does add to the complexity of the structure because there are more connections.

4.4.3 Preliminary calculations

The following design will not be simulated structurally, because it is such a complex and extensive structure. That is not the focus of this (design) research and would not amount in a better insight of the reusability of the project. To get a sense of realism some preliminary calculations have been made by hand below, to ensure the structural integrity is in the right order of magnitude. It is mainly used to check whether the profiles and steel elements can handle the forces involved.

Load case

A simplified steel truss structure seen in figure 4.14 is similar to many arena roof constructions. To determine the height of this structure the following load case is determined, which will be used to calculate the deflection and minimal element strength specifications.

Length beam:	*90m*
Loaded width surface area beam:	*12m*
Loaded surface area/beam:	*1080m2*
Maximum deflection:	*400mm (visual demand)*

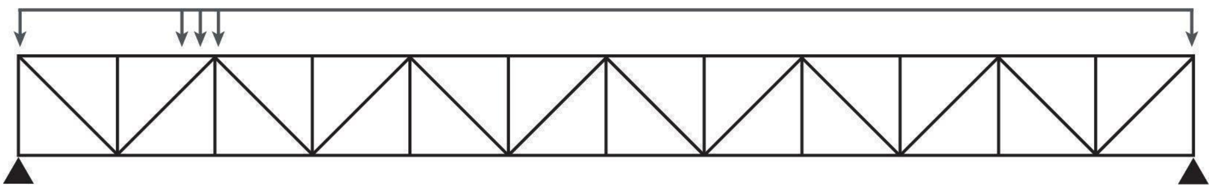


Figure 4.14. The load case for a simplified truss structure

Description	Load	Load/m	Type of load
Screen/equipment	0,2 kN/m2 * 1.2	2.9 kN/m	*Dead load*
Load bearing structure	1,5 kN/m * 1.2	1,8 kN/m	*Dead load*
Secondary structure	*0 kN/m*	*0 kN/m*	*Dead load*
Roof cladding	0,3 kN/m2 * 1.2	4,3 kN/m	*Dead load*
Maintenance/water	0,5 kN/m * 1.5	0,75 kN/m	*Live load*
Wind load	0,5 kN/m2 * 1.5	9 kN/m	*Live load*
Total load (f)		**18,8 kN/m**	

Table 4.8. The load case for an Olympic arena

The goal is to find the minimal height of the roof structure, therefore in the following calculations that will be left as a variable *(x)*.

First, the load on each node (F) will be determined with the following formula;

$F = f(kN/m) * x(m);$ *(Formula 1.1)*

$F = 28{,}5x;$ *(Formula 1.2)*

The maximum moment can be determined using the following formula;

$Mmax = (\frac{1}{4}l^2 * f) - (\frac{1}{8}l^2 * f);$ *(Formula 2.1)*

$Mmax = 5{,}8 * 10^4 - 2{,}9 * 10^4 = 1{,}9 * 10^4;$ [kNm] *(Formula 2.2)*

The maximum force on a single element would be;

$Fmax = \frac{1{,}9*10^4}{x}$ [kN] *(Formula 3.1)*

The minimum surface the pulling rod would have to be (diagonal steel element) , with the maximum tensile strength of steel 235N/mm^2;

$Smin = (\frac{1{,}9*10^4}{x} * 10^3)/235;$ [mm^2] *(Formula 4.1)*

In any further calculations in this stage the pressure rods must be checked whether they will not nod. This check will be taken into account further in the design. Now the deflection will be calculated with the following formula;

$\omega = \frac{5}{384} * \frac{ql^4}{EI}$ [mm] *(Formula 5.1)*

With;

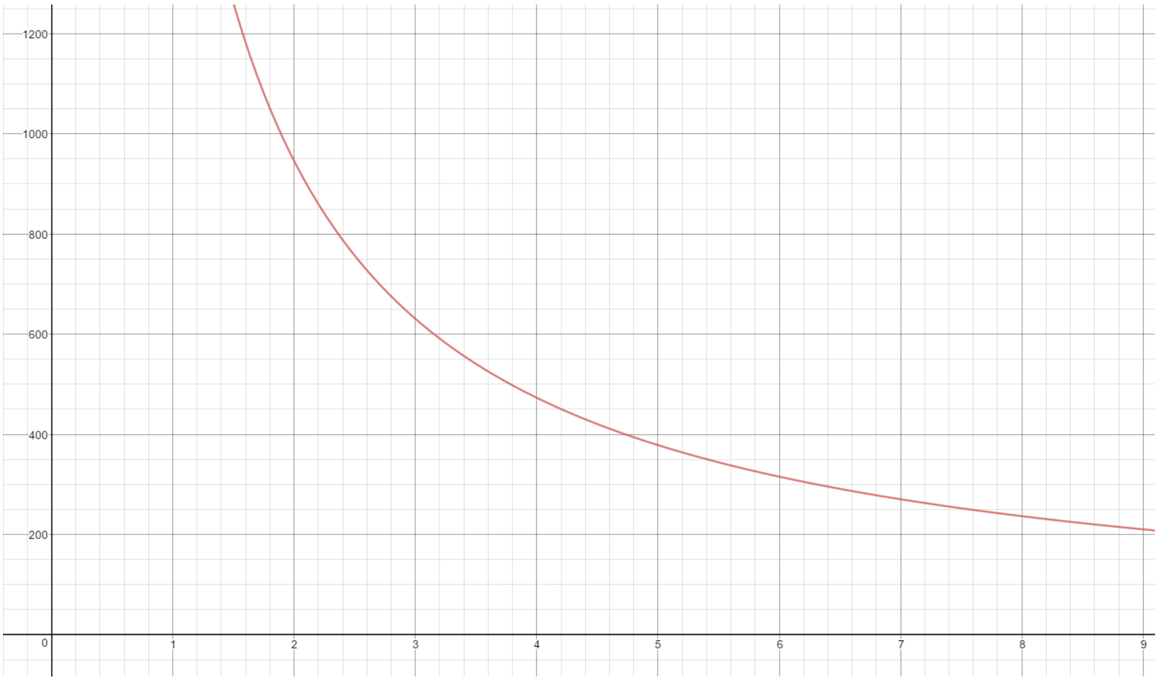
E = 210000

I = 0,5 S_{min} x^2 = $(\frac{1{,}9*10^4}{x} * 10^3) * \frac{1}{235} * \frac{1}{2}x$

Gives;

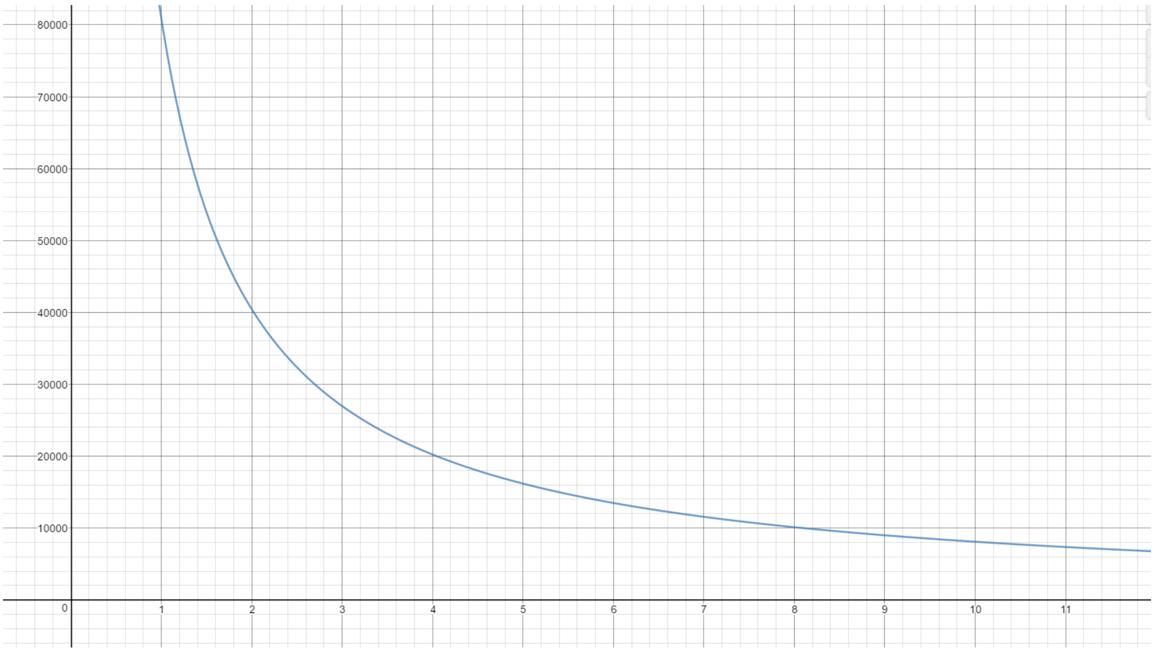
$\omega = \frac{5}{384} * \frac{18{,}8*10^6*90^4}{210000*(\frac{1{,}9*10^4}{x}*10^3)*\frac{1}{235}*\frac{1}{2}x}$ *(Formula 6.1)*

When this formula is plotted we find that a construction height of 5m is needed to remain below a maximum deflection of 400mm;



Graph 4.1. The height of the roof construction (x) plotted against the deflection (y)

Corresponding to this formula there is a minimum profile surface area needed to take the bending moment, which is plotted in a formula below. We find that for a 5m high steel construction a profile that has minimum of $1{,}6*10^4$ mm^2 surface area is needed.



Graph 4.2. The height of the roof construction (x) plotted against the profile surface area (y)

4.5 Post-event strategy requirements

Considering the post-event strategies discussed in the previous chapter, a strategy for a temporary Olympic arena must be selected. First of all, in this scenario the arena cannot be built with already used elements from other stadia or other projects. For such a strategy to work there is more expertise and knowledge required about the current used steel market in Europe. Chances are small to find a match for such a specific build. The goal is to design a new product that can be reused.

For this project goals have been set to state how much of the project will be reused. It would be impossible to reuse every single component of the arena. For some components recycling is a more ecological option. Especially if a material requires little energy to recycle this can be a more viable option. In table 4.9 the goals for each design aspect has been stated. These values have been set based primarily on reference projects, such as the basketball arena (London Olympics 2012).

	Reuse (any form)	**Recycle/ upcycle**	**Waste**
Structure Primary	70% in mass	0-25% in mass	5%
Structure Secondary	70% in mass	0-25% in mass	5%
Facade	0-50% in surface area	0-50% in surface area	0%
Climate system	75% in volume	0-25% in volume	10%
Foundation	0-80% in mass	0-50% in mass	0 %

table 4.9. Goals for each component of the venue

Although there are many advantages to reusing, with all its challenges and effort needed it can easily be seen as a burden. Luckily this project is situated in a privileged position, where it is regarded with much media attention and public interest. This could be used as an asset to promote and 'sell' the design. It would require the construction to be recognisable and visible to the public.

Furthermore, a *kit of parts* document will be one of the requirements for this design. It can be explained by the following quote from A.S. Howe: "Kit of parts theory refers to the study and application of object-oriented building techniques, where building components are pre-designed / pre-engineered / prefabricated for inclusion in joint-based (linear element), panel-based (planar element), module-based (solid element), and deployable (time element) construction systems (2003)". Although its name hardly ever mentioned anymore, the principles are still valid. An overview as can be seen in figure 4.15.

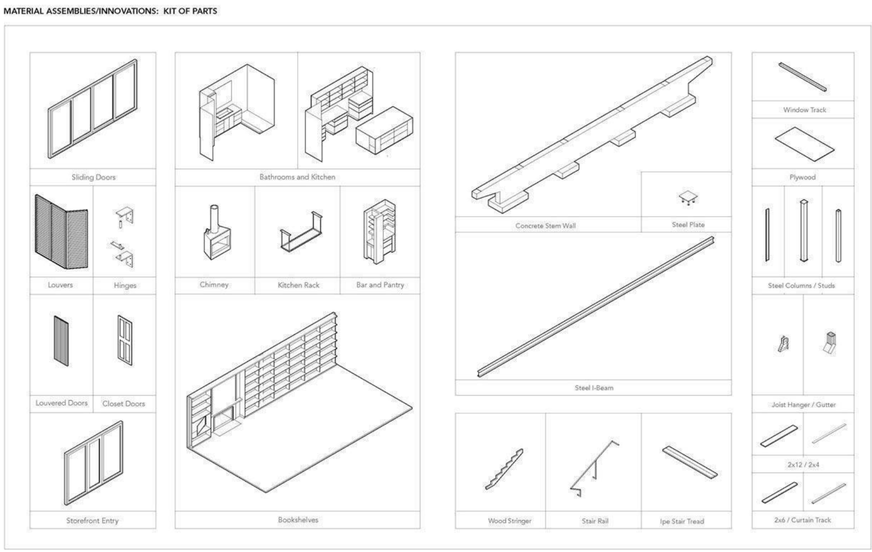


Figure 4.15. *Example of a 'kit of parts' house design.* Retrieved on 6 December 2017 from https://cdn.architecturelab.net/wp-content/uploads/2015/03/Kit-of-Parts.jpg

By its clear and simple documentation it discourages the use of many different components. Less variety in the building process will positively influence the reusability of the venue, as it requires less effort to find a 'reuse strategy' for all components. The *kit of parts* document is not intended to influence the design directly, but can be used as a proof of concept. Although useful, this document does not go into detail about any of the components. One of the barriers for reuse is a lack of documentation.

The reusability of a building is influenced by what *post-event use* (recycle, upcycle, relocate, adapt) is possible, which is influenced by: *building material, building technique and building elements.* The following arena is designed to be disassembled and reused after its intended use. According to the previous research and case studies reuse of building elements can be done in multiple ways. More specifically, reuse of elements can manifest in other building types, other fields of design or even other industries. For example, the facades of the temporary handball arena of the Rio Olympics are designed to be reused as facades for four schools. Hence the facade design deals with requirements from two different building types.

For some case studies where reuse of building elements in a design has been considered, only one post-use is considered, as seen in table 4.10. This can be a risky strategy as the case studies show the intended reuse strategy is not always carried out. Presumably a design that can be reused by more than one post-event use has a higher chance to actually be reused successfully.

	Reuse strategy	Actual reuse
London 2012, Olympic Stadium	Two strategies: 1. Recycle whole stadium; or 2. Adapt capacity from .. to .., and recycle elements;	- Downsize capacity from .. to .. ; - Elements were recycled; - Lightning transformed;
Rio 2016, Handball Arena	- Reuse facade material as facades for 4 schools; - Recycle concrete seating bowl; - Structural reuse strategy unknown;	- Not reused, abandoned
London 2012, Water Polo Arena	- Elements will be returned to the supply chain - Membranes will be recycled	- Elements returned to supply chain - Membranes recycled
Sydney 2000, Olympic Stadium	- Transform capacity - Steel construction reused in another stadium	- Steel members reused - Concrete waste

Table 4.10. An overview of several case studies which shows what strategy was intended.

The ability of building elements to be reused in any of these post-event uses depends on many factors, and arguably it is impossible to quantify the reusability of every building element beforehand of the design. Nonetheless it is safe to assume that some factors are crucial when determining whether a building element is easier to reuse. For instance if building elements comply to standardization (if present) from the intended post-event use industry, it is more likely to be reused in this sector.

The required strategy for the design of a reusable and temporary arena following below should include the mention of several reuse options. Expecting not for every post-event use become reality, but rather to show several strategies that are possible for reuse.

4.6 Conclusions

The requirements for a temporary and reusable Olympic Arena has been researched. These are then used in order to form a design strategy for a future Olympic arena, as a case study the Volleyball arena for the Olympic Games of 2024 held in Paris. The requirements set by the IOC describe the temporary nature of the venue, which means that the whole structure must be removed after the games.

First a design focus has been determined. By analysing previous case studies of temporary sport arenas it became clear that several aspects of the design are already quite reusable and would not require more research. This includes the playing field, the seating bowl and infrastructure. Three aspects of an arena design are part of the design focus: *column construction, roof construction and façade design*. Considering these aspects influence the carbon footprint greatly, it is here where the most progress can be made regarding sustainable design.

Secondly, general requirements regarding capacity and size were established by analysing similar case studies. Two separate volumes are required for this arena as stated by the Paris bid books, with a capacity of 13.010 and 5.560 visitors. One requirement of the design is to include a solution for both volumes. The estimated dimensions of the arena can be found in table 4.4.

Then, requirements regarding climate, program, light plan and acoustics were determined. For a climate system material use is the most important factor that influences whether the system is sustainable. Controversially, this is not determined by the energy consumption during use of the venue. It was determined that light, acoustics and program are not influenced by the temporary nature of the design, and will not play a big role in the design requirements.

Next, requirements regarding roof construction have been established by means of hand calculations and case studies. First several construction principles were established with case studies and literature research. The results can be found in table 4.6 and 4.7, where these principles have been compared.

By hand calculations two graphs could be plotted. Graph 4.1 describing the deflection against the height of a steel truss spanning 90m. Graph 4.2 plots the height of the steel truss (spanning 90m) against the profile surface area. There is a correlation between the height of the roof construction, the allowed deflection and the required profile. This correlation is used to determine what profile the members need to be, and vice versa. It is shown that a height of 4-5 meters is necessary to stay below the maximum deflection of 400 mm. The required profiles need a surface area of at least 200.000 mm^2. This corresponds to a profiles like HEB300 or HEA500. In general these

Lastly, requirements for a reuse strategy were determined. First, goals were set to what percentage the arena should be reusable and what percentage would be fit for recycling. The strategy to fulfil these goals is to have the design take into account for several post-event uses. As previous examples of temporary sport venues show the intended post-event use is not always realized, which leaves an unused building as a legacy.

5 Design of a reusable Olympic arena

5.1 Design strategy

The Volleyball arena for the Paris Olympics 2024 will be a temporary venue. According to the research several requirements have been stated, which forms the basis for this design. Usually when large public works are designed these requirements are implemented in an optimized design. For example, this could include a structural analysis to optimise the structure to the most lightweight configuration. In terms of a façade such an optimization could be to reduce the number of unique parts. These optimizations are based on cost efficiency, in the examples above that would be material reduction and process cost reduction accordingly. It must be noted that this design focuses on the reusability of the steel construction. Further references to 'the design' are limited to the steel construction only.

Financially speaking, most projects in the built environment consider the construction phase and the user phase (Crawford, 2011). Rarely, if ever, are the demolition or disassembly phase of the building considered in this equation. Usually that phase is reached after decades of use and is therefore of less relevance to the current contractor (figure 5.1). Contrarily, for a temporary arena the demolition phase of a the building is reached much sooner, for temporary Olympic venues this is often a few (6 -12) months (figure 5.2). It is therefore essential to consider the demolition phase in the financial equation, which consequently influences the parameters to which the building is optimized.

To account for this in the following design two parameters are considered most important in the demolition phase: demountability and reusability. Factors that determine the demountability of a structure comprise of the time to disassemble, and the ability to retrieve building materials after the disassembly stage (both factors are further categorized in chapter 3.3). The reusability of a building is influenced by what *post-event use* (recycle, upcycle, relocate, adapt) is possible, which is influenced by: *building material, building technique and building elements.*

It is not conventional to consider the cost of demolition in the design phase, as it will rarely be profitable for the owner of the building. Waste is the end product and therefore considered useless, even so when materials can be/are recycled. The goal for the following design is the contrary, where the end product are profitable building elements for reuse (figure 5.2). Consequently, the design will be optimized towards *demountability* and *reusability*.

To do so the requirements of reuse of the design are implemented, which are described in table 4.10. A combination of reuse and recycling is required, while adaptation on location is not possible (every part of the arena is temporary). Instead of implementing one reuse strategy for a post-event use, the design accounts for all four scenarios of post-even use. The reason for such an approach is a based on the case studies of former arena's where the ambition was to reuse. What these arena's had in common was their singular reuse strategy, there was no plan B so to say. When the strategy is somehow not realized, the building becomes arguably less sustainable than a permanent arena, because all effort (and extra building material) is wasted.

Presumably, if it would be possible to design an arena to account for a multitude of post-use scenarios chances are increased whether the arena will actually be reused. Each post-event use will therefore be considered: *recycle, upcycle, relocate* and *transform.* Although multiple possibilities will be considered, it does not mean they are all equal in terms of cost efficiency, practicality and sustainability.

It must be noted that for the options *transformation* and *upcycling* chances are that not all building material will be able to be reused. When the building is transformed into another volume or shape it is unlikely that all materials fit in a new design. Also, when upcycling is considered it would be safe to assume that the number of those elements does not perfectly fit the demand of the market for those elements. It is another reason why *recycling* as post-event use must be considered.

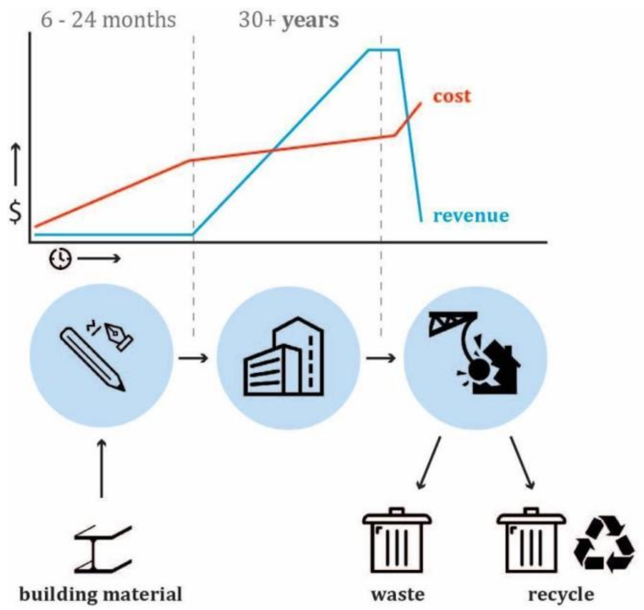


Figure 5.1. A schematic visualisation of a typical building process

Figure 5.2. A schematic visualisation of the building process of a temporary venue for the Olympic games optimized for reuse

5.2 Reuse strategy

The four post-event uses discussed above are *recycling, upcycling, relocating* and *transforming.* For each possibility the strategy will be discussed below, in the following order: *1 Relocation, 2 Transformation, 3 upcycling* & *4 Recycling*.

After determining the reuse strategy a *research by design* was done on each of these strategies. Meaning that these strategies are tested and compared against a standard design. Further information on the research can be found in chapter 5.6.

5.2.1 Relocate & transform configuration

Relocating the entire arena to a different location for either permanent use, or temporary use, would be the most sustainable option. Similar to the idea of the basketball arena for the London Olympic games 2012 (case study x), the arena would be a travelling arena. It is the most sustainable option because it reuses all components, including the inevitable unique building parts. Would the arena be relocated whole, there are several factors that influence the design: *demountability, transportation, climate,* and *prestige & adaptability.*

Assembling and disassembling the whole arena is required for all reuse strategies, but to do so multiple times in case of *relocation* requires a more *robust* and *faster* building process. This will be further discussed below.

Transportation of the whole arena becomes a more critical demand when *relocation* is considered. Each of the multitude of locations influence the requirements on transport, for instance dimensions and weight. In case the location is yet unknown or variable, building elements should be kept to international transportation restrictions. In most cases, this means building elements must be able to fit inside a freight container (table 3.2).

For this design a moderate European *climate* is considered, without additional requirements imposed by the local climate. Considering the construction might be located to a different climate it can influence the design. Steel itself is a very suitable material for any climate, and is not influenced by temperature and direct sunlight. It is influenced by saltier climates, and therefore the design should consider its initial location as if it were in a salty climate.

Although the steel construction is not influenced greatly due to climate, the opposite is true for the façade of the arena. Further information regarding the façade will be discussed in chapter x, as for this chapter only the steel construction is considered.

The Olympic games have always been an event involved with a lot of *prestige* for the organising city and country. It is a way to present itself to the world, and often the identity of the guest city or country is desired to take a central position in the design process of Olympic venues. To a certain extend this is also true for non-Olympic sport venues.

Unfortunately reusing an existing design is not always considered prestigious, as the design is similar to something built before. A reusable design could circumvent this problem if it could transform its look and volume. In an ideal situation this would not require any more unique elements and would leave no elements unused, although that would limit the form freedom of the alterations. Alternatively, if would be useful to know early in the design process what kind of alterations are possible, and if applicable, what elements are additionally needed and what elements cannot be reused.

Additionally, adaptability of the structure from a pragmatic view is desired as requirements (regarding capacity for example) would likely be different in another location.

Again it would be useful to know the amount of additional and/or unused elements for such an adaptation early in the design process.

To account for adaptability described above a parametric model is used. A parametric design is a tool that can be used early in a design process to quickly calculate and visualize several design. As mentioned above, it would be useful for a reusable design process to know beforehand what the implications are to material use by certain design decisions. Ideally this could lead to a optimization process, for which a parametric design is necessary.

The program selected for this is Grasshopper, which is a visual code environment supported by Rhinoceros. Figure 5.3 shows an impression of that environment. Input to this code can be any geometry drawn in Rhinoceros, or geometry that is described by coordinates, vectors and/or curves. Without going into much detail of the workings of this particular piece of code, the input given is useful to describe as it determines what kind of form freedom is possible. More information about the parametric design can be found in chapter 5.5.

First the required capacity and the corresponding geometry is considered, which can be found in figure 5.3. Subsequently three curves that can be adjusted manually describe the main shape of the arena (Figure 5.4). The middle curve describes the upper roofline and creates an irregular slanted roof, combined by the other two curves which describe the outer boundaries of the arena.

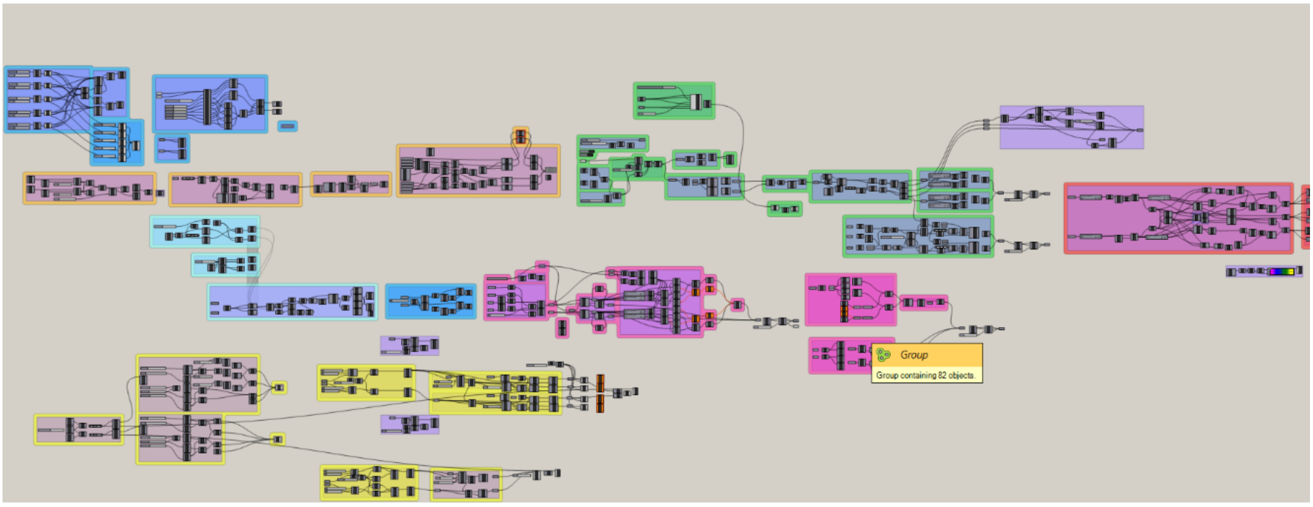


Figure 5.3. An impression of Grasshopper visual code environment

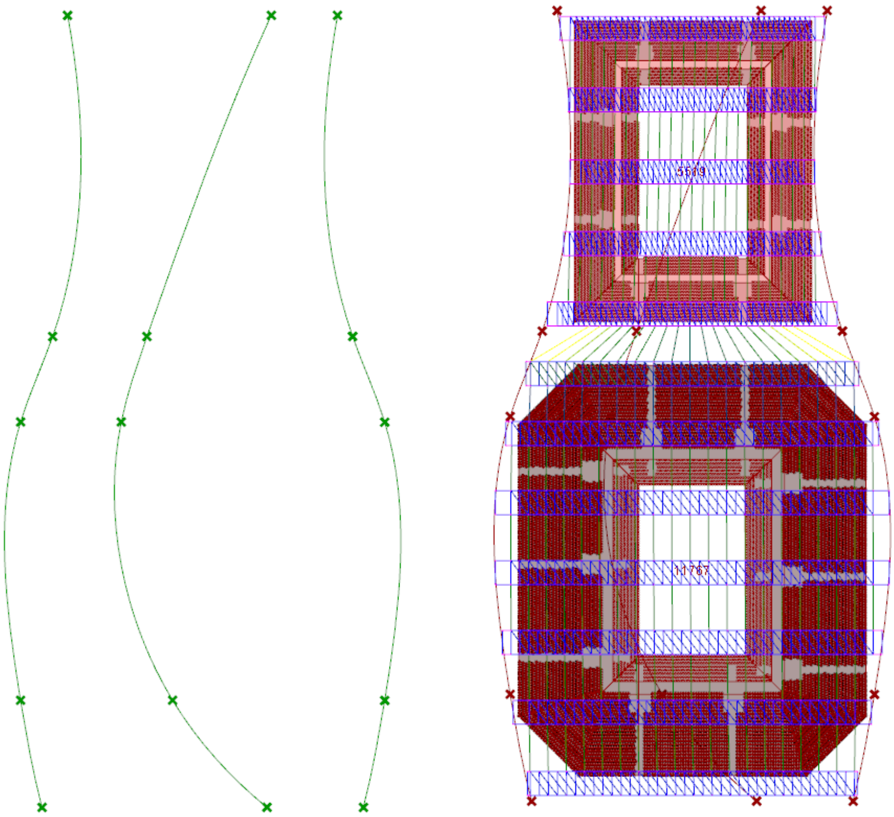


Figure 5.4. Top view. Left are the input curves shown, which can be changed to form other shapes, right is the output shown.

Four variants that result from such changes of input parameters are shown in figure 5.5. In these variants the following parameters have been changed: the roofline, the outline of the façade and the height of the roof. In these variants the capacity of visitors remains the same.

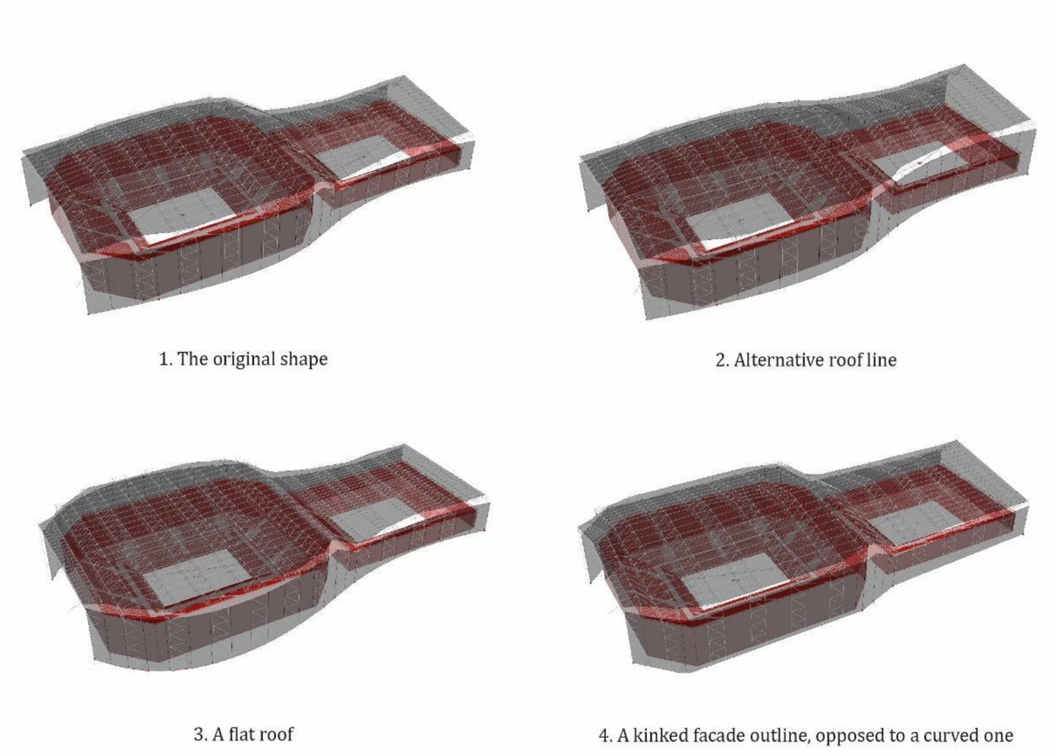


Figure 5.5a. Four variants of the Olympic arena with a similar capacity (separated in two volumes), this is a small selection of a vast amount of alternative shapes.

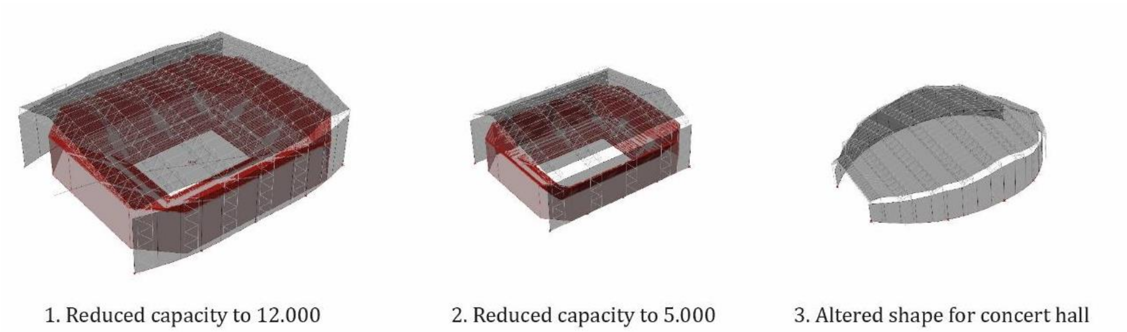


Figure 5.5b. Three variants of the Olympic arena with a reduced capacity or with a different function altogether.

5.2.2 Transform to other building format

Transforming the design into another arena might be straightforward, but is not without risks as described above. Alternatively, the building elements can be used to transform the construction into constructions from other building formats. Steel construction is widespread and is influenced by standardization as discussed before. After consulting several companies experienced in steel construction (*TATA Steel, Acelor Mittal* and *IMd raadgevende inginieurs)* it became apparent that reuse in steel construction is definitely possible ,regardless of the origin of the structure (personal communication, 6 February 2018, appendix G). The barriers of reusing steel have been discussed before in *chapter 2* of this thesis. This design proposal will focus on several barriers of reusing steel (construction) when considering transformation in other building formats.

First, several steel construction building formats are selected into which the steel construction of the arena will be transformed. These building formats have been chosen because they present either a large portion of the steel construction industry, or they have structural similarities to the steel construction of the arena. These building formats are:

Architecture

- Sport facilities
  - Stadiums (5000+ visitors) [appendix C]
  - Local sport halls [appendix C]
- Leisure
  - Concert halls/arenas [appendix C]
- Steel structured portal constructions
  - Warehouses [appendix B]
  - Retail [appendix B]
- High Rise
  - Offices [appendix A]

Civil engineering

- Temporary steel construction
  - Cranes [appendix D]
- Infrastructure
  - Highway (footbridge) crossings [appendix C]

Each building format is summarized and visualized in the corresponding appendices (see above). At least three characteristics of those building formats are highlighted in these visualizations: dimensions, connection methods and common profiles (if applicable). An attempt to add any other information that characterizes the building format has been made.

These characteristics represent what the steel construction of the temporary arena could be built into, where they form guidelines to more detailed requirements of that construction. It would be naïve to think that one design for a temporary arena could be built into every one of these building formats efficiently. Though it visualizes what dimensions and steel profiles are needed to approach the characteristics of other building formats. Also, it shows that some building formats overlap and could potentially be used in more than one format.

For instance, a hypothetical contractor could be interested in building the temporary arena, and then transform the construction into permanent high-rise offices. If the dimensions of that high-rise design are known, they could be implemented in the arena design. Essentially, that contractor is making two designs simultaneously. This strategy was attempted for the Olympics of Rio 2016. Alternatively, a design could also be made without one particular reuse format in mind. Such a design would optimize towards as many building formats as possible, considering multiple uses.

Whichever approach, a preliminary parametric digital model could help to calculate and visualize such decisions. This means that optimisation is conducted by parameters that affect the dimensions of the components. The input parameters would contain the requested dimensions, for instance the length of a steel beam in a certain component of the building (figure 5.6). Another input parameter could describe what percentage of beams (in number, weight or length) are allowed to deviate from the requested length.

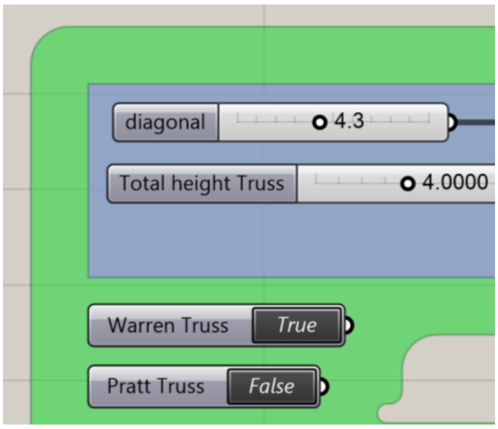


Figure 5.6a. Examples of possible input parameters: *diagonal length, height of the truss* and *type of truss.*

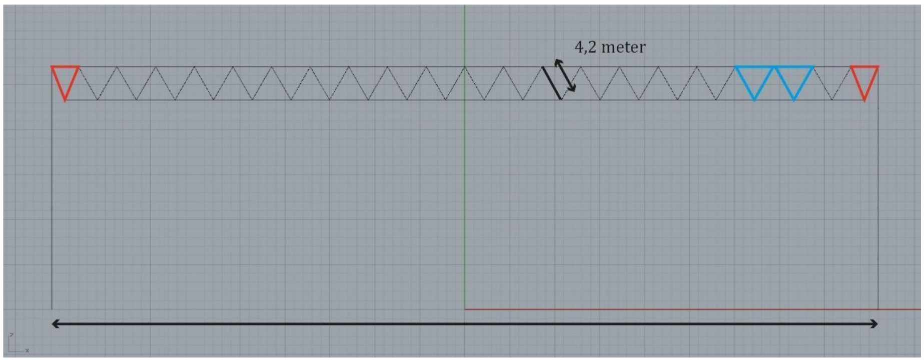


Figure 5.6b. Example of a truss with predetermined lengths of diagonals. Note that the width is not always a multiple of the requested length, and therefore unique elements are needed.

The example above singles out one element and adjusts the dimensions of the truss accordingly. Notice in figure 5.6b that such a requirement introduces several uniquely dimensioned elements, unless the total length would be a multiple of the requested length.

The efficiency of an optimised model towards set lengths of members can be increased by introducing more parameters to the geometry. For instance, setting the requirement that all truss lengths must be multiples of the before mentioned length. This means that the form freedom of a the arena will be compromised, in order to comply to the demands. The amount of deviation from the original form could be controlled by another parameter.

An example of such form of reuse is to use data that has been gathered from *steel portal construction* (appendix B). Based on the geometries found in the arena design, a design for a portal construction has been made. In figure 5.7 an overview of both the arena design and the amount of portal constructions that can be made from it.

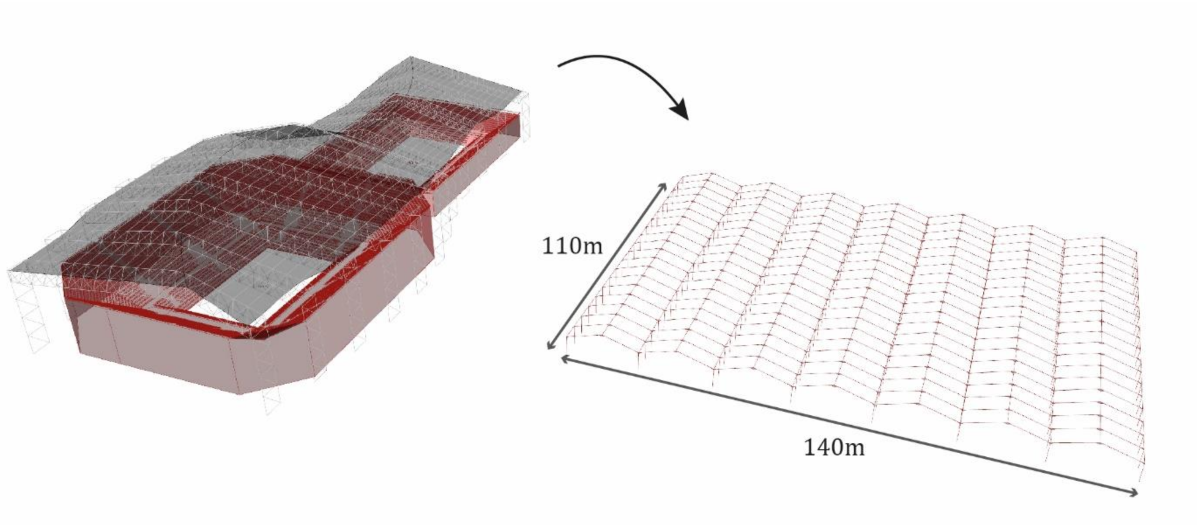


Figure 5.7. Example of reuse in another building format. Construction from the temporary arena can be used to build a grid of portal constructions with dimensions of 140x120 meters.

Note that for portal constructions moment connections are required, which means more material is needed for this reuse option. Also, not all construction from the arena can be used, in the current form approximately *36%* of the steel of the arena is used in these portal constructions.

5.2.3 Upcycle elements

Another form of reuse would be to upcycle the elements used in the construction. To upcycle steel beams from temporary use means the element are absorbed in steel construction for a longer period after its temporary use. Similar to the previous strategy, but different because the post-event use is unknown. To increase the chances of reuse the steel should be applicable to multiple sectors if possible. Two factors determine mainly whether a profile is applicable to a sector: *quality of the stee*l and *profil*e (personal experience, IMd raadgevende ingenieurs, 6 Februari 2018) .

To upcycle an element for an unknown steel construction industry two aspects are important. First of all insight of the current steel industry demand is required. The largest sectors in steel industry determine what the most numerous steel products currently produced are. Therefore it has been attempted to research the most common steel products in sector of construction are. Which can be subdivided in markets that are mentioned before, such as high-rise construction, portal construction, and so forth. It must be noted that these markets are not necessarily the largest in steel construction. For example the sectors of transport and machinery are also very large consumers of steel, as seen in figure 5.8 (68th Steel Committee Meeting, 2010).

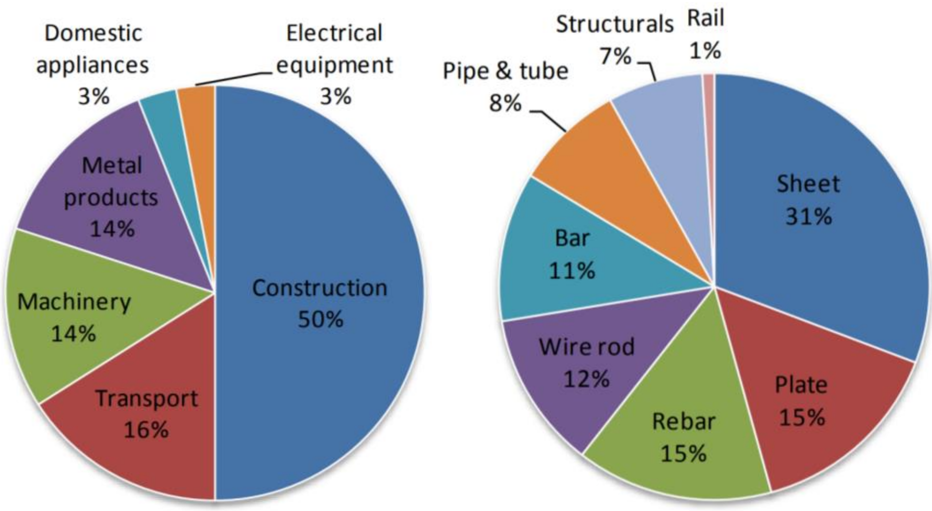
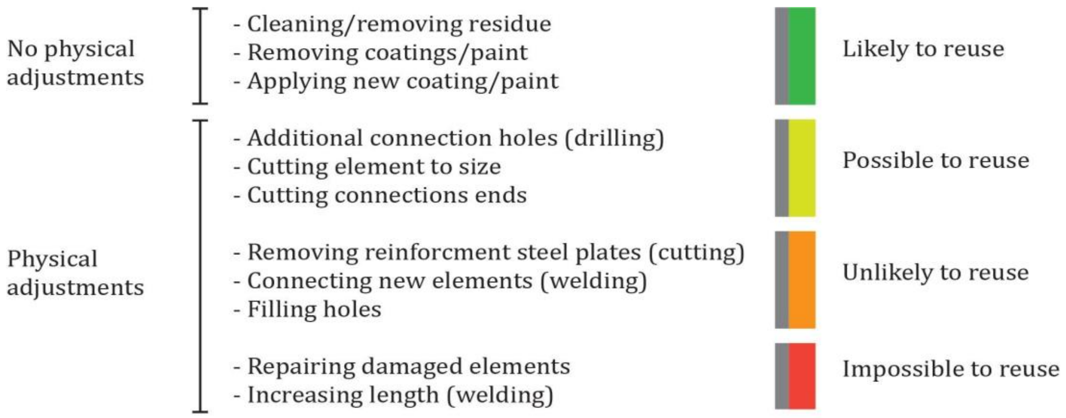


Figure 5.8. Chart showing the gross sizes of several sectors in the steel industry (left). Chart showing gross estimate of product ranges in steel production (right) (68th Steel Committee Meeting, 2010).

From figure 5.8 can be concluded that *structurals* (structural steel) make up only a small portion (7%) of steel production. This percentage is a lot smaller than the share of construction of the first chart because rebar, bars, pipes & tubes and plates are also used in construction. Although *structurals* is not the largest product range, this design focuses on that range because this is what the arena will be made of. By focussing on that product range less alterations to the individual elements are required.

Attempts to find the most commonly produced profiles in the product range of *structurals* has proven to be complicated. An interview at *IMd raadgevende ingenieurs* with an engineer gave some insight into the matter. According to Wiltjer many profiles have been standardized (IPE, HEA, HEB, etc.) and are therefore very numerous in the steel profile market (personal communication, February 6 2018). Any profiles ranging in height from 100mm to 400mm are very common and widely accepted as the norm. This is further confirmed by a document that was the result of a research done by a collaboration of *TATA steel* and '*Bouwen met staal*' (personal communication with Bauke Bonnema Hoekstra, 23 January 2018). This document can be found in appendix x.

Assuming a common profile is used in the construction of the design, rarely those steel elements can be reused without alterations. Whether reusing such an element is profitable depends on the number of alterations needed and the difficulty of the alteration. Two categories of alterations are recognized for this design: *structural* and *non-structural*. The first includes any alterations influencing the mechanical properties and/or dimensions of the element. The second category includes alterations to coatings of the element. Below are eleven alterations that are commonly done on steel profiles before the building process, or after reclamation of used steel elements. They are ordered in terms of difficulty.



After the right profiles and connections are selected, it would be necessary to document the steel used in the design. Information about individual element length, connection method and number of unique elements. A visual tool can be provided by the parametric model, which shows different lengths of elements in different colours, as seen in figure 5.9. It gives feedback to a designer when several colours are shown to similar members, which indicates a large amount of unique elements in the design. The next step would be to precisely measure the impact on these factors by certain design choices.

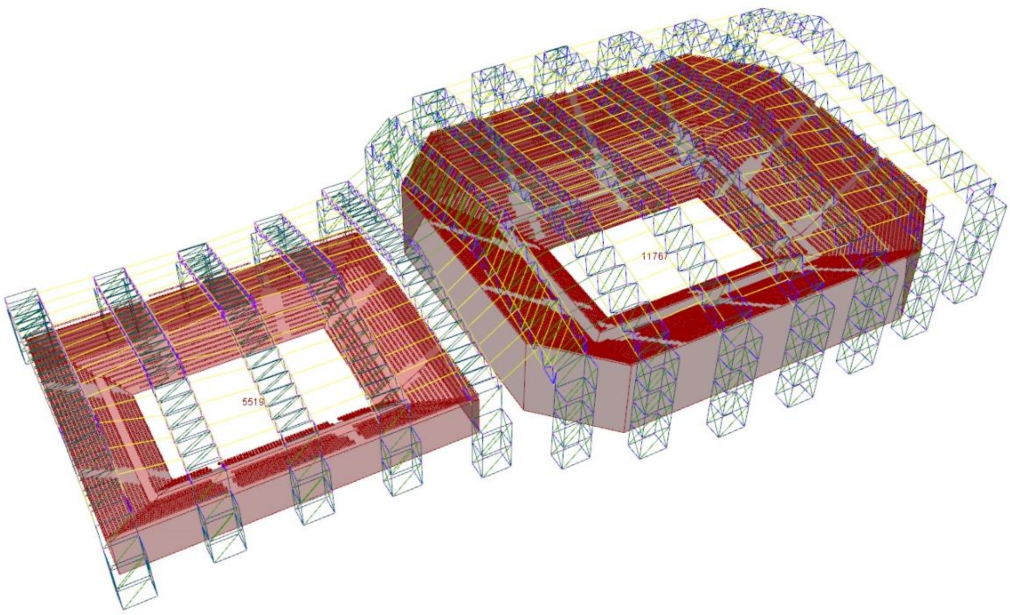


Figure 5.9. A visual tool provided by the parametric model to show different lengths of individual members.

5.2.4 Recycle

Simply stated, all steel elements that cannot be reused by any of the strategies above can be recycled. The only requirement for recycling must be that it can be disassembled, as all steel can be recycled regardless of the exact chemical composition. Although recycling is an improvement opposed to waste, it is not a very desirable strategy (as explained in chapter x). Therefore, the amount of recycled steel should be kept to a minimum in the design.

The most effect can be achieved by minimizing the amount of unique elements in the construction, and minimizing the total weight in connections of the steel constructions. Because these two types of elements are least likely to be reused.

5.3 Design overview

After describing the strategies of reuse above, a design was made. An overview of the general shape will be shown and shortly explained to provide some context. First a short reminder of the design focus will be discussed. Thereafter the concepts that shaped the arena will be discussed and explained. Next, ideas on construction methods, structural schemes and stability will be addressed. Lastly, the façade concept will be shortly discussed. These three themes provide the basis of the design, after which the report can continue further onto more detailed aspects of the design.

A short reminder on the design focus will follow next. First of all, the seating bowl will not form part of the design although it will provide the required volume (size) of the arena that needs to be enclosed. The steel load bearing construction will form the largest part of the design, including stability of the whole structure, as well as detailed designs of connections of structure. Next, the façade design will form a smaller part of the total design. This includes the materialization, and a method to mount that material to the load bearing construction.

5.3.1 Conceptual design

For the conceptual design for the volleyball arena it is easy to fall into a category of temporary looking venues. Take for example the London Olympics, where all temporary venues were cladded in a (white) membrane material while their general shape was simple and not very exciting or challenging. On the other end of the spectrum there are the designs from the Rio Olympics, which have more permanent look. Mainly because of a more permanent appearance in materialisation (wood and steel cladding).

For the design for this research a more daring shape is desired, with curved facades and roofs. Similar to examples like the Allianz arena (figure 5.10), where a simple but elegant design feature encloses a large volume with very little variation and complexity. Note that although the material (ETFE membrane) is often used for temporary design, applied in the right way it can have a much more permanent appearance.

Figure 5.10. The elegant & simple design of the Allianz Arena is an inspiration for the design of the Volleyball arena.
Retrieved from: https://nl.wikipedia.org/wiki/Allianz_Arena#/media/File:Allianz_Arena_Pahu.jpg

The design consists of several portal construction (chapter x) repeating across the length of the arena. The roof is sloped in two direction to allow rainwater to run off. By gradually changing the dimensions and angles of each portal construction the surfaces of the roof and facade change. To accentuate this change each portal construction will be projected and elevated slightly on the facade and roof. An additional benefit is that imperfections in the shape due to alteration on the construction dimensions are less noticeable.

To attach the membrane to the construction a secondary construction fills in the gap where needed (chapter x). The elevation of the membrane at certain locations is not constant, but also at a slight angle (figure 5.11).

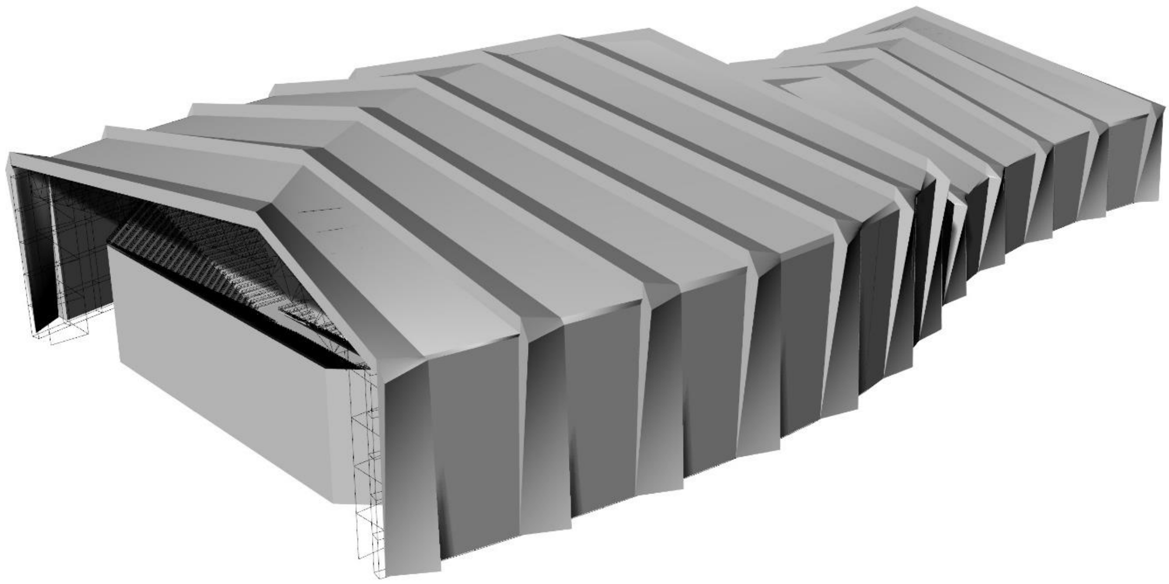


Figure 5.11a. Perspective view in greyscale. An early impression of shape and scale.

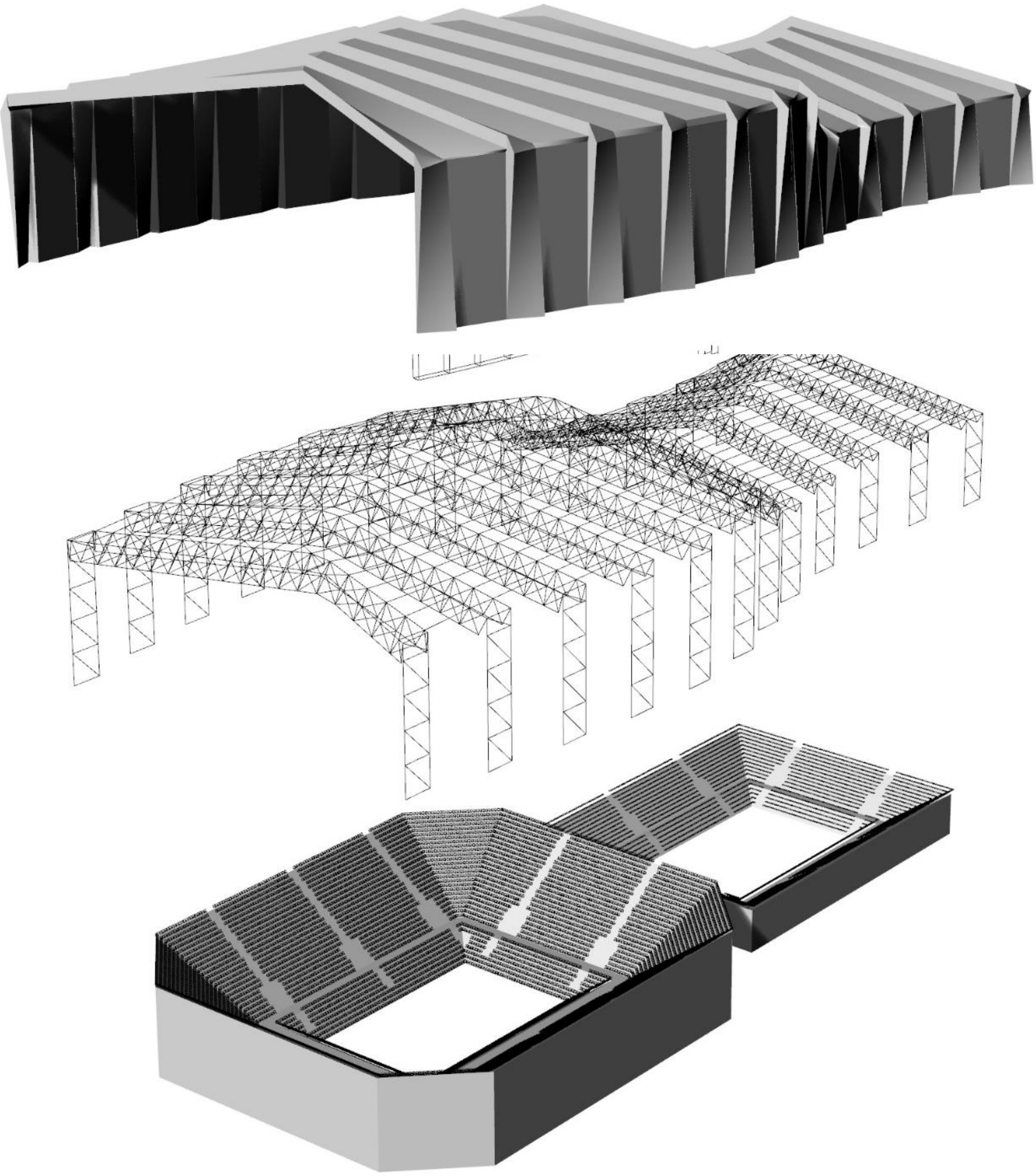


Figure 5.11b. Exploded view of the design proposal, showing construction, façade and the seating bowl.

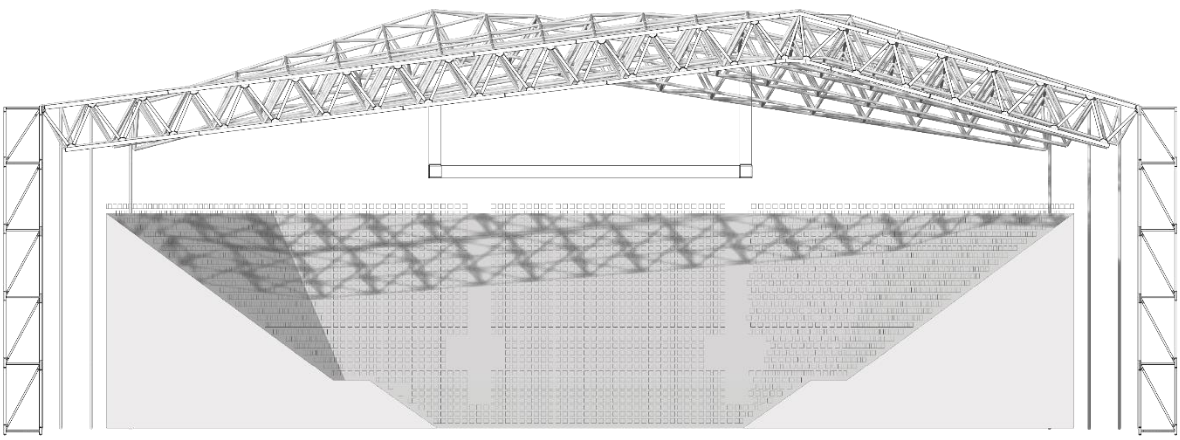


Figure 5.12. Section of the design proposal, showing construction and the seating bowl.

5.3.2 Portal construction

For the load bearing construction a portal construction was selected as the most suitable from a reuse point of view. It is a well-known and widespread construction method. The columns and beams can independently be constructed, installed and later reused. The connection between column and beam can either be a shear or a moment connection. Examples of either connection with a corresponding structural scheme can be found in figure 5.13.

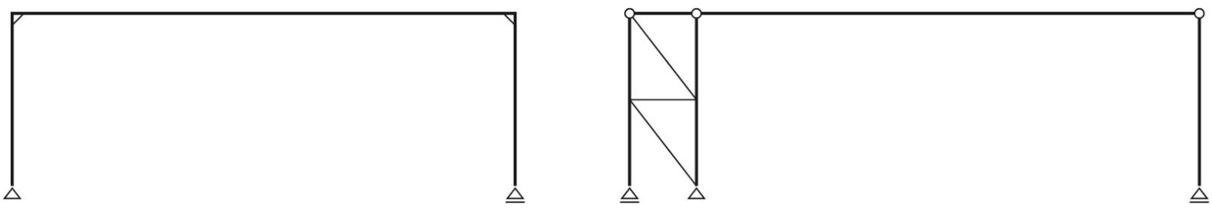


Figure 5.13. Two portal constructions with moment connections (a), and shear connections (b).

As the name implies, a moment connection converts loads in the horizontal plane to a moment at the location where the beam and column meet. Stability is solved in this area of the structure, not requiring any other stability elements. This connection requires extra material, and as a consequence these connections are often more expensive to build. Also, when considering these connections for large spans such as an sports arena which is required to be demountable, assembling and disassembling time is increased due to the many bolts involved.

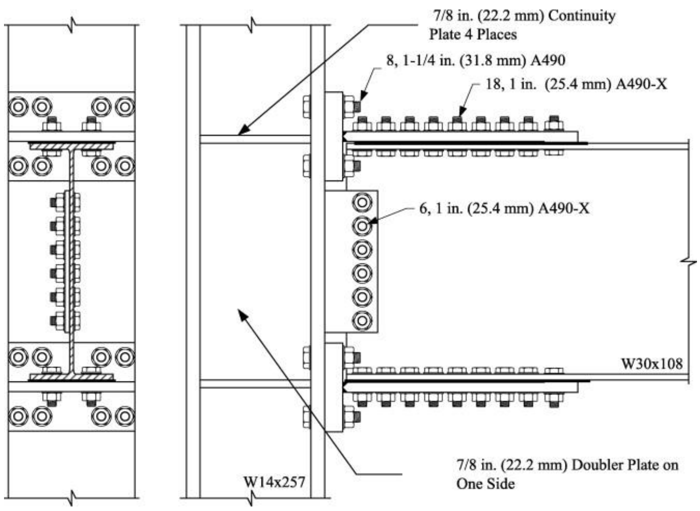


Figure 5.14. An example of a bolted moment connection in steel construction which shows the large amount of bolts for such a connection

Another consequence of a portal construction with a moment connection is the influence on the column members. As wind loads and other forces perpendicular to the beam have to be transported to either the moment connection or the foundation the dimensions of these members increases compared to the design by tension/compression members. On the other hand, this construction method requires minimal depth, resulting in a smaller facade surface area compared to a shear connection.

Alternatively to a moment connection a shear connection can be selected. Shear connections are designed so that only the loads in the vertical direction are transported from the beam to the column. Other loads such as wind loads have to be solved elsewhere in the structure, for example by tension or compression members. Alternatively, the columns are clamped at the connection to the foundation. This is similar to a moment connection described above, only then at the bottom of the column. This option is not a possibility for a temporary and demountable arena, as it has a far reaching effect on the foundation, which is not considered for this design.

Compression or tension members are often located between columns on a location where there would be a wall. Such a location is not as obvious in case of a portal construction because it consists of only two columns and the area in between requires to be an open space. In order to employ a shear connection depth needs to be added to the column as seen in figure 5.15.

This has several consequences on the demountability, individual members and facade surface area. First of all when a second row of columns are employed there are more connections between members, which influences demountability. Secondly, individual members can be of smaller dimensions as wind loads are transported over smaller distances compared to the moment connection. Lastly, adding depth to the column construction decreases usable floor space. Compared to a moment connection this will increase the facade surface area when the same floor area (or seating bowl) is considered.

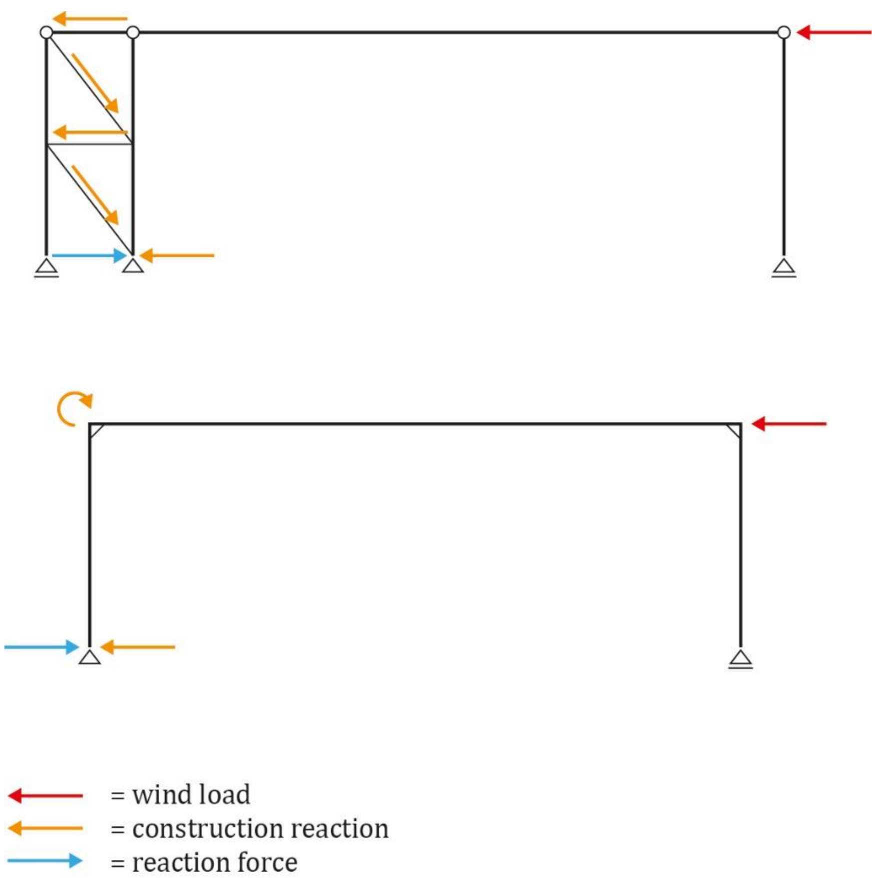


Figure 5.15. Wind load distribution on a moment (lower image) and a shear connection (upper image) portal construction

For the final design a shear connection was chosen, with an additional depth to the column to insure stability in the structure. This was decided while keeping demountability and reusability in in mind.

First of all, it proved to be difficult to determine at this stage of the design which method (shear connection or moment connection) is more demountable. For a moment connection many bolts are used in one place, which have to be installed on location. On the other hand, a shear connection has the consequence of having a larger number of connections, which also requires many bolts which may or may not be installed in factory or on location.

In terms of reusability there are more differences between the two principles. The shear connection with additional depth to the columns has the benefit of smaller profiles for the individual members. This is considered a major improvement to the reusability of the load bearing structure. Opposed to a moment connection this implication enlarges the facade surface area. Because the arena is a temporary structure and the facade is considered a very thin and low demanding layer of the design, this is not considered a major drawback. Considering the steel structure is more likely to be reused this way, which is has more mass and has larger footprint, it was deemed a more sustainable option.

In order to insure stability of the steel structure in the other direction (perpendicular to the portal construction) examples of other large steel spans were studied. In many occasions, the roof is constructed as a stiff plane by adding compression or tension members. In conventional buildings two rows of such elements in a grid suffice, in perpendicular directions. Examples of larger steel structures show that such ‘rows’ become more numerous, often implemented every other row of the grid. This can be seen in figure 5.16.

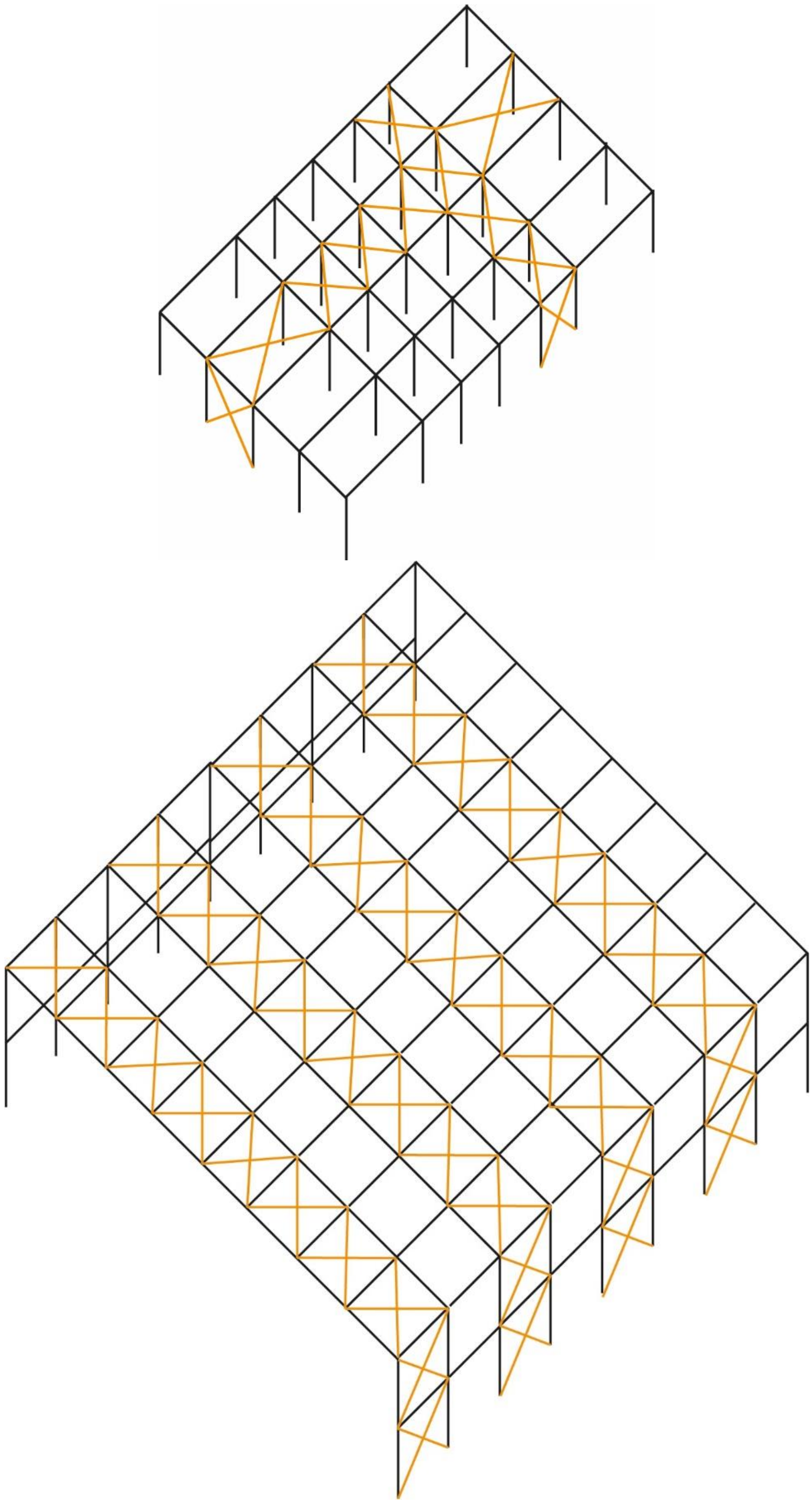


Figure 5.16. Stability in many conventional buildings (upper scheme), and stability implemented in larger steel construction (lower scheme).

5.3.3 Roof construction

In a way the stability solution exemplified above can be seen as two columns and beams being connected. An additional benefit is that fluctuations in wind loads acting on the roof structure are always shared by two members, making the structure more rigid. Also, in the case of trusses it prevents the truss from buckling. Trusses might be constructed to hold the load, it remains a very 'narrow' profile compared to its height. This is the similar problem when columns tend to buckle. Therefore the principle of rows of stability elements will also be used for the design of the load bearing structure of the arena. In figure 5.17 the principles described above come together in a scheme.

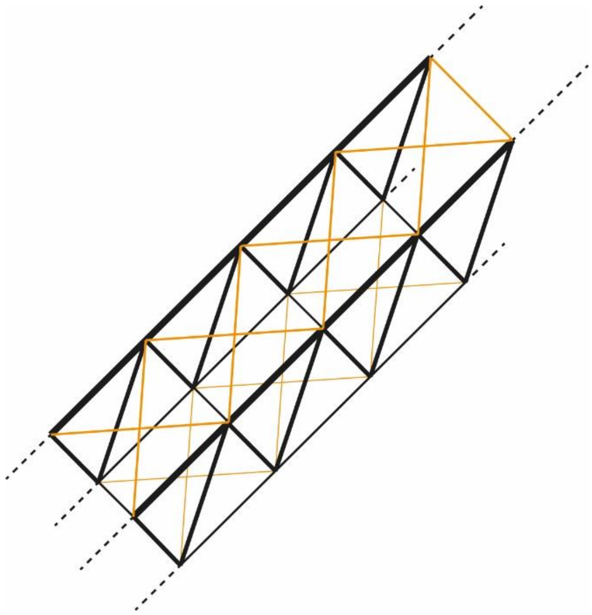


Figure 5.17. Stability in in two trusses connected. Fluctuating wind loads are therefore always shared by two members, and it prevents the truss from buckling.

An additional advantage of connecting the trusses is that the portal construction has become a stable construction on its own. This allows for different configurations which is necessary to relocate and adapt the arena.

Also, because one of the requirements of the arena is the allowance for alternative designs (relocate & adapt). The parametric design has an input of multiple curves which implement a curvature on the facade and the roof. The portal structure is therefore irregular in shape, as it has to follow this curvature. In addition, the warren truss is sloped towards both ends, which creates another variable. Where the two sloped warren trusses meet a kink in the warren truss is located, which also influences the total length of each arm of the warren truss (figure 5.18). Because the location of the kink is also variable this should be a moment connection. In practice it means that the truss will continue, albeit with a unique element connecting both arms of the truss.

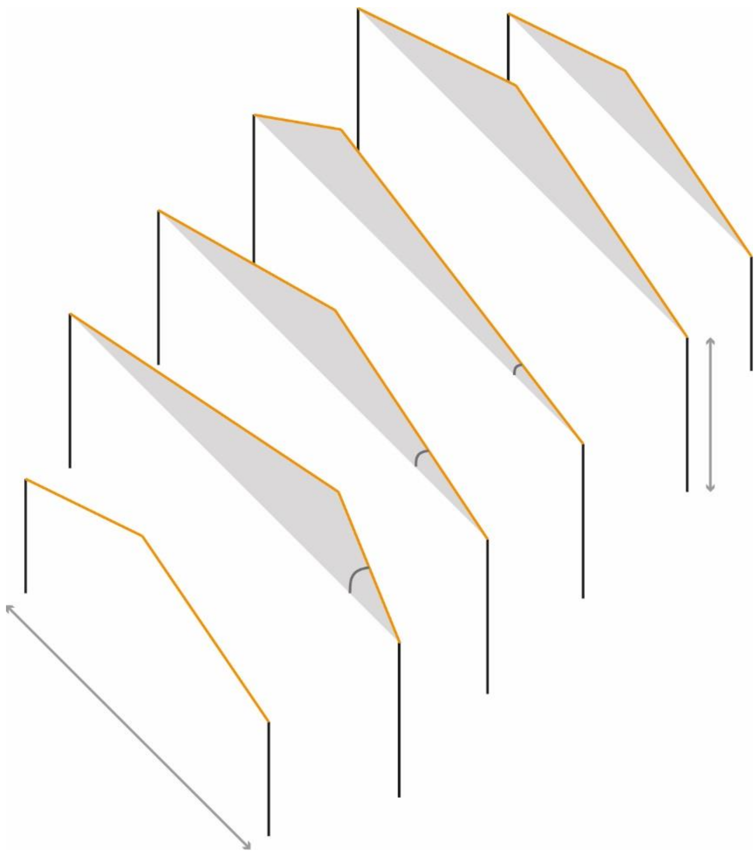


Figure 5.18. Irregularities in span, dimensions and slope angle occur in the steel construction constantly.

Lastly, these portal constructions need to be connected in the perpendicular direction (figure 5.19). This addition to the structure is to improve the structural integrity of the arena. The structure will be able to transfer wind forces in the perpendicular direction of the portal construction across multiple portals. In smaller projects these are often referred to as spacers, and for this design they fulfil the same role, albeit being larger.

One benefit is that the total deformation will become less, as each portal has the capability to transfer these forces to the foundation because of the stability elements explained in figure 5.15. Secondly, deformation between neighbouring portals will decrease, which is important when installations such as lights and facades are attached. Also, it is unacceptable for the deformation between two portal construction to be visible by eye, as that would decrease a sense of security.

As figure 5.19 suggests, these additional elements are different in size, angle of connection and slope. This poses a challenge for the final technical elaboration considering reuse and demountability, as these elements are often unique in geometry. It should be noted that data gained from the parametric model showed that these element (spacers) connections to the trusses are angled only in one direction

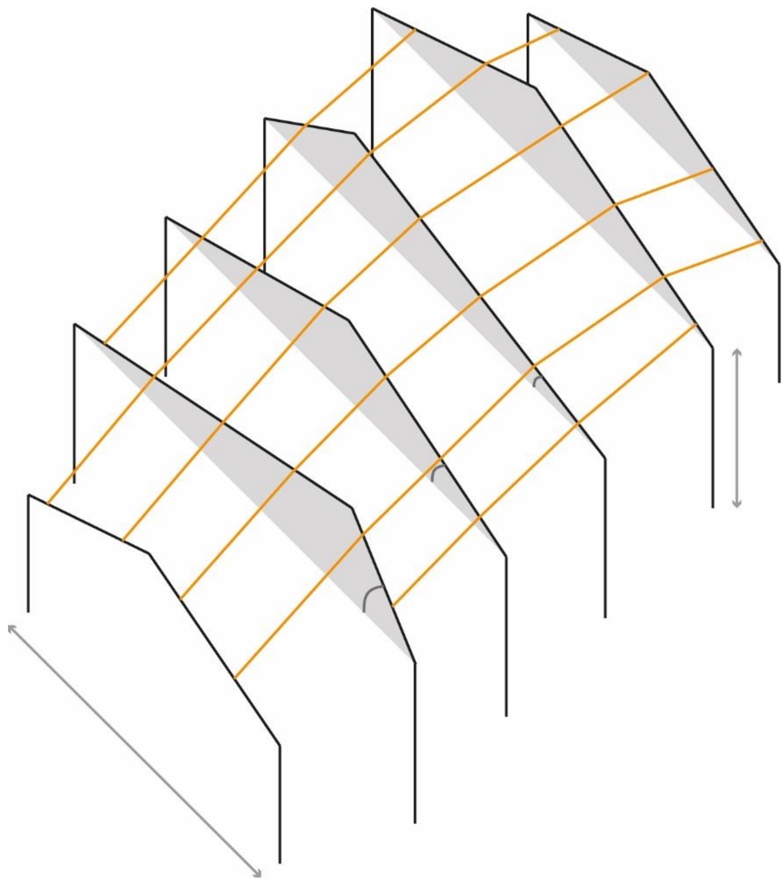


Figure 5.19. Irregularities in length, connection angle and slope are present in the spacers of the construction.

From the information above there can be concluded that there are two main design issues that need special attention regarding the roof structure. First, the portal constructions are irregular in shape while required to be reusable as described in *chapter 5.2.* Secondly, the spacers have a similar complexity because they have a variable length, slope and connection angle.

5.3.4 Column construction

For the column construction there are some different principles at hand compared to the roof structure. Ideally the columns are rectangular in shape and are more similar to each other, with height being the only variable as shown in figure 5.20. This means that although the columns are not loaded similarly or positioned in a grid, roughly the same construction is used. The resulting columns design has many similar members, and therefore is better for reuse.

Observed from up close the column construction is further explained next. The diagonals in the column structure are only loaded in tension, while the vertical members are only loaded in compression, as seen in figure 5.21. This is important when selecting the correct steel profile.

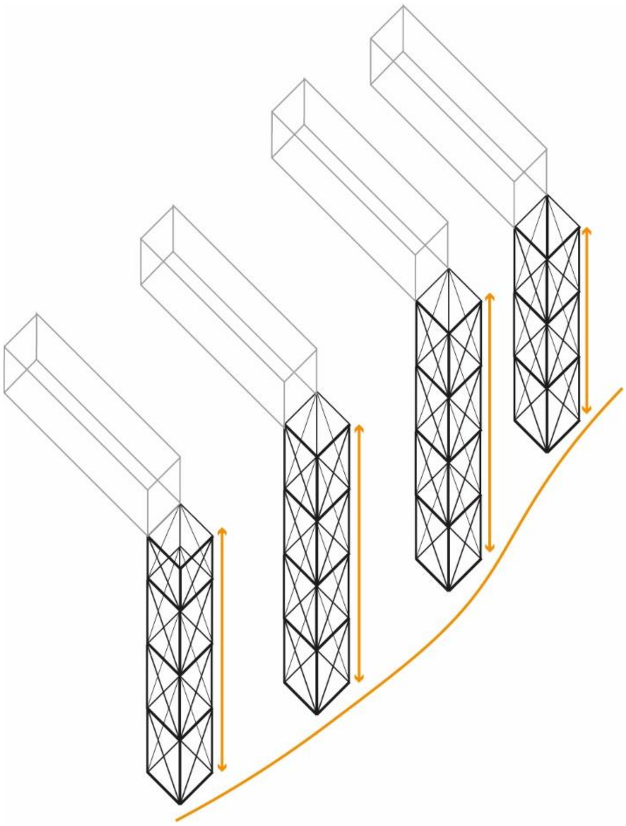


Figure 5.20. Despite the position of the columns not being in a grid and being loaded differently, the only variable between them is height.

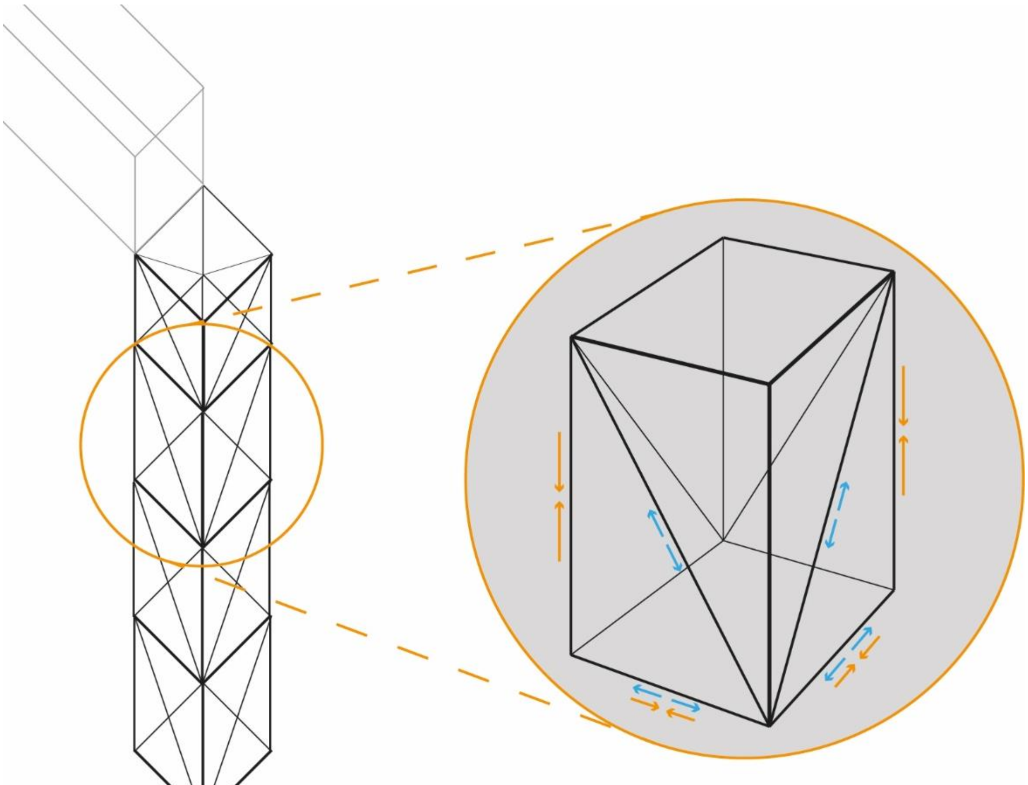


Figure 5.21. In this structure the diagonals are only loaded in tension, while the vertical members are only loaded in compression. Horizontal members can be loaded both ways.

In figure 5.21 it can be seen that the column structure consists mainly of long beams and tension members. These members join in 'nodes' each time, where either 4 or 8 members connect in one location. The main difficulty of this structure is how to solve that node.

As the figures above show, the column structures resemble a much more common steel structure type. Therefore, it can be concluded that there are less design issues found in this part of the structure. Only the connection described above will form a challenge, when considering the most reusable solution.

5.3.5 Façade design

The elaboration of the façade design of this project is restricted for this research in terms of detail and building technology. Because it is stated that the load bearing construction has the most impact on the environment, the effect of a reusable façade is not further explored. The material chosen for the façade will be a membrane of PVC, which is used in circus tents. This material can be stretched along distances of over 20 metres, and is therefore ideal for large temporary structures. Membranes are the most lightweight materials and can be recycled even.

In an ideal case, the membrane would be mounted directly on the load bearing construction, reducing the need for a secondary construction. It is therefore of importance for the design of the load bearing construction to stay as close to the original design.

Effort has been put into a shape the membrane is formed in. The shape follows the repetition of the portal construction of the roof an columns, but with a twist in the façade and the roof. This can be seen in figure 5.21b.

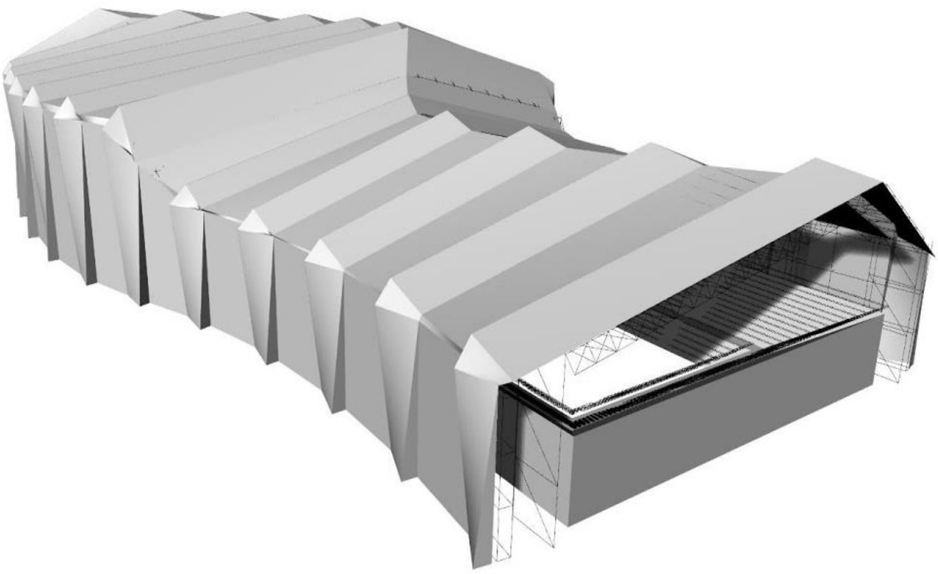


Figure 5.21b. The façade of the arena is a membrane of PVC that wraps around the load bearing construction. It is mostly mounted directly to the load bearing construction.

5.4 Technical elaboration

In this chapter the technical aspects of the design are elaborated and discussed. The main focus of this elaboration is to combine the *demountable* and *reuse* strategies with the design concepts. First, the impact of the demountable requirements is discussed. Then, the roof structure, columns structure and façade design are separately elaborated, with their corresponding technical drawings.

5.4.1 Demountability

One of the requirements stated is for the design to be a demountable structure. This term needs further definition when applied to a design, because demountability is not a measurable term. Similarly, the concept of *design for deconstruction* (DfD) state that '*Elements and components need to be light weight, rapidly assembled & disassembled, and reusable'.* Projects that require a demountable structure individually state the requirements of said demountability, often measured in time to assemble & disassemble. For this design, the six parameters by Güngör (2006) will serve as guidelines to a demountable design. These are:

1 Allowance to non-destructive disassembly
2 Complexity of disassembly motion
3 Tool complexity
4 Reusability
5 Allowance for automated non-destructive disassembly
6 Time to disassemble

Tree connections in the structural design are considered fundamental in the design, which are located in figure 5.22, inside the red circles. C1 and C2 are located in the truss system, while C3 is located in the column section.

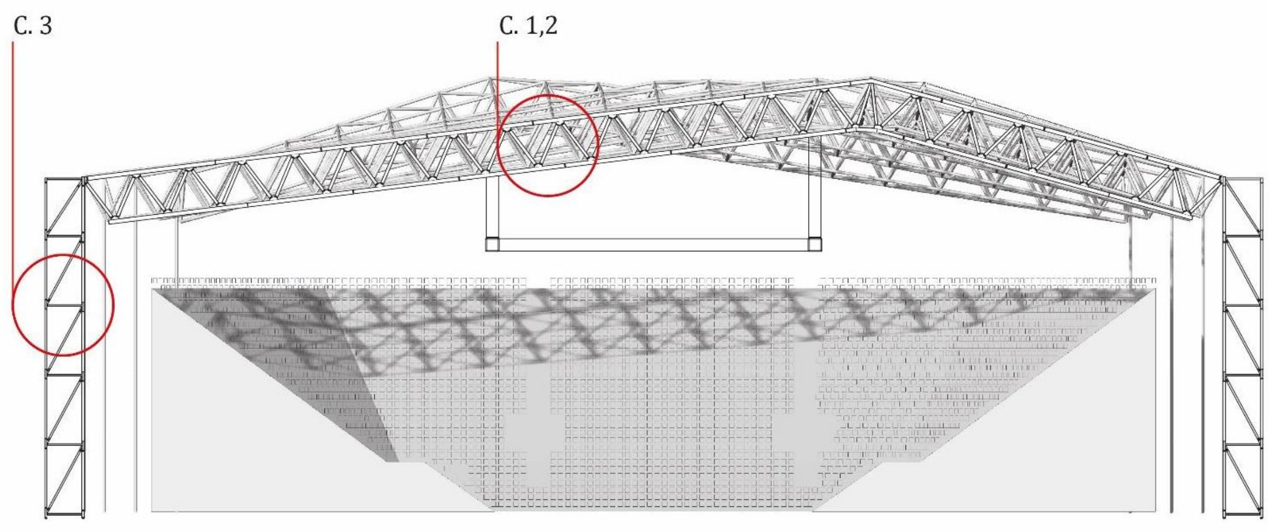


Figure 5.22. Section of the steel construction, marked with three principle connections (schematic).

5.4.1 Roof structure – Connection C1 & C2

Figure 5.23 shows the precise location of connection C1 and Connection C2. Connection C1 is a knot in the structure where several members at different angles, in a combination of flexible end-plate connections and full-plate connections come together. This knot has been carefully designed such that it fulfils the requirements.

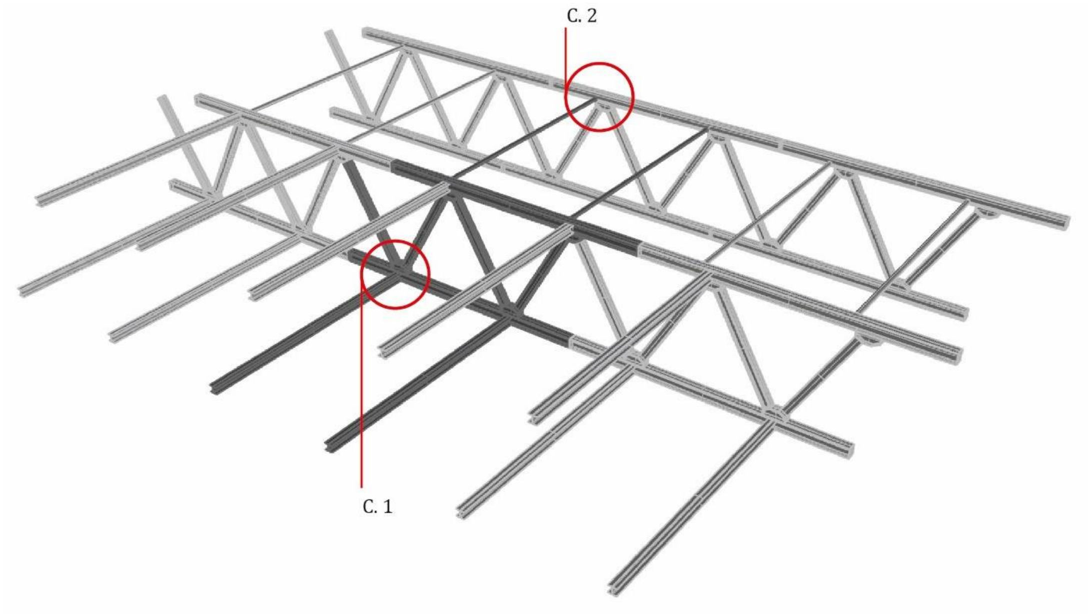


Figure 5.23. The location of connection C1 and C2.

In the parametric design it is shown that a warren truss can be seen as a collection of triangles connected together, with each member having the same length. In the case of the design this length is in the range of 4 to 5 meters. This impacts the reusability of the warren truss in two ways. First it was concluded that if the truss was indeed built with members of the same length it would imply that for each connection six members would meet at each 'node' of the truss (figure 5.24, left). Although multiples of the same length might be positive as stated in the upcycle principle, a length of 4 to 5 meters is not a very common dimension in the built environment.

Also, although the steel members might be fit for reuse, the knots in this approach are most likely not reusable. This is because this approach is not commonly used for steel structures, unless the steel structure is very irregular and every knot is different.

A different approach opposed to the one described above, is to integrate the knot into members such that one member stretches along multiple knots. This is further shown in figure 5.24 (right). This has two consequences considering reuse of the truss, first involves the increased length of some members, secondly integrated connections have the potential to reduce waste material (that can be recycled). It also could influences the demountability of the truss, if there are fewer bolts needed to assemble the truss in.

As stated, a length of 4 to 5 m is not a very common measurement in steel construction. Thus it would benefit the reusability of the truss if that could be increased to a more suitable length. In the design a length has been chosen that is simply a multiple of the length used for the truss members. It means the connection between upper and lower members is constantly at the same location. This is further shown in figure 5.25.

This means that on a larger scale this construction can be repeated to form larger spans as seen in figure 5.25. In theory this can be done in any order, which is advantageous considering the reuse strategy of *relocate & adapt*, because it allows the roof to be constructed in several configuration with mostly the same element.

Additionally for this approach the knots are integrated into the member, further reducing material waste provided that these integrated knots allow for reuse. This is a challenge as the warren truss design has angles of 60 degrees, whereas contemporary architecture consist of more perpendicular angles. This presents an unusual design requirement for further technical elaboration.

Figure 5.24. Two approaches in the assembly of bolted trusses, 1. consists of knots and members of the same length,(left) 2. the upper and lower members are extended across multiple integrated knots. (right)

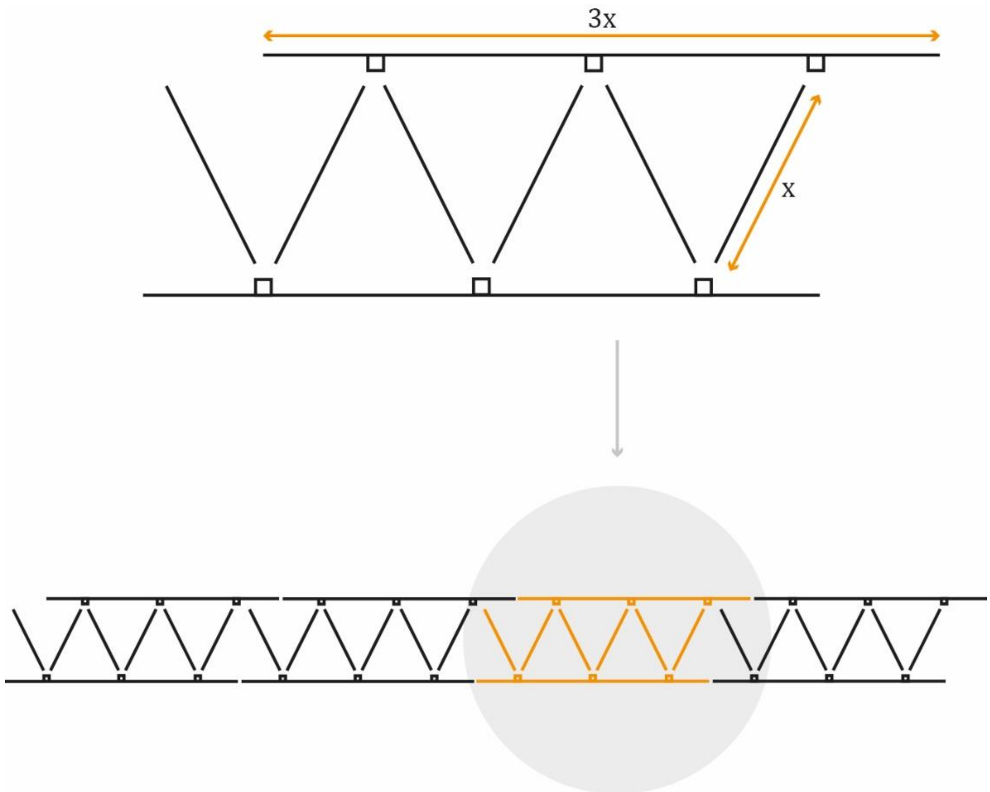


Figure 5.25. In the design the extended upper and lower members are a multiple of the truss length, such that the location of the connection is always the same.

Zooming in further into the elaboration of the technical detail, there are several issues at hand. First of all, the diagonals of the warren truss are connected an angle of 60 degrees, which is uncommon as described above. Secondly the connection method required is dependent on the type of loads involved. Finally the connections need to be bolted, in order to be demountable.

Connecting the diagonals at 60 degrees mainly influences the fourth point of the parameters by Güngör (2006), which is reusability. Because this is a relative uncommon angle in construction, a solution has been found to allow members to be connected at a more common angle of 90 degrees (perpendicular). This is schematically shown in figure 5.26.

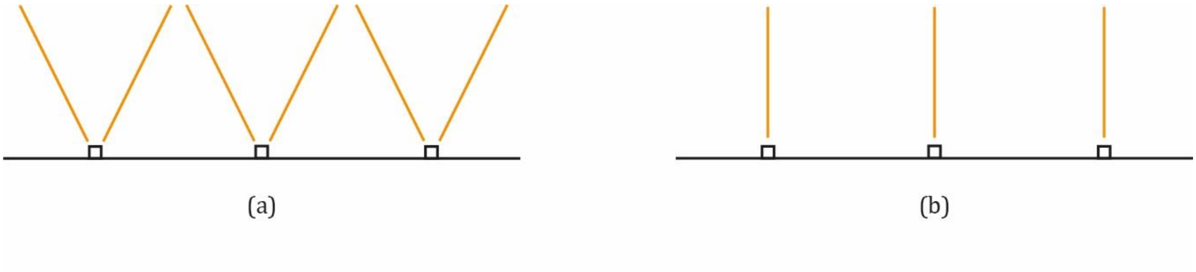


Figure 5.26. The connection that fits the diagonals of the truss to the upper and lower and upper members requires members to be connected at 60 degrees (a) or 90 degrees (b).

This is realized by introducing a connection plate to the continuous upper and lower beams at the location where the diagonals meet. This plate is shaped such that it allows beams to connect as described in figure 5.26. plate has welded flanges on all sides to allow for bolted connections, as shown in figure 5.27. This element can be bolted on straight elements which allows for complete disassembly, or part disassembly. Complete disassembly would allow the connection plate to be assembled elsewhere on a beam/column by drilling only a few holes. In case the connection plate is not required when elements are reused it allows the beam to be reused by the upcycle strategy.

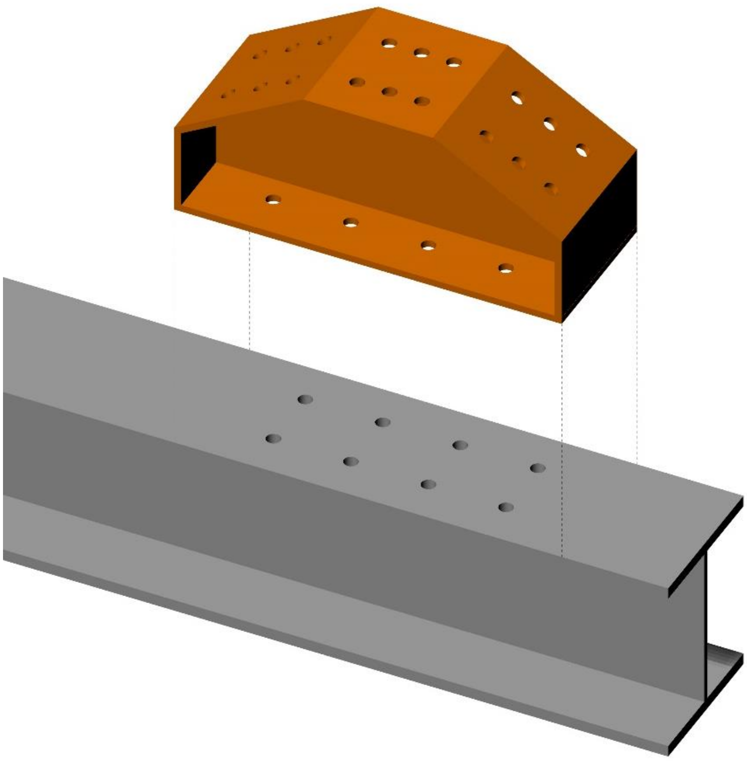


Figure 5.27. A close-up view of the connection plate that allows beams to be connected at 60 degrees of 90 degrees.

Then there is the matter of the connection method from diagonal beams to the connection plate. Information on types of bolted connection referenced in chapter 3.3. As the connection requires to transfer the loads of tension and compression to the upper and lower beams of the truss, it is mainly a matter of surface area, as described in chapter 4.4.3. Because only *full end plate* connections include the full surface area of the profile, these connections are required in the diagonals. Also the upper and lower beam connections require full end plate connections. These connections are not the most common in the steel industry, but can be implemented in many projects with little effort. The final technical drawing can be seen in figure 5.28.

In this drawing a beam is shown that is perpendicular to the upper and lower beams. This is the beam that is responsible for the stability as described in chapter 5.3.3, which is why the connection is perpendicular. Again, this connection needs to be a full plate connection as it transfers tension and compression.

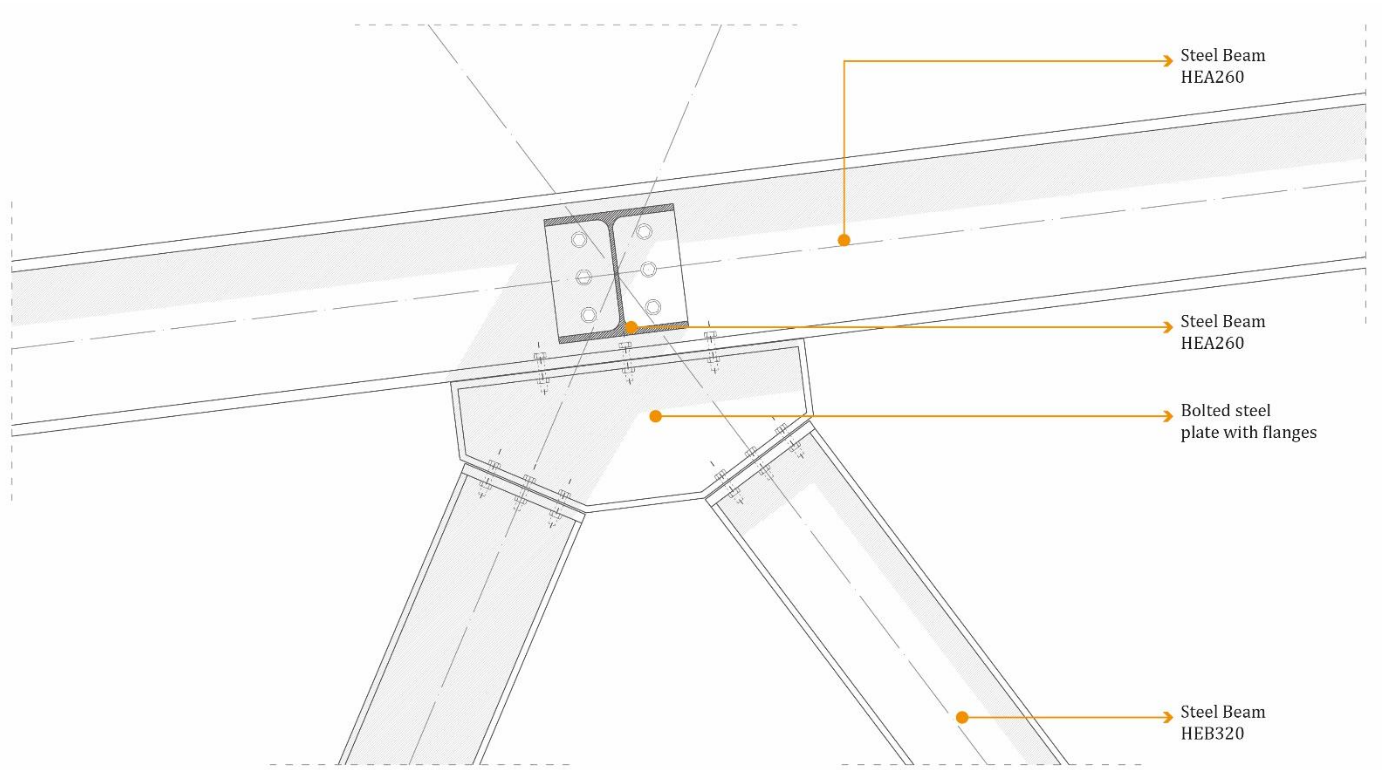


Figure 5.28. Connection C1, a flexible end-plate connection at an angle. (Scale unknown), see appendix for more information

Connection C2 is different, which is the connection between the spacers that connect the trusses. The difficulty of this connection is that is has two variables that change with almost every member. First the angle at which the member is connected changes, and secondly the length of each member is different. Note that the angle that changes only in one plane, seen perpendicular to the direction of the truss (figure 5.29). In the other plane, seen from above, the connection is perpendicular to the beam.

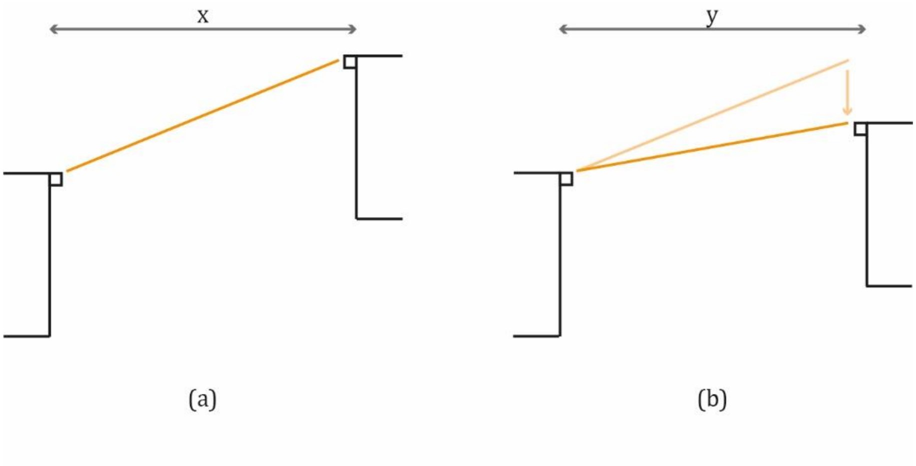


Figure 5.29. The spacers have different angles at almost every connection, but only in one plane.

To solve this connection with some form of standardization the following solution has been chosen. The connection selected is a hinged connection, which can transfer tension and compression similarly to the members above, but can be fitted at every angle. It is common for the members with such a connection and function to have a circular profile, which will be used in this design as well. A visualisation of the connection can be seen in figure 5.30.

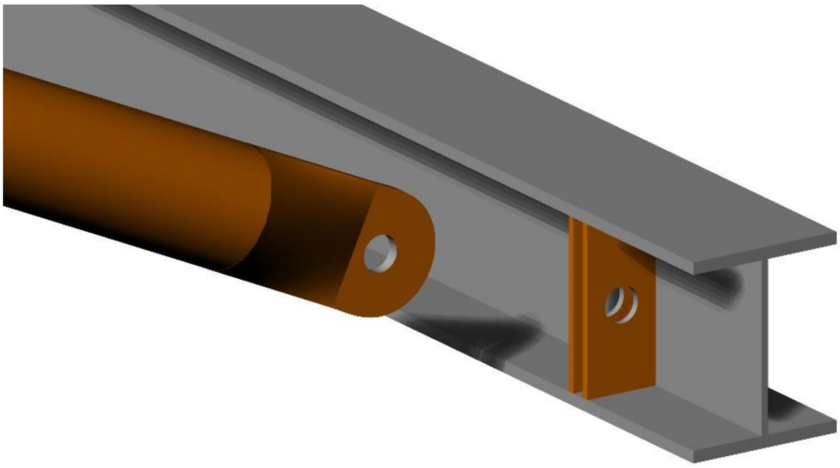


Figure 5.30. A close-up view of the connection of the spacer and the upper beam of the truss. The connection can be connected at every angle.

As seen in figure 5.30 the connection requires welded plates to the beam for the connection to work. Because the implication is a permanent intervention to the beam, the plates are kept within the 'boundary' of the profile. By staying within that boundary the profile is easier to reuse.

5.4.2 Column structure - Connection C3

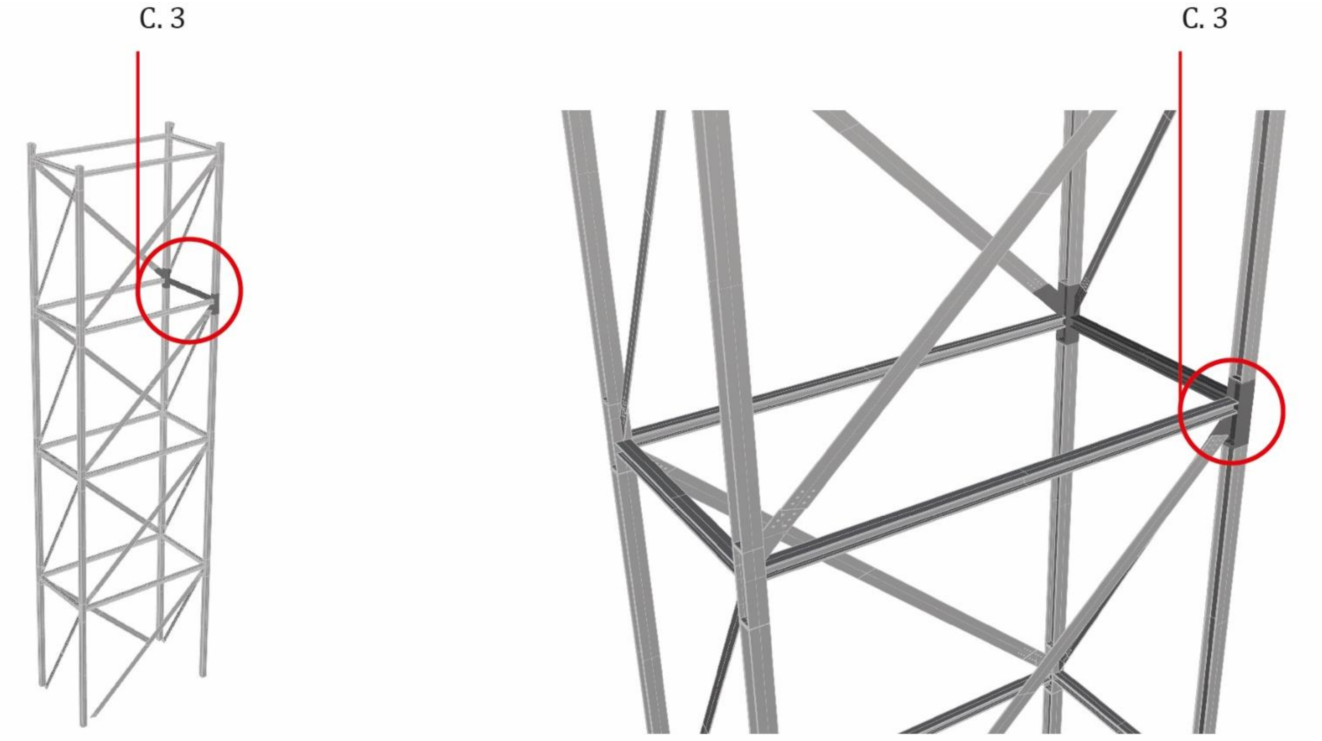


Figure 5.31. The location of Connection C3

The columns of the design are inspired by temporary steel constructions used for large spans, for example those in figure 3.31. These constructions are quite large, which would normally decrease usable floor space for example. For a temporary reusable venue it is an ideal solutions because the individual members are smaller in profile, and longer in length. Both of which increases reusability. As described above, the columns require thickness (3 meters), to allow for tension beams which can take on wind loads.

Connection C3 (figure 5.32) is a connection where many members come together, namely four beams, and two stabilizing steel members. It has been attempted to place all the required welding in the knot of this connection, leaving as many members unscathed. Again, all beams are connection with full end-plate connections. Note that the stability elements in the column are plates instead of beams, as these stability elements are loaded only in tension.

As seen in figure 5.32, all members in this construction can be found amongst the most common steel beams. Also, except the connecting element (in dark grey in figure 5.31) all connections are bolted, which allows for disassembling. In this case the connecting element is likely the only element which cannot be reused.

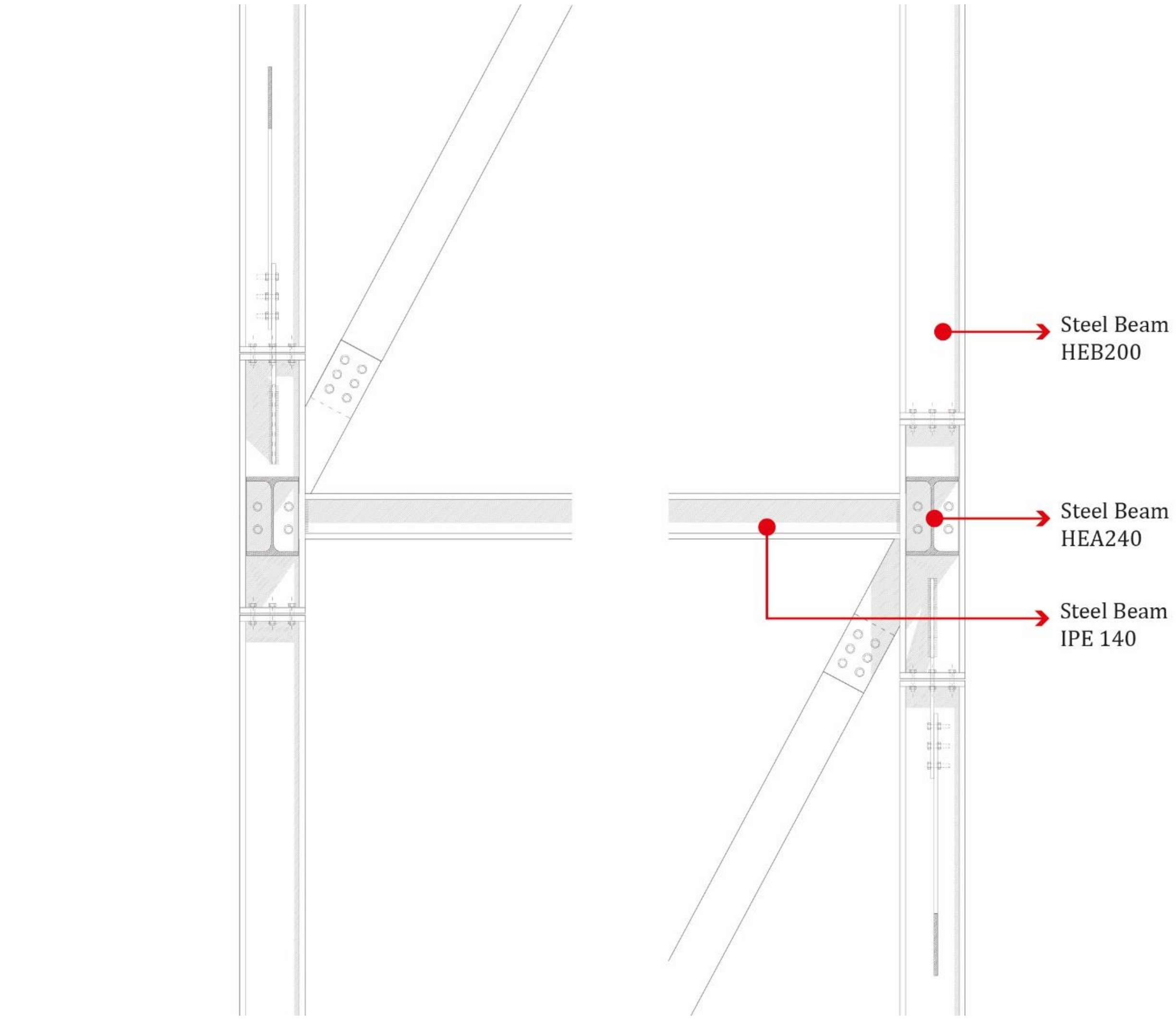


Figure 5.32. Connection C3, many members meet at one knot, it has been attempted to keep all complexity in one element (scale unknown), see appendix for more information

5.5 Parametric model

Following will be a compact explanation of the parametric model that is used in the next chapter: *research by design*. It will consist of a description of what an parametric model means for this research. Then the optimization rules will be explained, accompanied with findings that have been concluded during the computational process. This resulted in two types of design, which will be elaborated on further.

5.5.1 Description

A parametric model (or design) can be described as a process by algorithmic thinking that enables the visualisation of a design, influenced by parameters. Grasshopper is a program that functions as a plug-in for Rhinoceros which uses such a process. For the following *research by design* (chapter 5.6) this program is used to test the technical elaboration and the reuse strategy, along with a visualisation of the design.

Following will be a summary of how this algorithm works. It can be described as two major parts of design. The first part is *computing geometry*, second is a *optimization process*. Computing geometry is relatively straightforward, as it follows the same steps as designing in any digital environment. Which steps have been used in the algorithm will be explained. The optimization process is mainly focussed on adapting the geometry from the *computing geometry* process to change the outcome towards an optimal configuration. Two optimal configurations are aimed for in this algorithm: optimal towards reuse, optimal towards construction.

For a clear description figure 5.33 will support the textual explanation in several steps. Each step in figure 5.33 will be referenced to in the textual explanation by a notation like so (number). The form of the arena design is generated from several input curves. These curves represent a complex shape early in a design process (1). The algorithm starts with a division of that curve that determines the gross placement of the columns, with a parameter that determines the distance between columns, and the height of the columns (2). Then, the columns are paired because it is necessary for the roof construction as described in chapter 5.3.3, with the exact distance between those columns determined by a parameter (3). Then, the column construction as described in chapter 5.3.4 can easily be added, with a parameter determining the depth of the column (4). Then, another input curve is added to determine the roof slope. This curve is projected on horizontal curves between the columns, such that the basis of a portal construction is computed (5). Along those curves warren trusses are added, with the height of that truss controlled by a parameter. This parameter is controlled first by hand, but then checked by structural calculations in the algorithm. This results in different heights of trusses, depending on span of the truss (6). Paired trusses are then connected as described in chapter 5.3.3 (7). Lastly, the spacers in the roof construction are added, while a parameter controls the distance between thee spacers (8).

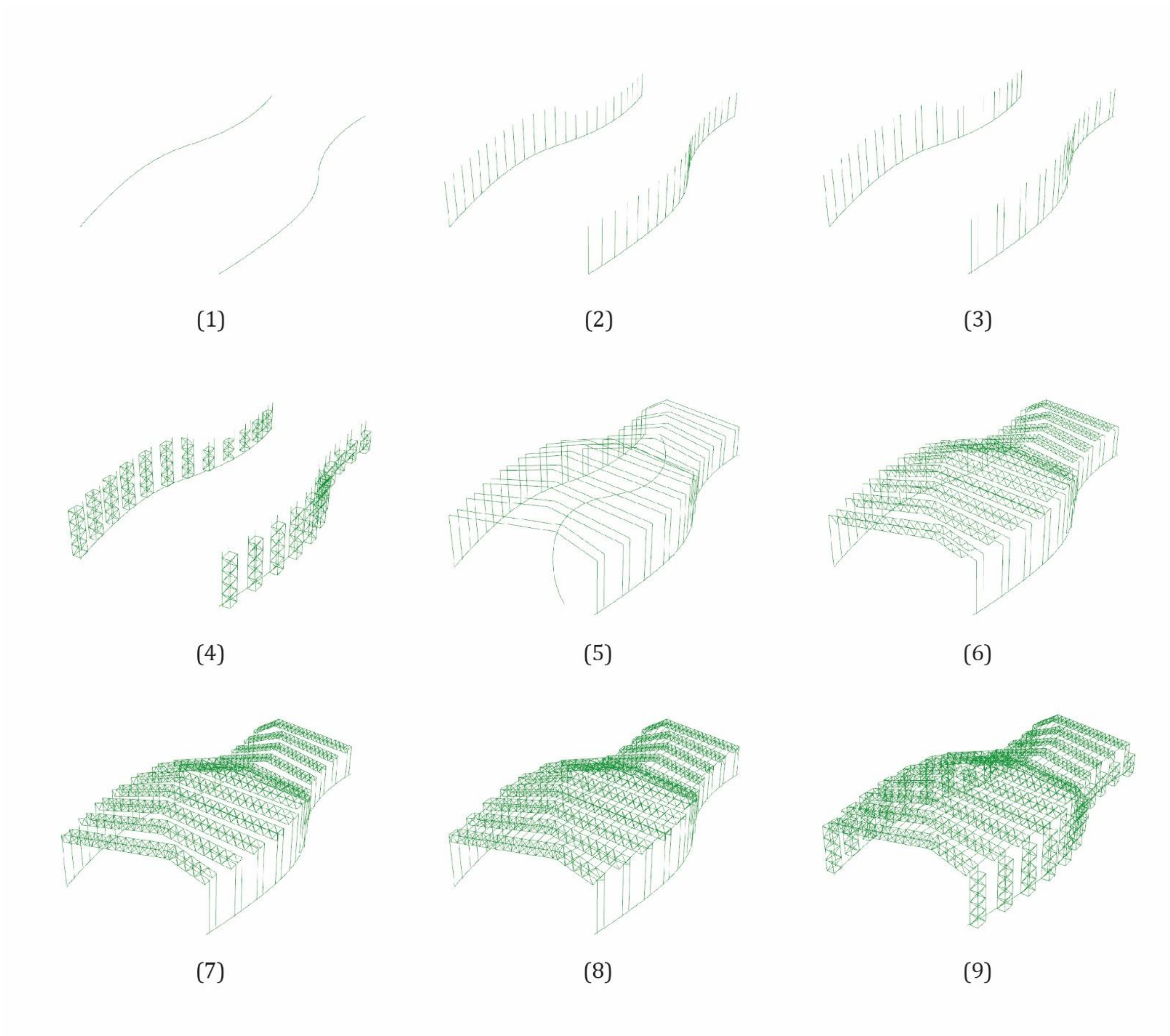


Figure 5.33. An algorithm computes the geometric shape of the construction, determined by several parameters.

The parametric model is limited to dimensions of members of the construction. It does not include any detailed information on connection method, materialization, structural behaviour and other aspects of design. Although that information is not included in the algorithm it can be applied by the comprehensive documentation that the model is able to produce. This documentation consists of categorizations of similar members (for instance all diagonals in the structure). That means that optimization within any of the terms described above (connection, etc.) is not possible within the algorithm.

The second part of the parametric model is aimed to modify the parameters such that an optimal configuration forms. In this model optimization is required towards reuse or structure. Several implementations in the algorithm allow the parameters to be manipulated by calculations or analysis to achieve that goal. It can be found in the following categories: 1

column placement, 2 column height, 3 truss height, 4 column depth, 5 spacers. Each of these categories will be explained.

The reason why optimization towards reuse is chosen is obvious, it is the goal of this research. The design is compared to a design optimized toward structure, which translates to a structure with minimal material use. This optimization is common practise in steel construction, as it is meant to be cost efficient and sustainable because material use is reduced.

The column placement seen at (2) in figure 5.33 is evenly across the input curves. Because it can be derived from chapter 5.3.3 that trusses must be connected as pairs, this is also required for the columns. The distance between two trusses is controlled by a parameter in the algorithm, and can be calculated for each portal construction individually.

The column height is determined by input from parameters which values are determined similar to the curves at stage (1). Again, because trusses are paired the corresponding columns should be of similar height. That means the eventual height of the columns is altered by a parameter controlled by the algorithm.

The truss height is based on input from sources as described in chapter 5.2 when reuse is optimized towards, but can also be influenced by the hand calculations described in 4.4.3 when an optimal construction is required. Both optimizations are represented in the algorithm as a parameter that can be controlled by hand or computed by the algorithm, or a combination of both.

Quite similar to the truss height, the column depth is controlled by a parameter that is again controlled by hand, computed by the algorithm or a combination or both.

5.5.2 Optimization

As described two types of optimization are considered and realized in two different designs. The first design will be optimized towards reusability, the second design towards structural. In the six categories described above this optimization will manifest itself in the design, which will be explained next.

Optimization towards reuse is mainly expressed by standardization of elements in the model. That means the algorithm is geared towards the repetition of reusable members. First, input is gathered as explained in chapter 5.2, which determines values for the parameters. Then in some cases these parameters are altered slightly to prevent weird results in the form of oversized and very inefficient structures.

1. Column placement (reuse optimisation)

As discussed above, the column placement is altered by a parameter. In case of optimization towards reuse this parameter has been selected to stay at the same value for all column pairs. The reasoning behind this was that this would produce many similar members, which is advantageous for the *upcycle* reuse strategy. Furthermore, similar members it would allow interchanging them in the roof structure in different configurations, which is advantageous for the *relocate & adapt* strategy. The placement of the columns is shown in figure 5.34, with the dotted lines representing the column placement before the optimization.

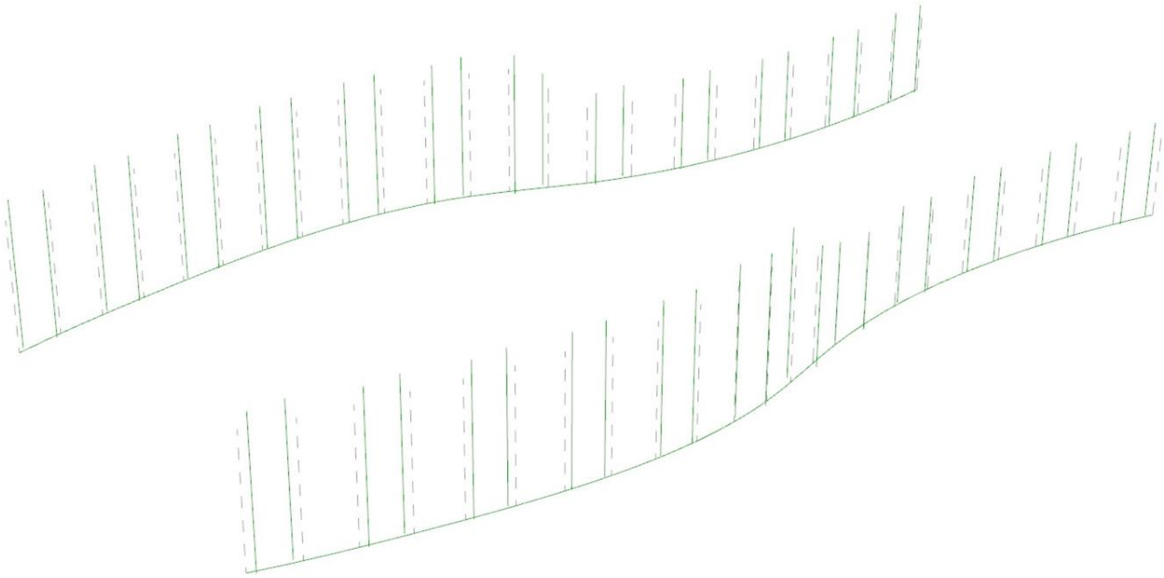


Figure 5.34. Placement of the columns is altered by the algorithm towards standardization.

2. Column height (reuse optimisation)

The column height is altered by a parameter as well. For this instance the purpose is to simplify the roof construction, such that there are fewer angled surfaces. This is achieved by rounding the height of the columns to a multiple of a certain value. In the optimized design towards reuse this value is set to 3 meter, which allows for a homogeneous roof line where it meets the façade. Notice that the shape of the arena is compromised as seen in figure 5.35.

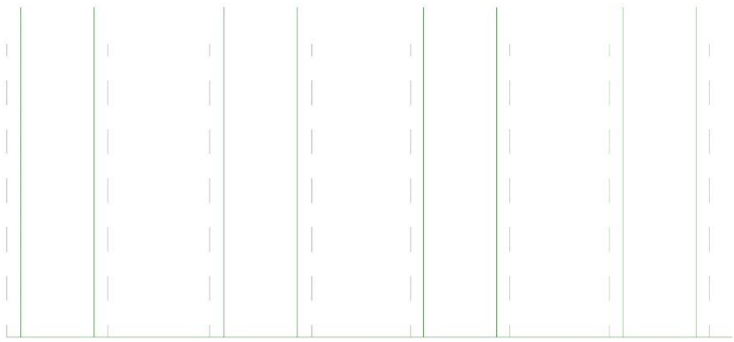


Figure 5.35. height of the columns is altered by the algorithm towards standardization

3. Truss height (reuse optimisation)

Similarly to the column placement a parameter controls the height of the truss, in combination with manual input. In case of the design optimized towards reuse first a value is selected that is reusable according to the *transform to other building format* strategy. This value is 4,2 meters, which allows for reuse in both high rise construction and portal construction. This value is verified with the hand calculations from chapter 4.4.3.

Then, another form of optimization is introduced. The span of the portal constructions are not similar throughout the arena, and would therefore not require the same height everywhere from a structural point of view. This means more material is used than required, especially considering the roof structure forms the largest part of the material (table 5.1). Therefore the parameter controlling the height of the trusses is dependent on span as well. This means that a calculation in the algorithm decides whether the height of a truss can be lower than the input parameter of 4,2 meters. This is the case for about three quarters of the trusses.

The amount of variance is controlled by yet another parameter. This parameter decides on the number of different heights there are allowed. For example, the algorithm allows for a variable truss height to reduce the material use, but it restricts the amount of variance by only two different heights. This results in a compromise between reusability and material reduction. In figure 5.36 the implication on the design can be found.

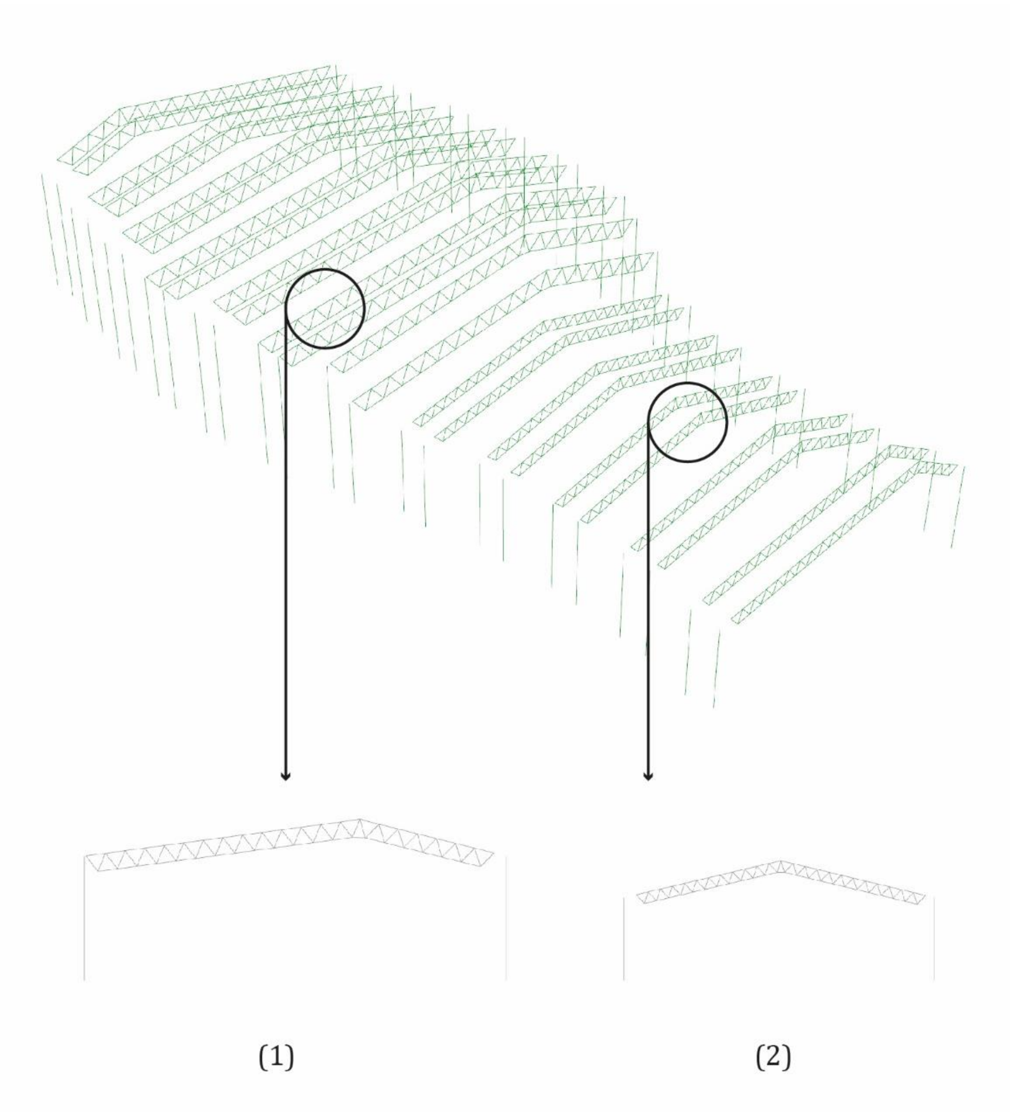


Figure 5.36. Height of the trusses is altered by the algorithm towards standardization, in combination with material reduction. In this configuration two heights of trusses (1 & 2) are represented.

4. Column depth (reuse optimisation)

The column depth uses the same parameter as the truss height construction, meaning that the depth of the column is proportional to the truss height. Admittedly, this is an oversimplification of the column construction, as there are more factors that influence the column depth, for example column height. For the purpose of the research the fact that there is a variable depth that can be controlled by a parameter is usable. This is shown in figure 5.37.

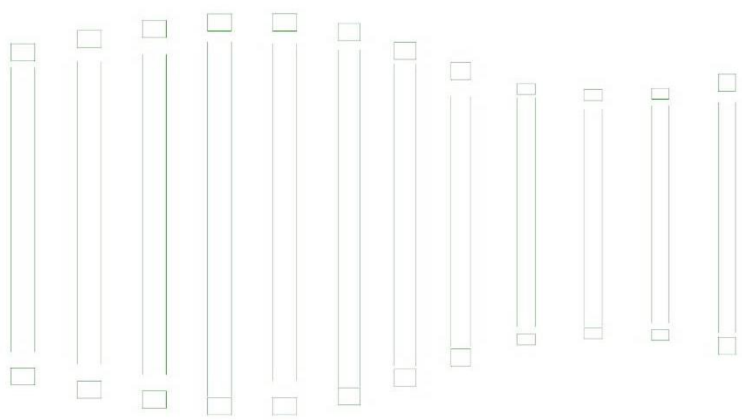


Figure 5.37. Depth of the columns is altered by the algorithm towards standardization, in combination with material reduction. In this configuration two depths of columns are represented.

1. Column placement (structural optimisation)

In case of optimization towards construction the value of the parameter that controls the distance between a pair of columns is proportional to the span of the truss. Similarly to the truss height, the variance is restricted. In this design 5 different distances are allowed, and all distances are rounded towards decimetres. This results in the rearrangement seen in figure 5.38.

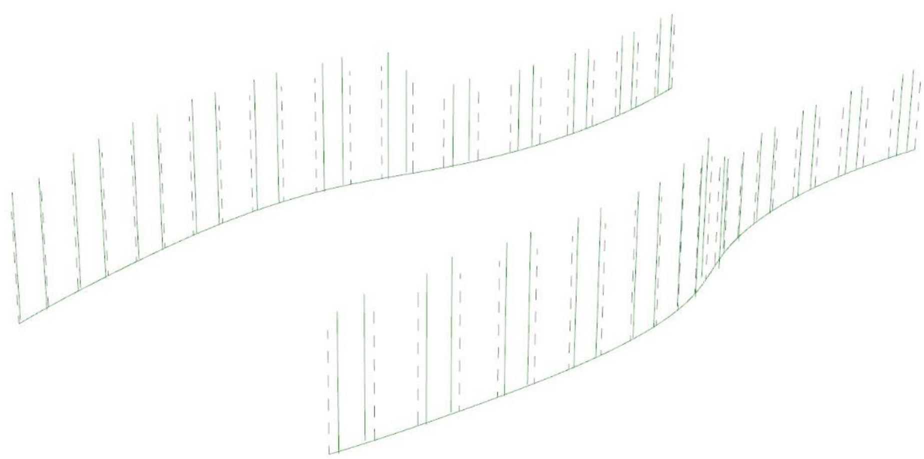


Figure 5.38. Placement of the columns is altered by the algorithm towards standardization.

2. Column height (structural optimisation)

Compared to the reuse optimization design, a similar approach was applied to the column height. Instead of having the columns in a multiple of 3 meters, this parameter was restricted to 1 meter instead. The expected result was a more curved roof line. In reality, this change turned out to be much less dramatic, as none of the column lengths changed compared to the reuse optimization design. The reason was that the input curve controlling the column height was too shallow to invoke a difference, meaning the input curve doesn't vary in height for more than 1 meter.

3. Truss height (structural optimisation)

In case of the truss heights, the parameter that controls the height is much less restricted when the design requires for optimization towards structure. This represents an engineer calculating the required height of each portal construction to minimalize the required material. For this design the maximum amount of different truss heights was set to 8, instead of 2. Again, the starting value of the truss height is 4,2 meters. In figure 5.39 the results are shown, in the end 5 different heights were required according to the algorithm.

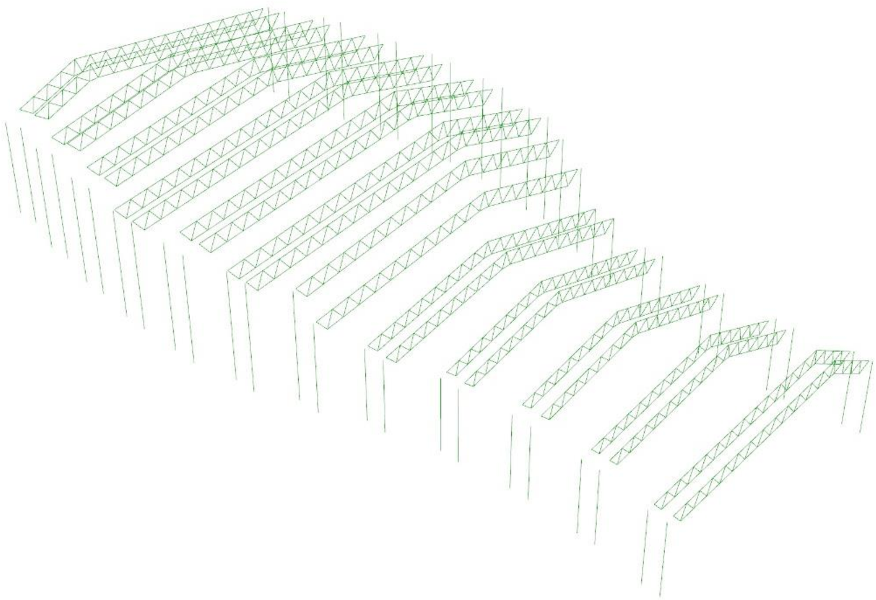


Figure 5.39. height of the trusses is altered by the algorithm towards minimal material use. In this configuration five heights of trusses are represented.

4. Column depth (structural optimisation)

Similarly to the optimal reuse design the column depths are proportional to the portal span, which means there are also 5 different depths present in the optimal structural design.

5.5.3 Results

In the following chapter the results of the two designs are presented in an overview. This overview primarily contains all geometry of the steel construction, with the lengths of the individual members. They are categorized by type of member, such that connections, function and profile are similar.

In two tables, one for each design, the geometry is represented as follows. First, there are seven categories of types of members: *1. Truss diagonals, 2. Truss upper & lower, 3. Roof spacers, 4. Truss pair connectors 5. Column verticals, 6. Column Horizontals, 7. Column Diagonals.* The second column will show the combined length of those members, followed by the percentage of what that number represents in the total structure. Then in the fourth column the number of different lengths are shown.

The number of different member lengths is not a conclusive value without the corresponding amount of that member length. That is why below the tables multiple graphs are shown which contain information of each member length with the corresponding amount of that member.

Reuse optimized	Combined length of members (m)	Ratio of total length	Number of different members
Truss Diagonals	3787	0.175 (17.5%)	5
Truss upper & lower	3698	0.170 (17,0%)	19
Roof spacers	1906	0.088 (8,8%)	26
Truss pair connectors	6045	0.279 (27,9%)	11
Column verticals	1866	0.086 (8,6%)	3
Column Horizontals	1933	0.089 (8,9%)	2
Column diagonals	2434	0.112 (11,2%)	5
Total	**21672**	-	-

Structurally optimized	Combined length of members (m)	Ratio of total length	Number of different members
Truss Diagonals	3443	0.172 (17,2%)	9
Truss upper & lower	3698	0.184 (18,4%)	20
Roof spacers	1835	0.092 (9,2%)	28
Truss pair connectors	5056	0.252 (25,%)	22
Column verticals	1844	0.092 (9,2%)	5
Column Horizontals	1735	0.087 (8,7%)	9
Column diagonals	2135	0.107 (10,7%)	16
Total	**19748**	-	-

Table 5.1. An overview of members from several categories documented from two optimized designed, one towards reuse, the other towards minimal material use (structural optimisation).

In the parametric model two types of geometry are computed, which is done in two steps. Both use the input curves as guides at the start of the geometry generation. The first type is optimized towards construction, which translates to minimal material use, while the second type is optimized towards reuse.

With input data from the hand calculations the first type of geometry is in shape very close to the original input curves. This leads to relatively many differently shaped members in the design optimized towards structure, compared to the second type of geometry.

The other type of geometry is computed in the second step, altering the first type of geometry by input data gained by the reuse strategy research. On two scales alterations are made. On a larger scale such that dimensions are rounded towards a multiple of a reusable measurement, for example the columns which are rounded to a multiple of 3 metres. On a smaller scale alterations are made on the dimensions of individual members such that they match in length to each other. For instance, the truss height variations due to differences in spans are restricted to two different heights. This results in two categories of lengths in which the individual diagonal members fit into.

By using this algorithm it has become possible to document the members from a complex and large steel structure quickly, optionally during the early stages of a design process. Data on the dimensions of individual members makes it possible to conduct a research that compares different iterations of the design, such as the two examples described above.

From the data in table 5.1 it can be concluded that the geometry optimized towards construction uses 8,9% less material (in length). As expected the material use is less, although the difference might be considered large. A decrease in material use influences cost, building time and manufacturing time in almost the same ratio because the design is made up almost entirely of the steel construction.

However, the geometry optimized towards reuse has less different members and less unique members, which will influence the reusability as described by the reuse strategies.

The data describes how many similar members a design uses, and how many unique solutions are needed. It is also possible to distribute members in categories of similar physical properties. This is useful considering reuse

5.6 Research by design

The following chapter contains a research by design, with information gained from the parametric model. This research has the purpose of being a first step towards optimization towards a better reusable steel structure. Meaning, what design implications regarding structure and form will result in a more reusable design.

For three reuse strategies (relocate, transform & upcycle) boundary conditions and parameters are set to determine what structure is better reusable. For the fourth strategy (recycle), it is decided not to include this strategy in the research. The reason for this is that the boundaries for recycling are difficult to translate into the parametric model, which would require more time.

In each chapter, two designs described in chapter 5.5 will be used in the research. Parameters as described in each of the strategies will allow for a comparison

5.6.1 Relocate & adapt

Adapting the design of the arena whilst reusing parts of the previous steel structure would be more sustainable then using new material. It is the goal to document what parts of the original steel structure can potentially be reused when it is adapted. Secondly two designs are compared, namely a design optimized towards reuse, and one optimized towards structural.

First, a catalogue of the two optimized designs is documented. It is comprised of information on all individual members of the load bearing structure: length and number. Then, a similar catalogue of the adapted designs is documented. These can then be cross referenced to determine which members are similar, and to what extent. Not only the number of members is important if the carbon footprint is considered. The length is also an influential factor, as these contain more material. Therefore, the length of these members are multiplied by the number of that member.

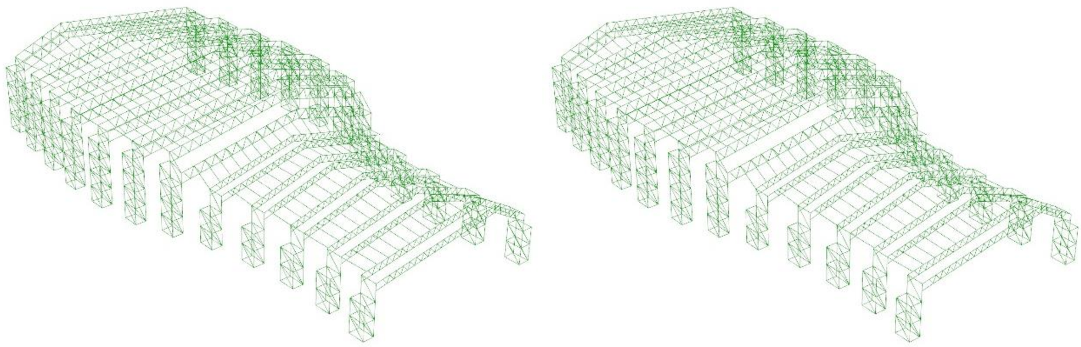
Simultaneously, data regarding the type of member is documented, for example whether it is a tension member in a column or diagonal part of the truss. This is important because these members do not have the profile and therefore cannot be exchanged when adapting the design. This data is shown below in several tables. Each table contains data on a different parts of the structure, ordered by type (and therefore profile).

Four parameters are measured in these tables. The first parameter is the combined length of all members in that part of the design that are reused in the adapted design. This value is compared to the initial amount of steel, which can be written as a percentage as the second parameter. Third the combined length of the adapted design is shown. Again, this value is compared to the combined amount of reused elements, expressed in a percentage as the fourth parameter. This value shows what percentage of the adapted design is made up of reused elements.

Three implications (adaptations) are considered for the steel structure. This is what the design is formed into after the initial use. First, a flat roof is implemented instead of the current double curved roof. It is predicted that relatively much of the initial roof structure can be reused, due to the similar scale of the total design.

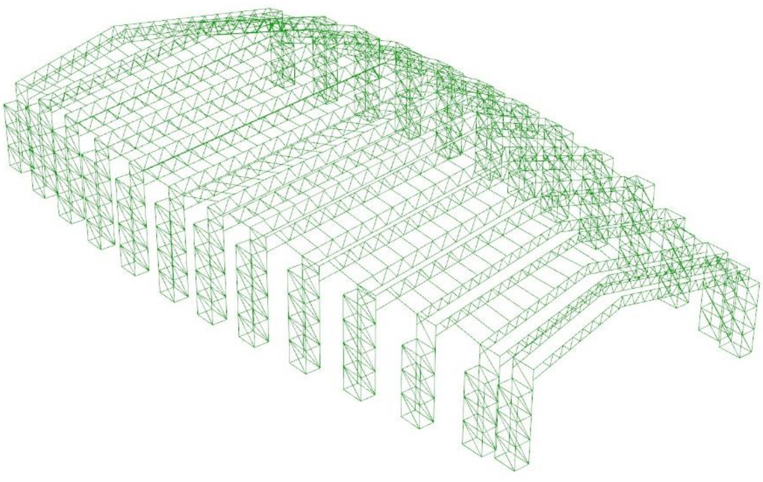
The second adaptation is a reduction in volume and capacity. Note that this is not the adaptation where the initial design is simply split in two separate volumes (as seen in figure 5.5b, 1&2). The initial design lends itself very well for such an adaptation, but it is deemed not very insightful for this research. That is because the results are very predictable, and the arena is not actually adapted, but rather relocated partly. It is therefore important to mention the possibility elsewhere, but it is not really necessary to add this design implications to the research. The actual reduction of volume brings the capacity of visitors back to 6.500 spectators. It is predicted that little of the initial structure is reused.

The third adaptation has a different input curves, as explained in figure 5.4, which changes the signature form of the arena. This influences the slope of the trusses, which in turn changes the members at the connection with the columns and at the kinks.

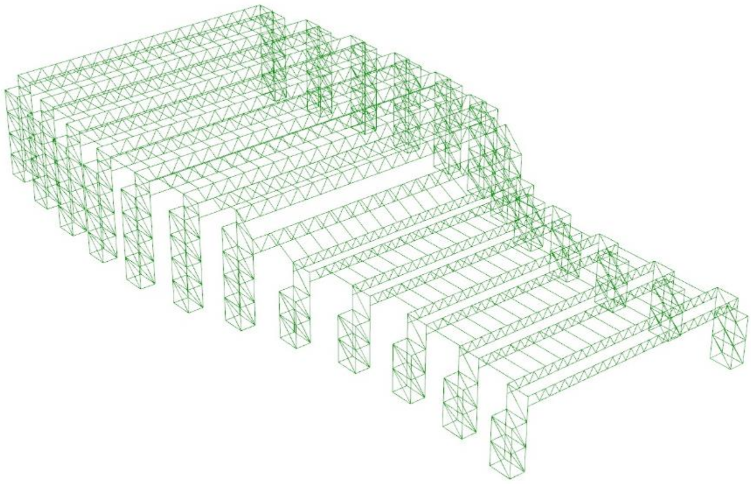


(1) **(2)**

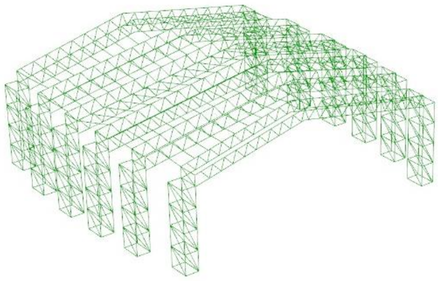
Figure 5.40. Two designs optimized to either reuse (1) or construction (2).



(1)



(2)



(3)

Figure 5.41. Three adapted designs used to research the reuse of construction when the initial design is changed. altered shape (1), flat roof (2), reduced volume (3).

Below the results of the research can be found.

Trusses (diagonals)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	3467 (all)	-	-	-
1 Flat roof	3419	99%	3419	100%
2 Reduced	1651	47%	1939	85%
3 Altered crv. 1	2608	75%	4274	61%

Trusses (upper & lower members)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	3698 (all)	-	-	-
1 Flat roof	3238	87,5%	3605	89,8%
2 Reduced	1765	47%	1995	88%
3 Altered crv. 1	3468	93%	4553	76%
Trusses (spacers)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	1906 (all)	-	-	-
1 Flat roof	1353	70,9%	1865	72,5%
2 Reduced	181	9,5%	901	20%
3 Altered crv. 1	808	42%	2226	36%
Trusses (pair connector)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	6037 (all)	-	-	-
1 Flat roof	4555	75,5%	4854	93,8%
2 Reduced	1363	22,6%	2894	47,1%
3 Altered crv. 1	1721	28,5%	6833	25,2%
Columns (vertical)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	1866 (all)	-	-	-
1 Flat roof	1866	100%	1866	100%
2 Reduced	1137	61%	1137	100%
3 Altered crv. 1	1856	99%	2297	80%
Columns (horizontal members)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	1933 (all)	-	-	-
1 Flat roof	1933	100%	1933	100%
2 Reduced	1171	60,5%	1171	100%
3 Altered crv. 1	1933	100%	2368	81%
Columns (diagonals)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	2434 (all)	-	-	-
1 Flat roof	2434	100%	2434	100%
2 Reduced	777	62%	777	100%
3 Altered crv. 1	2434	100%	3054	79%

Table 5.2. An overview of several categories of the construction optimized towards reuse, where three adaptations are plotted against the reused members.

Trusses (diagonals)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	3443 (all)	-	-	-
1 Flat roof	1671	48,5%	3419	48,9%
2 Reduced	1335	28,8%	1939	68,8%
3 Altered crv. 1	2243	65,1%	4274	52,5%
Trusses (upper & lower)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	3698 (all)	-	-	-
1 Flat roof	3238	87,6%	3605	89,8%
2 Reduced	1727	46,7%	1995	86,6%
3 Altered crv. 1	3468	93,8%	4553	76,2%
Trusses (spacers)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	1835(all)	-	-	-
1 Flat roof	892	48,6%	1865	47,8%
2 Reduced	209	11,4%	901	23,2%
3 Altered crv. 1	509	27,7%	2226	22,9%
Trusses (pair connector)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	5056(all)	-	-	-
1 Flat roof	1758	34,8%	4854	36,2%
2 Reduced	1995	40,0%	2894	68,9%
3 Altered crv. 1	2307	45,6%	6833	33,8%
Columns (vertical)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	1734 (all)	-	-	-
1 Flat roof	571	32,9%	1866	30,6%
2 Reduced	1137	65,6%	1137	100%
3 Altered crv. 1	639	36,9%	2297	56,2%
Columns (horizontal members)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	1844 (all)	-	-	-
1 Flat roof	1228	66,6%	1933	63,5%
2 Reduced	1171	63,5%	1171	100%
3 Altered crv. 1	1505	81,6%	2368	63,6%
Columns (diagonals)	Combined length of reused members (m)	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	2135 (all)	-	-	-
1 Flat roof	886	41,5%	2434	36,4%
2 Reduced	874	40,9%	1506	58,0%
3 Altered crv. 1	1344	63,0%	3054	44,1%

Table 5.3. An overview of several categories of the construction optimized towards construction, where three adaptations are plotted against the reused members.

The tables were shown above have been combined in two tables below.

Combined (reuse optimized)	Combined length of reused members	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case reuse optimization	21672 (all)	-	-	-
1 Flat roof	18805	**86,8%**	19979	**94,1%**
2 Reduced	8776	**40,2%**	11544	**76,0%**
3 Altered crv. 1	14834	**68,4%**	25606	**57,9%**

Combined (Structural Optimized)	Combined length of reused members	Percentage reused from initial design	Combined length of adaptation	Percentage of reused material in adaptation
Case structural optimization	19748 (all)	-	-	-
1 Flat roof	10244	**51,9%**	19979	**51,3%**
2 Reduced	8448	**42,8%**	11544	**73,2%**
3 Altered crv. 1	11506	**58,2%**	25606	**44,9%**

Tables 5.4 a & b. An combined overview of tables 5.2 and 5.3.

From the combined tables it can be seen that the amount of reused members is larger from the design optimized towards reuse as expected. The biggest difference can be found in the adaptation to flat roof, where the design optimized to *reuse* reuses 34,9% more steel. This can be explained because the designs are very similar.

Note that although the amount of reused members of the reduced design is larger with the *reuse* design, in percentage it performs actually worse than a structurally optimized design. This is caused by two things. First of all, with a reduction in size of the steel construction there are relative more coincidental matches of members between the two designs because there is a large pool to choose from so to speak. Secondly, the structurally optimised design has fewer members, which explains why there is difference in percentage.

What can be seen from the data is that the elements that make up the trusses are the most reusable categories (diagonals and upper and lower members). This is also where most optimization takes place in the parametric design, confirming that it works as expected.

The least reusable elements in the design are the spacers in the roof construction. Much variation was allowed in this category of the parametric model so this was to be expected. Also, this category makes up the second smallest amount of combined length in the design, which is in hindsight an unexpected positive effect. By allowing variety and unique elements in the least represented category of the design the amount of members unfit for reuse are further reduced.

It can be concluded that the changes made by the algorithm increases the reusability when relocation and adaptation is considered. It depends of what kind of adaptation is selected to what end the *design optimized towards reuse* performs better. An adaptation that is relatively small such as a change to the roof results in large improvement in reused members. This effect becomes smaller when the adaptation becomes larger.

When the scale of the adaptation is changed there is another effect that gains influence to the amount of reused members. When there is a large difference of total number of members in either databases there is an increased chance that matches between members are found by coincidence.

This can be interpreted as such that the optimized design towards reuse has the most effect on a sustainable design when the adaptation is very similar to the original. In other cases, where adaptations are very different from the original, optimization towards material use might prove to be more sustainable. Considering that material use is increased when optimized towards reuse.

5.6.2 Transform

The second part of this research by design focuses on the reuse strategy '*transform into other building formats*'. As described in more detail in chapter x, this strategy involves getting information from other building types. One type has been researched, namely steel portal construction. This construction type has been selected because it can be quantified into floor space easily. A reference to what such constructions look like can be found in figure 5.6.

Similarly as the previous chapter, a catalogue of parts of the two optimized configurations is used. The documentation includes a separation of different member types (tension member, diagonal, column, etc.), the length of individual members and the amount of those members.

Less parameters are used in this part of the research. First there is the combined length of all members, then the combined length of reused members and followed by a percentage of reused members. As a fourth parameters the floor space of the building types is shown.

Transform to portal construction	Combined length of members (m)	Combined length of reused members (m)	Ratio of total length	Combined floor space in transformation
Case reuse optimization	21672 (all)	7080	33,0%	20030 m^2
Case structural optimization	19748 (all)	5468	27,7%	13350 m^2

Table 5.5. Two optimized designs transformed into as many portal construction as possible, expressed in maximum floor space.

Based on this information it becomes clear that there is a difference in the amount of floor space between the two optimized designs. An increase of 33,3% in floor space can be found by transforming the *reuse design* opposed to the *structural design*. In terms of reused members there is only a difference of 5,2% in favour of the reuse design.

First of all, it is clear that this research does not comprise of enough data to conclude any hard statements. In hindsight this part of the research was much harder to realize, as it involves many more parameters that need to be translated in the parametric environment. In other words, in the time span of this research it was not possible to research any other building format, or any variants within the building formats.

It is best explained by the following observation. From the data gained in the parametric environment it became clear every design iteration (optimized to either reuse or construction) had different lengths of members in which they have a large amount of. However in the strategy *transform* a few dimensions were chosen to be 'very common', disregarding dimensions that are very close to it. This meant that it would not be fair to compare iterations, as some would excel at certain building types because they fell exactly into that category. In reality, this is not an exact value as there is often room for deviations.

Incorporating such allowed deviations proved to be too difficult for this research, which is why the research stayed relatively small. That way more time could spent on the other two strategies *relocate* and *upcycling.*

5.6.3 Upcycle

The third and last part of this research by design is focussed on the reuse strategy '*upcycle'*, as described in chapter x. When neither of the strategies in the previous chapter are realized, upcycling would be the final step before recycling. Importantly, to upcycle members from the initial design there is a likely chance that these members require alterations first. Which members require what alterations is researched and described below.

The goal is to determine what part of the members are likely to be upcycled, and what is required to bring them up to that stage. Then the results between the initial design and the 'standard' design can be compared.

Again the database of members of the initial design is used, described above. This time however, the parameters are much different. The ability to upcycle has been described in chapter x, and focuses mainly on connection method and profile. Added to that is the amount of similar members, which positively affects the reusability. Additionally, required alterations influence the ability to upcycle. Those four parameters are used in the following part of the research: *connection, amount, profile & alterations*.

These parameters are rated by the likelihood of the type of member being upcycled as follows:

1 Highly unlikely	(1)
2 Unlikely	(2)
3 Neutral	(3)
4 Likely	(4)
5 Highly Likely	(5)

These scores are then multiplied by the combined length of that member. This is necessary because a more numerous member has a larger effect on the total ability to upcycle than a lesser numerous member. The average scores are retrieved to form a combined score for each category.

The manifestation of a rating will be shortly explained below for each parameter. Starting with connection. Whether a connection is likely to be reused depends on the complexity of the connection and whether its appliance is widespread practise in steel construction. A very common connection would be rated with 'highly likely', while a unique connection would be rated highly unlikely.

The parameter '*amount*' is based on the number of similar members that small steel structures require. For instance the number of roof spacers in the average supermarket would be around 50 members, with a floor space of roughly 1250m^2. If the number of similar members is less than this number, it is rated unlikely or very unlikely, if the number of members exceed this number it will be rated likely or very likely.

The parameter 'profile' is rated by studying the information gained in chapter 5.2.2. regarding common profiles These tables consider either steel portal constructions, or steel columns for high rises. For all members except the vertical column members the first table will be used, for the vertical column members the latter table will be used. Within the first table a rating system is already present, which will be used. In case of the vertical column members they will be rated likely to be reused, if they are present on the table. The parameter 'alterations' is rated according to the description given in chapter 5.2.3.

Each type of member is classified in one of the following seven categories*: 1. Truss diagonals, 2. Truss upper & lower, 3. Roof spacers,* 4. Truss pair connectors *5. Column verticals, 6. Column Horizontals, 7. Column Diagonals*. In case there are several scores within one category, for example different scores for amount, the average score will be taken. The average score of each category is taken, which means all parameters are considered equally important.

This value is then multiplied by the ratio that the combined length of that category is of the total combined length of the structure. This multiplication is necessary to add the ratings from different categories, which represent a different combined length. By adding these multiplied values a score that represents the whole structure can be found. This can then be used to compare the 'reuse optimized' and 'structural optimized' designs. The results can be found below.

Reuse optimized	Combined length of members (m)	Ratio of total length	Connection	Amount >50 (average)	Profile (average)	Alterations	Average score	Avg. score x Ratio o. lngt
Truss Diagonals	3787	0.175 (17.5%)	5	5	2	4	4,0	0,70
Truss upper & lower	3698	0.170 (17,0%)	5	4	2	4	3,8	0,64
Roof spacers	1906	0.088 (8,8%)	3	1	4	4	3,0	0,26
Column verticals	1866	0.086 (8,6%)	5	4	2	4	3,8	0.33
Truss pair connectors	6045	0.279 (27,9%0	3	5	4	3	3,8	1.06
Column Horizontals	1933	0.089 (8,9%)	5	5	5	4	4,8	0,43
Column diagonals	2434	0.112 (11,2%)	3	4	2	4	3,2	0,36
Total	21672	-	-	-	-	-	-	**3,78**

Table 5.6. An overview of the construction optimized towards reuse, where categories of the construction are plotted against several aspects of upcycling

Structurally optimized	Combined length of members (m)	Ratio of total length	Connection	Amount >50 (average)	Profile (average)	Alterations	Combined score	Avg. score x Ratio o. lngt
Truss Diagonals	3443	0.172 (17,2%)	4	2	3	4	3,2	0,56
Truss upper & lower	3698	0.184 (18,4%)	4	3	3	4	3,5	0,64
Roof spacers	1835	0.092 (9,2%)	3	1	4	4	3,0	0,28
Truss pair connectors	5056	0.252 (25,%)	3	3	4	3	3,2	0.81
Column verticals	1844	0.092 (9,2%)	5	4	3	4	4,0	0.37
Column Horizontals	1735	0.087 (8,7%)	5	3	5	4	4,2	0,37
Column diagonals	2135	0.107 (10,7%)	3	3	2	4	3,0	0,32
Total	19748	-	-	-	-	-	-	**3,35**

Table 5.6. An overview of the construction optimized towards construction, where categories of the construction are plotted against several aspects of upcycling.

Following will be several observations regarding the results in the tables above, accompanied by a discussion on those observations. First, there are two major differences between the added scores between the two designs. The design optimized towards reuse has a better score on reuse (3,78 against 3,35), which translates that on average members from the first design are 'likely' to be upcycled, while the second design scores between 'neutral' and 'likely'. Secondly there is a difference in combined length of members. This means that the design optimized towards reuse requires 9% more material compared to the design optimized towards construction (in combined length). This decrease of material is represented in all categories but mostly in *truss diagonals*, *truss pair connectors* and all three categories for the column construction.

Considering individual categories, it is shown that in both designs the trusses influence the combined score the most. The greatest difference between the two designs is manifested in the category *truss diagonals and truss pair connectors*. Mainly this is because the parameter for *amount* is changed when optimized towards the most efficient construction. Also, the two other categories for the roof constructions show very little change between the two designs considering the current parameters.

Considering the categories in the column construction there are two notable changes, namely in the categories *column horizontals* and *column diagonals.* The values for the second design are lower, caused by a lower score for the parameter *amount*.

6 Conclusion

When it comes to the design of large sport venues, many aspects of architecture, engineering, cultural involvement and politics come together. For the summer and winter Olympic games this is true even more so. There is a growing incentive to make the Olympics a more sustainable event, both for the community as for a reduction of its carbon footprint. To account for a more sustainable social impact on the community there has been a growing trend of the deployment of temporary sport venues. On the other hand, whether these venues have a smaller carbon footprint is questionable.

It has been determined that a post-event use strategy (or circular design) is required for these venues to be sustainable. Although not a new idea, several projects with such a strategy have failed to be successful in their post-event use. The goal of this research has been to propose a design strategy that accounts for the barriers of reuse these previous projects encountered.

Four post-event use strategies can be identified: *recycle, upcycle, adapt* or *relocate*. For all strategies applies that the venue must be demountable, to such an extent that the individual parts can be reclaimed after its initial use. The only possible material for such a construction is steel, which is potentially suited well for reuse because of its properties. Yet certain barriers of reusing steel are present in our current economy. In short, scrap steel has a certain value for the steel industry, and as long that value is not overcome by a steel structure it is not likely to be reused. Another barrier for reusability is transportation, which limits the maximum dimensions of buildings elements that cannot be disassembled further. In short, dimensions should not exceed those of a shipping container to qualify for reuse across international borders.

A case has been chosen for a preliminary design: the Volleyball arena for the Olympic games of 2024 in Paris. This arena must contain two seating bowls, with a capacity of 5.560 and 13.010 visitors. Based on this information certain dimensions were then concluded. Three aspects of the design are part of the design focus: *load-bearing construction* and *façade*. Primarily the load bearing construction is considered most influential on the reusability of the design.

Concluding this research a preliminary design has been made for a temporary, demountable and reusable arena for the Olympic games. The required reuse strategy is to consider all four post-event uses in the design.

Complete relocation of the arena is considered the most sustainable from a perspective of material use. Most important in this scenario is the demountability of the design and the ability to transport the components.

Secondly, the possibility of reuse in other design formats (adaptation) has been considered. Several design formats have been considered, summarized in four infographics. Most important are the dimensions of members in these formats, and the profiles of those members. For example, a dimensions that can be found repeatedly in the design is linked directly to a floor height of 4,2m which is commonly used in public buildings.

Thirdly the strategy upcycling is applied, where the design of steel members encourages reuse by not yet known parts of the steel industry. Several implications on the design of steel members that influence the ability to upcycle are recognized and rated.

Lastly recycling is considered the least sustainable option, as it requires the most energy to return to the supply chain. Therefore the design should contain a minimal amount of unique members, and connections are designed towards minimal material use.

A parametric model has been designed to incorporate the requirements gained from the reuse strategies, as well as information retrieved from structural calculations. This has led to an algorithm that is able to translate curves from a creative design process to a steel structure. The parametric model can be further influenced by input parameters that changes member lengths directly. By changing these parameters the geometry can either be optimized towards minimal material use, or towards optimal reuse.

Both extremes of those two optimization processes have been generated and documented to conduct a *research by design*. This lead to the conclusion that a material increase of 8,9% in length would influence the reusability of the steel construction of the design in positive way. Focussing on the strategies *relocate* and *upcycling* this positive influence was confirmed.

For *relocate & adapt* it can be concluded that adaptations of the design that are relatively small, work really well with a design optimized towards reuse. For adaptations that are more radical the effect seen with a small adaptation diminishes, because a large difference in total material creates a larger chance of coincidental matches of similar members.

For *upcycle* it is shown that the design optimized towards reuse is performing better, mainly in the categories that have been changed in the parametric design. Showing the parametric model works as expected. The difference can mainly be found in the roof structure, which shows there is a correlation between a better reusable structure and standardization.

6.1 Recommendations

In the design much of the design consists of parametrically generated geometry. A next step in this design is computational optimization, which allows a program to generate an optimal design form. As the required output (reusable steel structures/elements) is measurable there is potential for such an improvement.

Secondly, the reuse strategy is currently based on generic forms and dimensions. Another strategy could be to focus on a more local scale, regarding in a research what is needed after the initial use of the arena. It is easy to imagine that in some cases this would be more sustainable due to less transport costs. Also there could be an additional benefit that such a design would benefit the local area, increasing the chances of reuse.

In the current report two different iterations of the design are researched and compared. They can be described as two extremes, either optimized towards reuse or minimal material use. It could very well be that the most realistic solution is a design that fits somewhere in between. It would require more iterations of the design to determine which strategy has the best balance.

7 Reflection

The following document is a reflection on graduation report. First the relationship between the theme of the graduation lab (sustainable sport venue design) and the research methodologies are discussed. Secondly the findings of the research are placed in social context.

The graduation theme this research started with is *Sustainable sport venue design*. Sport venues can be roughly divided in two categories, according to their size. Early in the research process a decision had to be made which kind of venue the research would focus on. At that time media attention was directed at the legacy of the Rio Olympics of 2016. Many venues had turned into 'white elephants', which is the definition for large abandoned buildings.

After more research was done by studying case studies the scale of the problem became evident. Many examples of a negative legacy of the Olympic Games created by abandoned sport venues can be found. This problem is currently recognised by the *International Olympic Committee* (IOC), which is why a *legacy plan* is now required for future Olympic Games.

One way to avoid white elephants is by building temporary instead of permanent venues. These have become increasingly more common in Olympic Games since the Sydney held the Olympics in 2000. Although less visible, this research highlighted the negative impact of such temporary structures if it is not built towards reuse. In relation to the theme of the graduation lab this aspect was in my opinion a lesser known aspect to temporary sport venues.

Another methodology used in this graduation is research by design. A parametric design has been used to generate multiple configurations of a steel construction for a design. Different constructions could therefore be easily documented and compared. Also by combining the literature research on reuse with the documentation of these construction they could be rated. In relation to the graduation lab this is a step towards computational design, where construction is analysed early on in a design process by algorithms.

To *reuse architecture* and to build *circular constructions* is a well-discussed topic, but articles refer mainly to the demolition of the current built environment. This complicated the search for scientific literature research. A large portion of this research tried to bring building temporary structures & reusing structures together.

When this project is put in a wider social context there is a very direct relationship with the public that visits or follows the Olympics. The venue will attract much media attention from all over the globe, and will reach many people. It should therefore also represents the idea of reusing architecture, which can be done with many more steel structures that are currently reused.

Although this design is quite unique because only a small amount of steel constructions are built for such a short lifetime, it can still contribute to a more sustainable building process for contemporary steel construction. A portion of the research is focussed on the difference between optimization towards minimal material use and optimization towards reuse. In other words, unique elements that fit the requirements precisely, or standardization of elements that not always match the requirements precisely. It is a tradeoff that influences any design process depending on what strategy is chosen.

8 References

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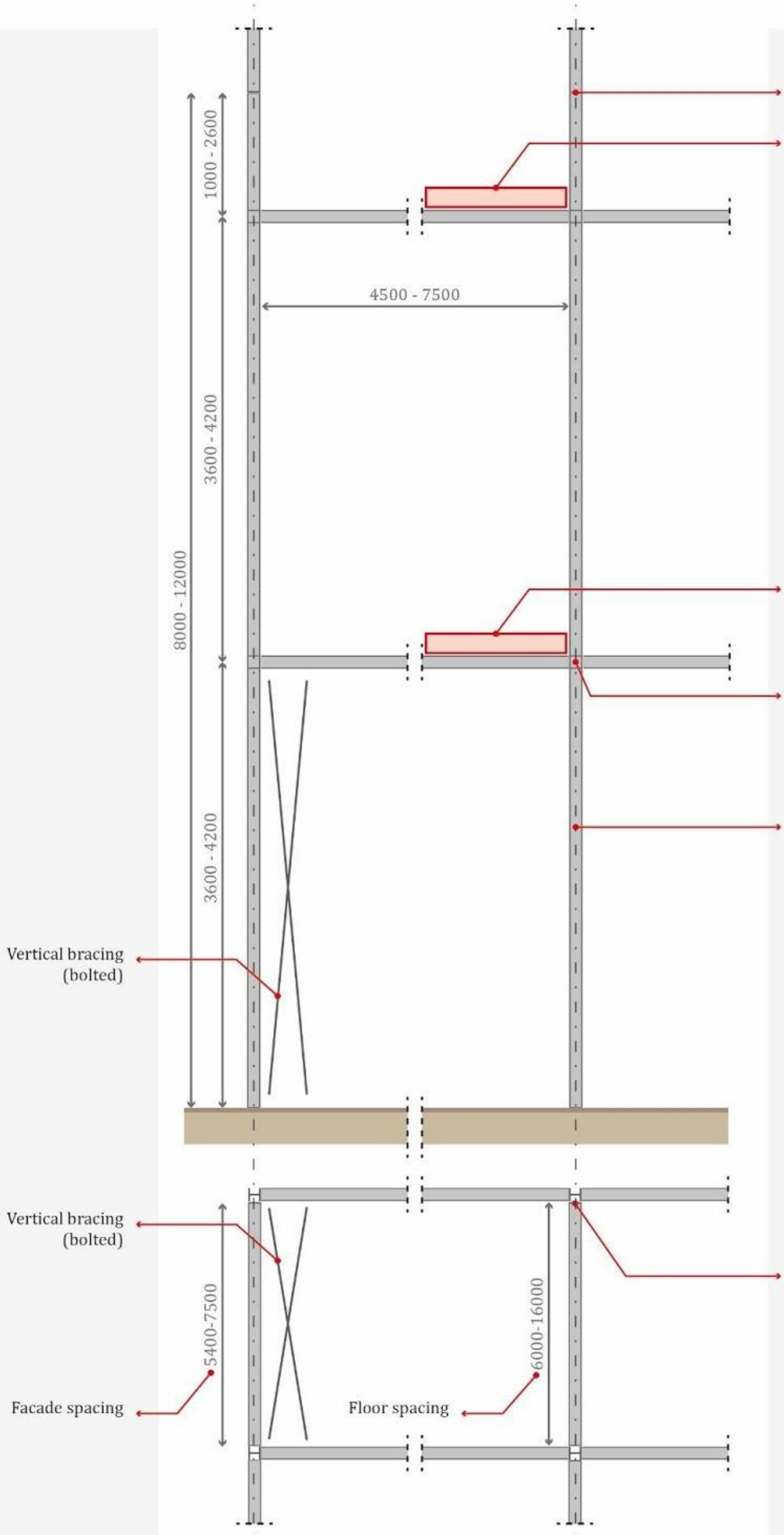
9 Appendix

Appendix A. Standarisation in high rise steel construction

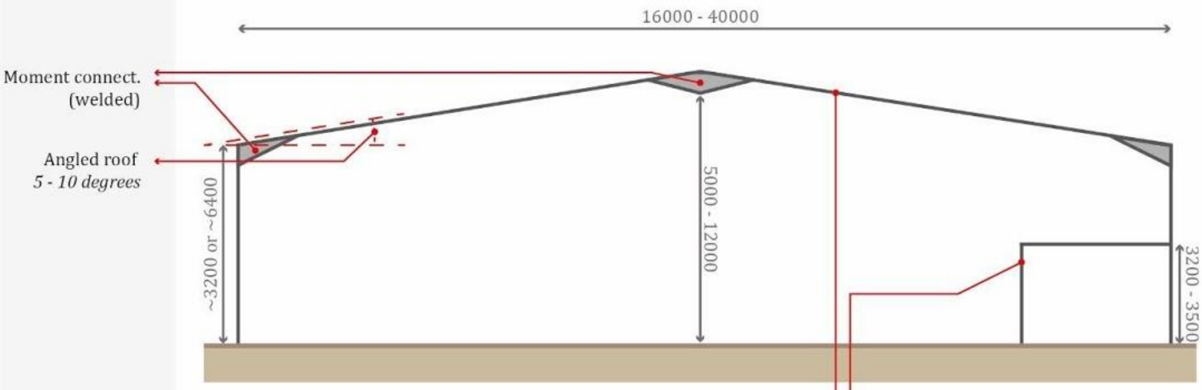


Area loading (kN/m2)	
Permanent loads	
Steelwork	0.35 – 0.7
Composite slabs	1.9 – 3.0
Precast slabs	3.0 – 4.5
Partitions	1.0
Services	0.25
Ceiling	0.1
Imposed loads	
Roof	0.6
Floors	2.5 – 5.0
Wind loads	0.8 – 1.5
Snow loads	0.6

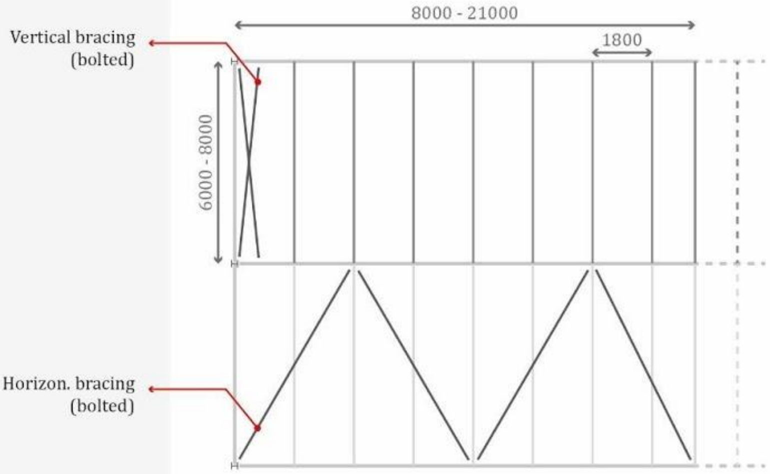
Nm. of floors	Column Profiles
1	152
2 - 4	203
3 - 8	254
5 - 12	305
10 - 40	356

Schematic vertical & horizontal section, 1:50

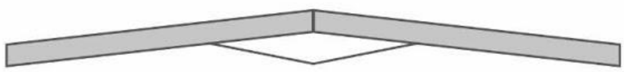
Appendix B. Standarisation in steel portal frame construction



Schematic vertical section, 1:200



Schematic horizontal section, 1:200



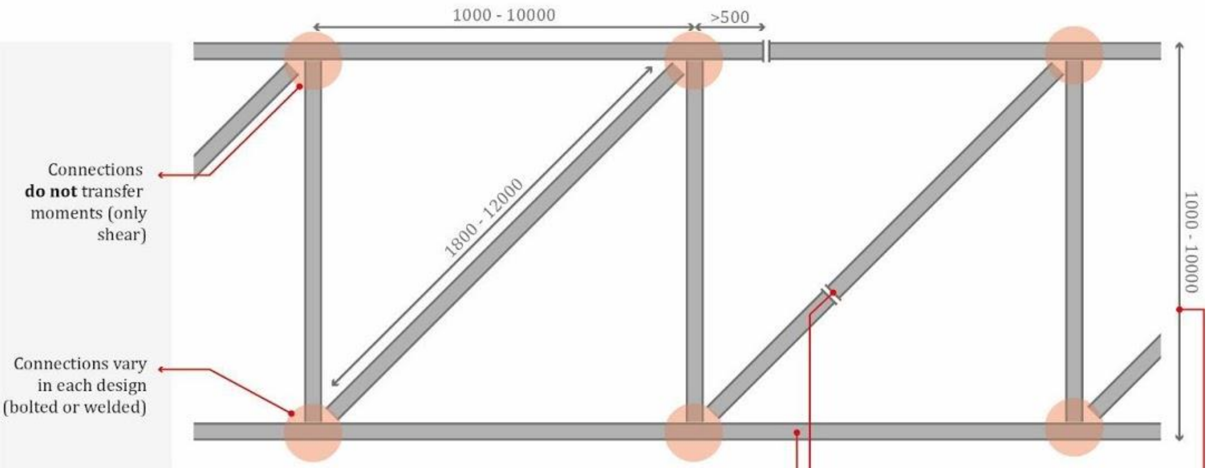
Apex haunch, 1:100

Cost effectiveness steel profiles
(bouwenmetstaal)

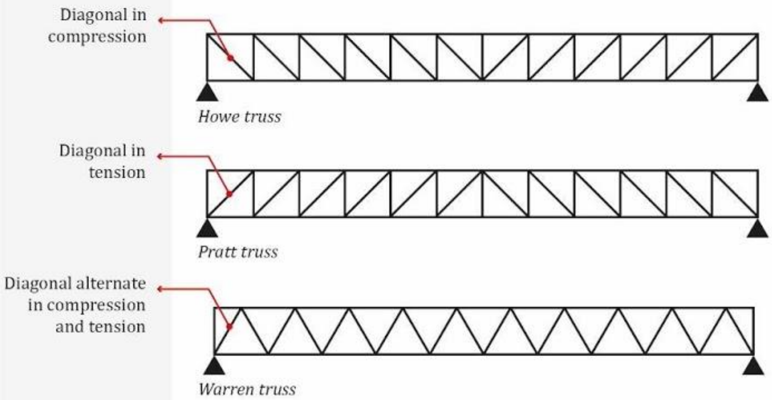
I-Beams	**Relative price/kg**
IPE 100-120	98%
IPE 140-220	98%
IPE 240-270	100%
IPE 300-400	100%
IPE 450-500	106%
IPE 550-600	112%
HEA/B 100-180	98%
HEA/B 200-320	102%
HEA/B 340-400	102%
HEA/B 450-600	111%
HEA/B 700-1000	116%

Square-Beams (Cl.)	**Relative price/kg**
40x40-90x90 3mm	109%
100x100 4-5-6 mm	109%
120x120 4-5-6 mm	112%
140x140 5-6 mm	115%
160x160 8 mm	140%
180x180 6-8 mm	117%
180x180 10 mm	140%
200x200 6-8 mm	117%
200x200 10-12,5 mm	140%
250x250 6 mm	117%
250x250 10-12,5 mm	140%
300x300 6-8-10 mm	142%
300x300 12,5 mm	142%

Appendix C. Common truss principles in large span steel construction (30+m)



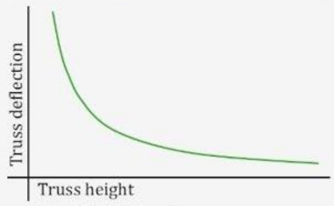
Splice connection *(compression/tension only)*



3 types of *orthogonal* trusses

Truss height requirements (mechanical) are determined by :

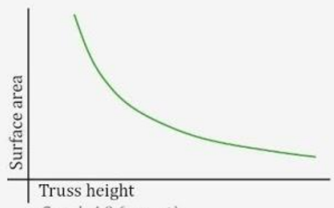
- Span (in meters)
- Allowed deflection
- Loads



Graph 4.1 (report)

Profile requirements (mechanical) are determined by :

- Surface area (in tension)
- Buckling (in compression)



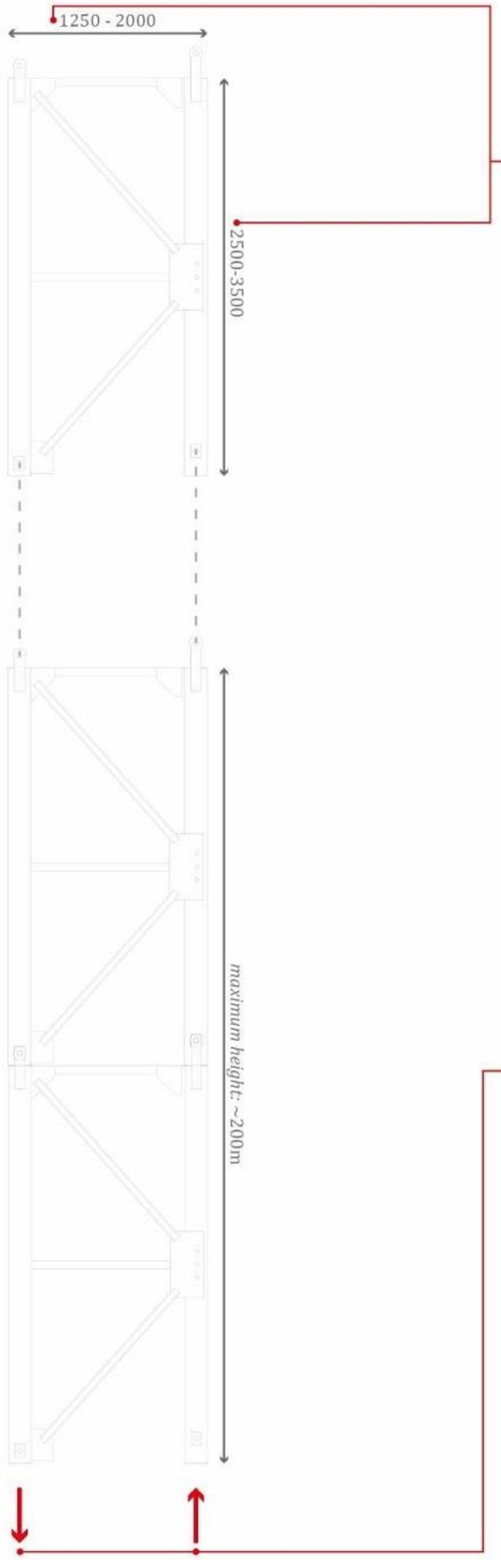
Graph 4.2 (report)

Common spans in:

- Concert halls	45-90m
- Sport halls	35-45m
- Highway footbridge	30-60m

Apex haunch, 1:100

Appendix D. Standarisation of temporary tower crane construction



Dimensions vary for each type of crane, company and country

Maximum loads (on 2 nodes)	
Tension	
240 t	<in service>
256 t	<out of service>
Compression	
143 t	<in service>
171 t	<out of service>

Maximum loads of cranes are generally much higher than columns used in architecture. This is due their ability to withstand large moments induced to their long arm.

ACE TC7059 Tower crane elements

Appendix E.

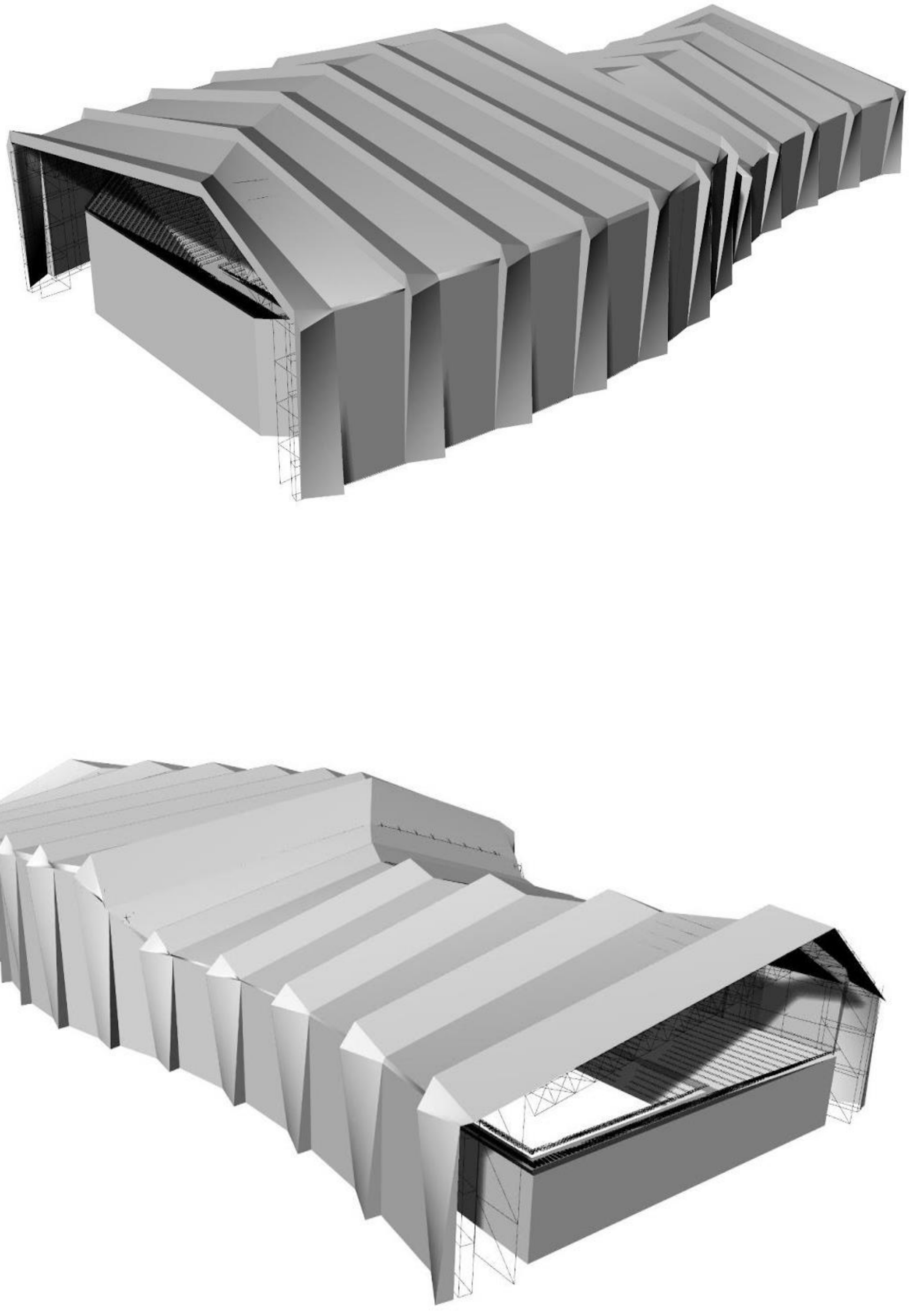
7.13. Voorkeurslijst profielen voor standaard hallen; staalsoort S235, tenzij anders aangegeven (peildatum 2017).

profiel	aanduiding	relatieve prijs per kg
balkstaal	IPE 100-120	98%
	IPE 140-220	98%
	IPE 240-270	100%
	IPE 300-400 ***(referentie)***	*100%*
	IPE 450-500	106%
	IPE 550-600	112%
	HEA/B 100-180	98%
	HEA/B 200-320	102%
	HEA/B 340-400	102%
	HEA/B 450-600	111%
	HEA/B 650-1000	116%
	UNP 100-120	98%
	UNP 140-320 **geen UPE-profielen??**	98%
	UNP 350-400	105%
hoekprofiel [2]	50x50x5; 60x60x6; 70x70x7; 80x80x8; 90x90x9; 100x100x10;	110%
	120x120x10; 120x120x12	122%
stafstaal, plat massief [2]	50x10; 60x10; 70x10; 80x10; 90x10; 100x10; 120x10; 120x15; 140x10	110%
	140x15	124%
buis, vierkant koudgevormd [3]	40x40x3; 50x50x3; 60x60x3; 70x70x3; 80x80x3; 90x90x3; 100x100x4; 100x100x5; 100x100x6	109%
	120x120x4; 120x120x5; 120x120x6	112%
	140x140x5; 140x140x6; 150x150x5; 150x150x6; 160x160x6	115%
	160x160x8[4]	140%
	180x180x6; 180x180x8	117%
	180x180x10[4]	140%
	200x200x6; 200x200x8	117%
	200x200x10[4]; 200x200x12,5[4]	140%
	250x250x6	117%
	250x250x10; 250x250x12,5; 300x300x6[4]; 300x300x8[4]; 300x300x10[4]; 300x300x12,5[4]	142%
buis, rond, gelast	~~60,3x2,9~~	113%
	~~76,1x3,25~~; ~~88,9x3,25~~ **alle vervangen door courante buisprofielen**	125%
	~~101,6x3,6~~	120%
	~~114,3x3,65~~	137%
	114,3x5	116%
	~~168,3x4,5~~; 193,7x5,6; 219,1x6,3	110%

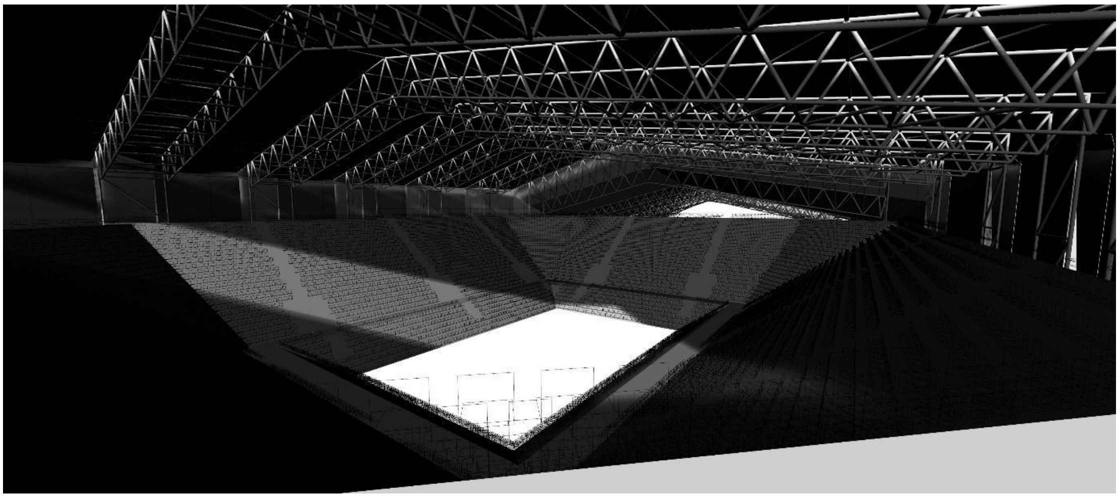
2. Diagonalen voor windverband: dak = hoekprofiel; gevel = strip.
3. Staalsoort S275, tenzij anders aangegeven
4. Staalsoort S355

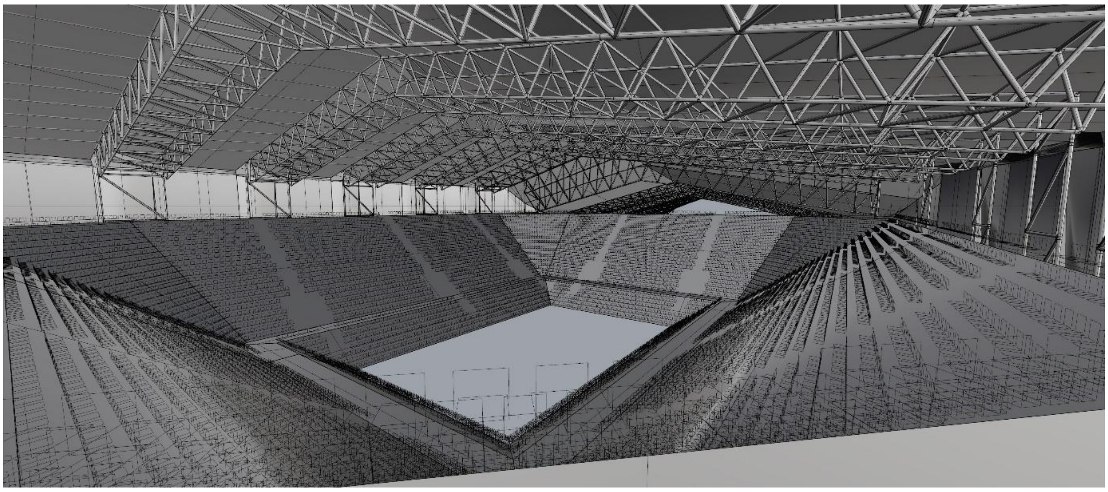
~~60,3x2,9~~ geen courant profiel volgens *Wegwijzer*

Appendix F.

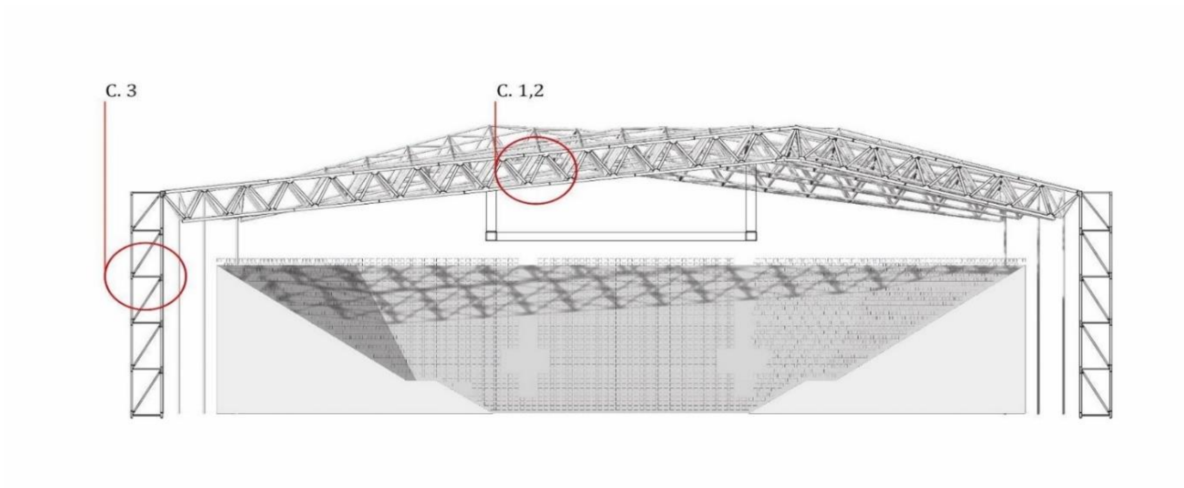


Appendix F1. Two impressions of the arena





Appendix F2. Two images from the inside of the arena, same point of view and perspective.



Appendix F3. Section of the steel construction, marked with three principle connections (schematic).

Appendix G.

Interview Lennart Wiltjer (iMD), 6 Februari 2018 (notes)

1 What are the greatest challenges currently for reuse of steel structures?

- *"Disassembling steel connections requires labour, and is therefore expensive.*
- *Lack of documentation. Constructions are rarely documented precisely and often do not match with reality of what is built."*

2 Which of those two option is most influential? *"Cost is not the greatest factor according to Wiltjer. Many projects require green labels and would be open to suggestions such as reused steel construction."*

3 Any barriers that have been mentioned in this research that do not match reality?

"Certain 'problems' that have been noted in this research are overestimated in terms of importance.

- *Removing coatings for example is not a very big problem. It means that sometimes the finishing of a product will not influence its reusability much.*
- *Also, cutting steel beams to size/removing the 'connection ends' is not deemed much of a problem. There are machines (in steelwork yards/factories) which can do these simple tasks easily."*

4 Can the cost of reused steel beat that of new steel? *"The price of reused steel can certainly be lower than new steel (in euro/kg). Manual labour is the most important factor if a building process should be made financially viable."*

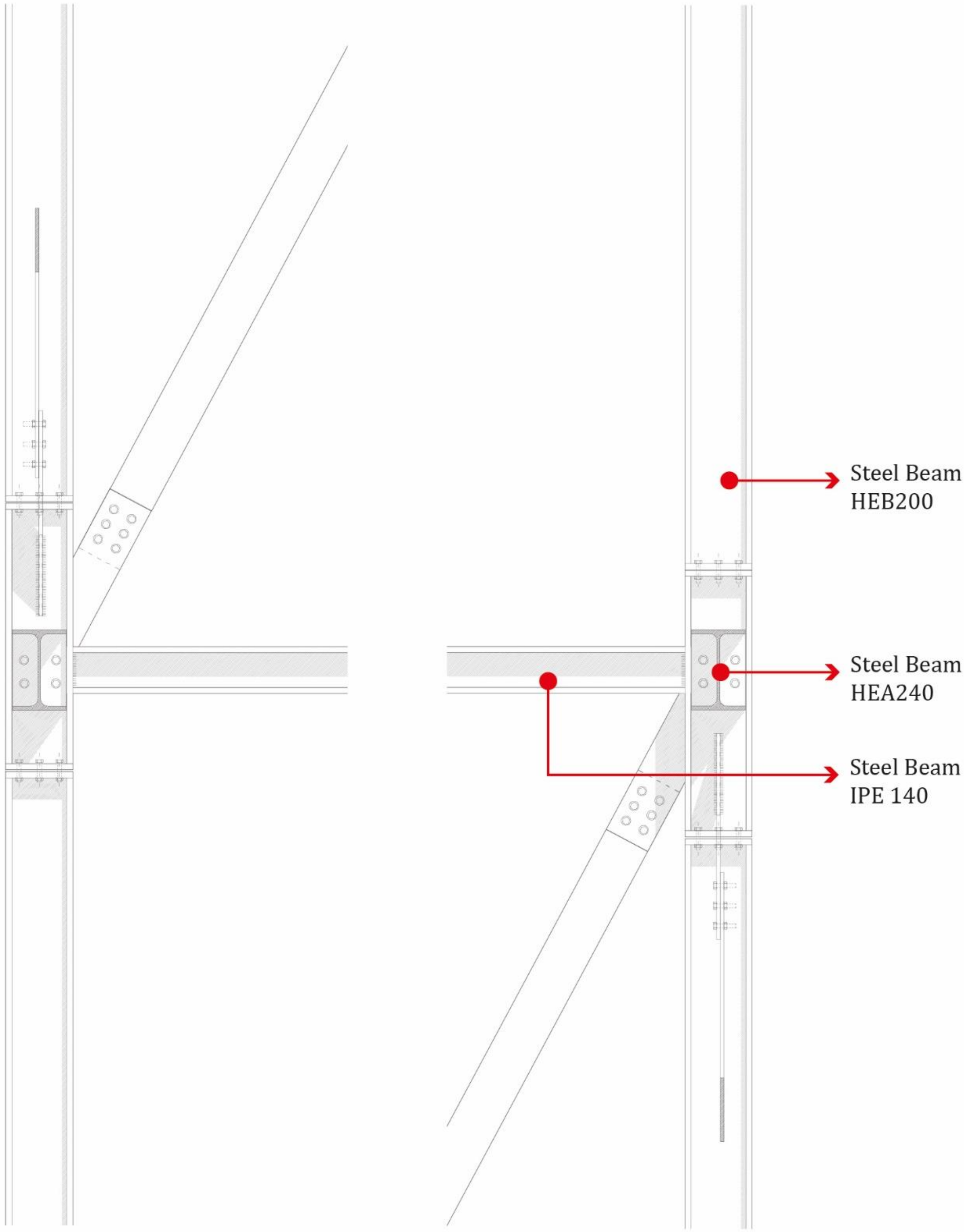
5 Is the current strategy in this research a realistic approach?

"The chosen reuse strategy is certainly possible, although it would be better if a 'follow-up' project was chosen beforehand. The current strategy relies on generic dimensions and averages. In practice all projects are unique and more often than not members will need adjustments even though they are very close. The most reusable project would leave only its individual members at the end of the project. "

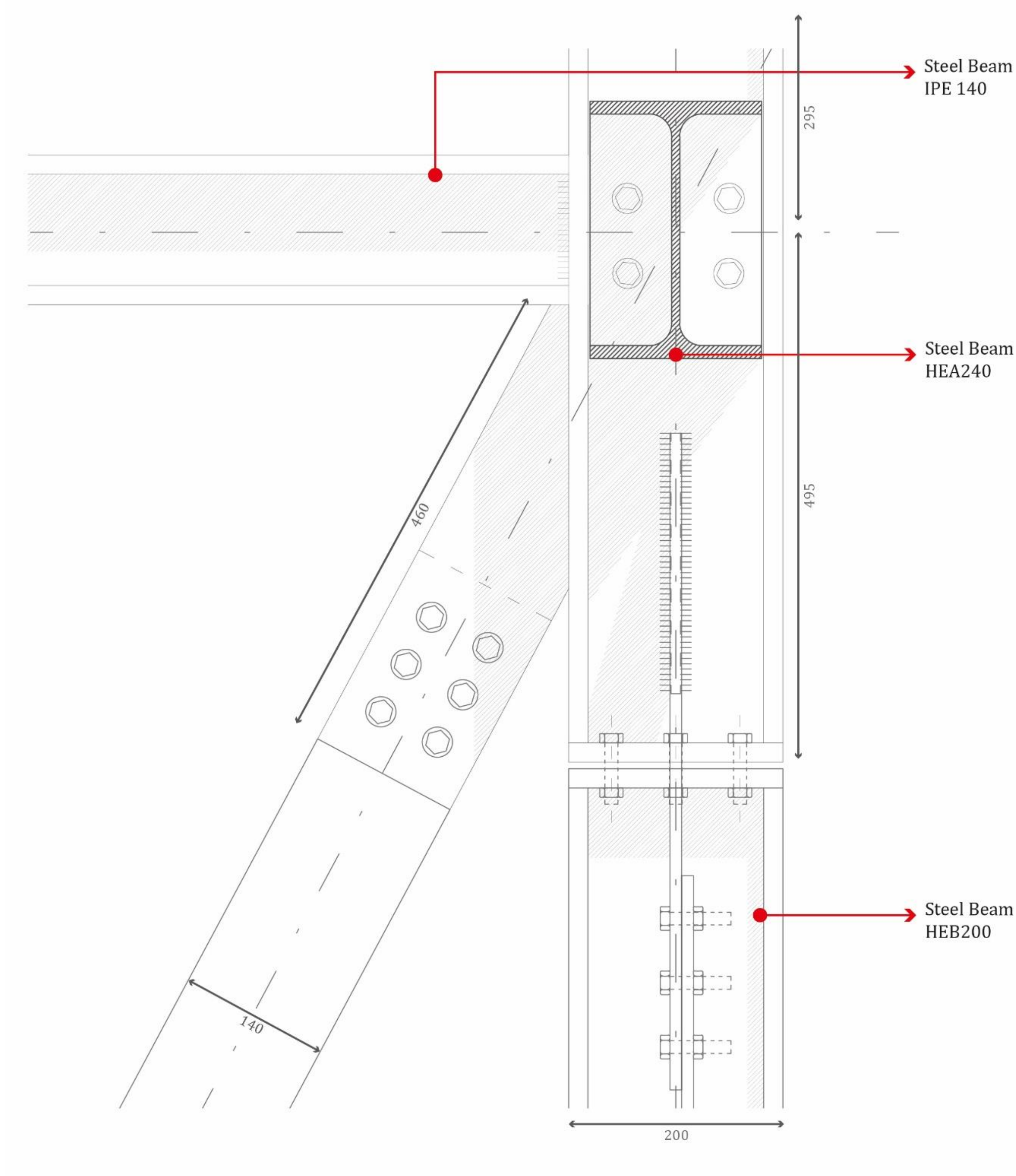
6 "But indeed, not all elements can be used in one project, accounting for multiple building types is a valid strategy."

7 "Crane elements as columns for this project is simply not a very good idea, the number of crane elements in this arena would exceed the demand for new elements by a lot. These elements can simply not be reused easily. Another suggestion is to apply the k'Nex approach. Knots and members (in larger dimensions than the trusses)."

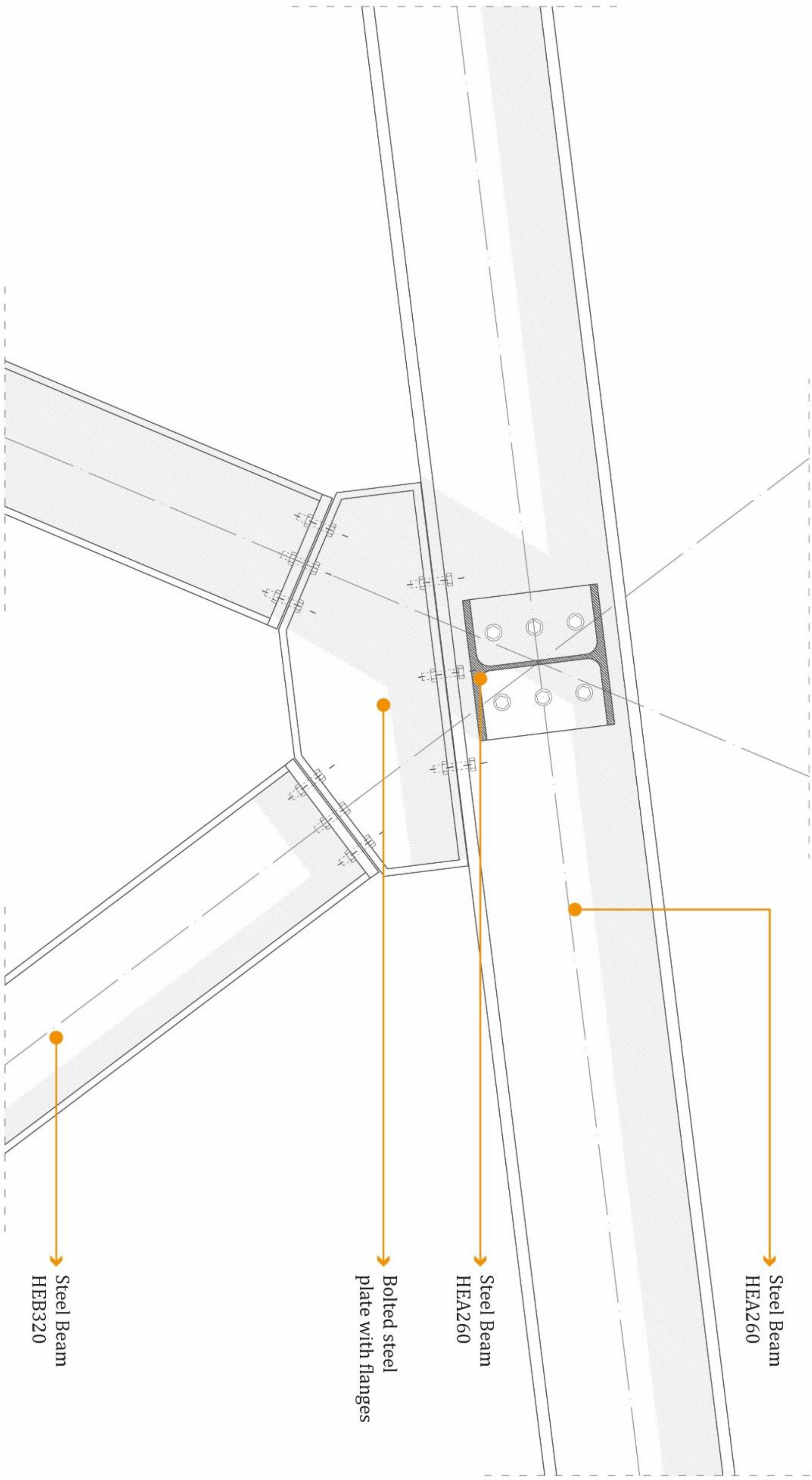
8 "The amount of bolts in a connection should be kept to a minimum (=less manual labour), which can be as few as 1 or 2 bolts even. In the example stated at pt. 7 round profiles with single bolts through them could provide a valid strategy and minimum building time."



Connection C3. Overview of the detail of the column construction.



Connection C3. Close up of the detail of the column construction.



Connection C1. Overview of the detail of the roof construction.