A life cycle approach to sustainable Olympic architecture
THE DUTCH DELTA GAMES 2028

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In front of you lays the research report of the architectural engineering graduation studio of the Delft University of Technology. Architectural engineering brings spatial, functional and technical possibilities and developments together. Architecture and engineering are irreversible connected with each other. Research in the field of technology leads to all kinds of improvements in architecture. This also works the other way around, where improvements in architecture helps inspire research and innovation. The goal of the graduation studio architectural engineering is to integrate research on engineering level and architecture, ultimately reaching a higher level of integrated design.

The research described in this report is closely related to the corresponding architectural design. The knowledge gained from the research is applied in the overall design. Visa versa, questions raised from the design are being researched.

The research is based on a life cycle approach to sustainable Olympic architecture. The short duration of the Olympics can influence the architectural designs necessary for the organisation of such an event. The research explores these influences in the past and future, giving insight in the way Olympic architecture can be designed for more than just one period.

The design is supported by the research concerning the floating capabilities of architecture. Furthermore the design is calculated to gain knowledge concerning the stability and rotation of floating buildings. These calculations and research resulted in some design parameters used for this design.

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Introduction

The environment of stadium design is changing towards more sustainable and durable designs. Reusing materials and parts of stadium construction will be more important in future events such as the Olympic Games. The times of spending great amounts of materials are over. For the Rotterdam 2028 Olympics this is just the case. An temporary event asks for a different way of designing venues.

Rotterdam Waalhaven is an unique location with great varieties in context and possibilities for future developments. The Olympic Games can become a driver for future developments and regeneration of a harbour area closely linked to the city of Rotterdam. The site gives the unique opportunity to design a floating stadium in the deep water of the Maas and its city harbour areas.

Designing with the thought of the afterlife asks for different insights and different ways of dealing with materials, connections and volumes. The basis structure of the research has been;

-Collecting sustainable ways of stadium design
-Combining these ways in one homogeneous concept.
-Understanding what the effects of flotation will be on a massive structure such as an entire stadium and on a smaller structure such as one stadium element.
-Understanding the Waalhaven area and the effects of an event such as the Olympic Games
What started in Athens 1896 as a small event has grown over a period of more than 100 years to the biggest show on earth: the Olympic and Paralympic Games. A demonstration of sport, the moment where athletes perform on the highest level, stretching the boundaries of human performance and architecture, the Olympic Games became more than just a sporting event. Only a small number of cities can say they have hosted the Olympic Games. The Olympic Games are a privilege, cities have to battle each other for the right to host the event. The Olympic Games leave a footprint behind, they can change the infrastructure of a city or put it on the global map. This Olympic transformation is part of the magic of the Olympic Games. The Games are about improving performance, when the architecture tries to replicate this performance in architectural thems, a kind of synergy is possible. Olympic architecture isn’t only about presenting the Games, it is about proposing the Olympic dream. But what will happen if this footprint is not the one of an Olympic winner, massive investments and risk are also associated with the Olympic Games. After the city of London won the bid of 2012 Games, the BBC stated: “will we still feel like winners after the circus leaves town” (BBC Four 2006). Grand architectural and Olympic visions can turn into nightmarish reality.

1.1. Athens post-Games hangover

After winning the Games is 1994, Athens was on a brief high, anticipating the return of the Games to their ancient birthplace. Athens spend over 4.5 billion euro on venues and infrastructure alone. Despite the inventiveness parts of architect Santiago Calatrava Olympic complex, most of the venues have become classic examples of what not to build. After corruption scandals and political interference, work fell behind schedule. Overtime payments to building forms and a massive security operation led to the budget exceeding 10 billion euro. With such a difficult build-up, organisers lost sight of the venues’ post-Games use to get everything done before the opening ceremony. You simply can’t deliver a legacy after the Games, you have to deliver a legacy before you hold the Games. This was the mayor mistake of Athens. Seven years after the greatest show on earth departed, Athens is saddled with arenas the city can’t afford ant few want to use, it suffered a massive Olympic hangover. All but 3 of the 22 Olympic venues were permanent rather than temporary, so white elephants dot the city. If waste was an Olympic sport, Greece should be world champions.

The aquatics center is among a cluster of venues in the Olympic park that was the showpiece of the 2004 Games. Now neglected and covered in graffiti, it is a far cry from the idyllic new park zone for sport and leisure (Beard 2011). Planning issues and a lack of interest in sports such as baseball, hockey and kayaking among football-mad Greeks means it is now considered a Games graveyard. The city of Athens is lacking public green space, the failure to utilize the Olympic park and sport complex area seems even more of a waste (Hersh 2008). Formerly glorious venues and stadiums are now derelict, covered in graffiti. The park is overrun with rubbish and weeds. Waste from nearby building sites, plastic bags and bottles move trough the empty boulevards. While concerts and football matches have been held here since 2004, the magnificent Olympic stadium is in a sorry state. The annual maintenance of the empty site has cost almost 500 million euro since the event. Nowadays the park is closed with metal fences and locked gates.

Tents have been erected on grounds that, before the Olympics, where playing fields for children. Fountains are broken and rusting. Targets with gaping holes in them are what remains of an archery training centre, post-use of the stadium for baseball is small because of its triangular shape (Athens tried to promote them as football grounds but figured that the shape of the stands and field where not suited). Water rapids for the kayak competition have run dry. The velodrome is empty, bird droppings cover the seatings and the backs are spray-painted with graffiti.

The Olympic Village, converted to a workers’ housing settlement in the north of Athens, is another example of failed legacy usage. The plaque to commemorate the Games is covered in spray-paint while the central promenade is overgrown with weeds and covered in dog mess, bottles, cracked paving stones and spray-paint cans. The village was built in the isolated district of Pamitha, a sprawling and neglected area of Athens. The village is not suited for a
community. Two schools are at double intended capacity, there is only one supermarket and the nearest public transport is a rail station more than half a kilometre away. Many residents are complaining about the lack of community facilities and amenities. Vandalism has attacked the former administration block, where corridors are covered with glass, rooms are burned out and air-conditioning units have been plundered for copper wiring (Beard 2011).

Although failure is imminent, there is one major positive post-Games achievement. The public infrastructure of Athens was completely revised for the Olympics. The new airport is built on the outskirts of the city, decreasing noise levels. The city's metro system is gloriously efficient, gridlock and pollution have been decreased as a consequence, thrusting Athens in the 21st century.

While the country's budget has plunged into red, some say the borrowing costs of the event have reached 37 billion euro, the Olympic legacy dominates political life in Athens (Malone 2008). Greece’s economic crisis, a 100 billion bailout narrowly prevented it going bankrupt last year, means authorities are keener than ever to hide the venues hidden from public view. But it was not just the money that Greece paid for the Olympic Games, there was also a high price concerning human lives. Because of the shortage of time, constructors ignored the safety standards. 13 Greeks and foreign workers lost their lives, so the venues could be finished on time. Unfortunately Athens is not the only hosting city with painful post-Games legacy.

1.2. Examples of failed post-Games legacy

In the Olympic Games of Montreal 1976 delays to the construction laid to rumours that the Games could be called off. The Quebec provincial government took over construction when
it became evident in 1975 that work had fallen far behind schedule. Work was still under way weeks before the opening date. In the end they went ahead even thought the stadium hadn’t been completed and the retractable roof did not work. Today the people of Montreal rarely use these venues, but it has taken them 30 years to pay of the 1 billion euro debt they inherited by hosting the Games (BBC Four 2006).

By 1984 the Olympics were considered such a poison challenge, that Los Angeles was the only city to bid for it. Architectural niceties were few and far between. For Los Angeles this gamble paid off, corporate sponsoring and their refusal of putting fans in fancy new venues enabled them to turn a rare profit. For Architecture in the spirit of the Olympics movement you should look elsewhere. But this tactic backfired when America hosted the Olympics in 1996. Atlanta was so naked in its pursuit for corporate cash that it became known as the Coca-Cola Games. Its relentless commercialism embarrassed the Olympic movement and worse left now benefit for the local people. The local community was promised jobs and a communal facilities, but just like Athens there is now a fence around the area and the community is as poor as it was before.

After the mess left behind in the deep south, the Olympic brand badly needed a success story. Sydney’s green Games of 2000 where widely praised for their environmental achievements. They managed to transform a noxious swamp into an Olympic site. But even this story didn’t have a happy ending. The Olympic facilities didn’t have proper post-Games usages, it is not being used and concentrated to one area, so it became some sort of ghost town. By putting all of the main venues in Homebush Bay, not particularly close to the center of Sydney, they missed the opportunity to make the venues alive every day of the year.

For the 2008 Games in Beijing large parts of the city were rebuild, but these promised rebuilds came at a cost. In Beijing the sacrifices have been immense, it is estimated that 300.000 people have been evicted to make way for the new venues. Vast parts of the city have been flattened so China could squeeze out every last drop of prestige (BBC Four 2006). With the Herzog & de Meuron Olympic stadium and Watercube by PTW Architects, they had multiple architectural masterpieces. But the Olympic venues are just a small part of Beijing’s masterplan, the city spent over 15 billion euro creating an infrastructure worthy of the Games. The legacy of Beijing is about putting the city on the global map, the Olympic green has become a new popular tourist spot. But besides the hosting of a number of events, the Italian soccer Super Cup and the Race of Champions, the Bird’s Nest is considered a white elephant due to the lack of a permanent function (Hickson 2009).

1.3. The Barcelona effect
The Olympics don’t have to be a pointless dissipation, a city can use them as a catalyst for regeneration and can afford to do it properly. Barcelona engineered just such a triumph with their games in 1992. According to architect Fedderico Correa, Barcelona needed this regeneration for years, but it hadn’t been done due to the Franco regime (BBC Four 2006). It had all to do with planning, Barcelona worked because it was in a framework for 20-30 years as example of proper city planning. The urban transformation generated by the Games had far-reaching economic and social impacts. The plans were all interconnected, integrated into the urban setting, subtle, detailed down to the smallest square. The Olympic Games left a long term legacy in terms of public perception, new housing and sport facilities.

Barcelona was a relatively unknown city before the Olympics despite its historic context. The city took the Olympic Games to showcase its culture and history at an international level. Tourism was for Barcelona an unique tool in its ability to translate this global attention into long-term economic growth. But tourism was not the only key factor for success. The Barcelona Games, held just 10 years after the establishment of democracy, allowed the residents of the city to show their passion for change and how they had embraced democracy and modernity. The coming together of different political and social classes in an unique project that was supported by everyone was a key element for the achievement of the Games (Hilier 2010).

The Olympic Games had an enormous impact on urban development in Barcelona, transforming it from an industrial city to one that combines industry with art, culture and commerce. This was achieved through the application of the urban regeneration plan which included improvements to the city’s transport infrastructure, public services as well as Olympic related facilities. Barcelona was opened to the sea with the construction of the Olympic village and Olympic port. Modern sport facilities were built in the Olympic zones of Montjuïc, Diagonal and Vall

Barcelona’s Olympic city marketing
* Olympic venues were located at multiple sites in the city, giving the historical context extra attention. By locating the main venues on the Montjuic mountain, extraordinary backdrops were created.
d’Hebron. The Olympic village was transformed into hotels and tourism facilities after the Games. The construction of the ring road around the city helped to reduce the density of the traffic. The airport was modernised and expanded and historic buildings were restored. Renowned architects like Santiago Calatrava and Ieoh Ming Pei were invited to design the new buildings. The whole city was transformed into a future business and tourism destination. Barcelona is a different place now than it was before the Olympics. The Barcelona way of rethinking the Olympics and introducing legacy is now known as the ‘Barcelona effect’.

1.4. London 2012 legacy

London will incorporate some of the Barcelona principles in their Olympic masterplan. They know that the Olympics is more than just 17 days of sport. The Olympic park should be for the people in the surrounding areas, a mixture of sport and leisure with community participation, as well as a place were the best British athletes can train. Foreign Office Architects are responsible for the design of the Olympic masterplan, they tried to make an Olympic site that won’t turn into another Olympic graveyard. The masterplan is build up in two different modes, the Olympic mode and the legacy mode. The organisers promised to build the biggest park seen in an European city in the last 200 years. The park is developed to minimise the subsequent transformation and should leave an excellent platform for the future development of new neighbourhoods. It anticipates the area being transformed from Olympic park into a new urban quarter, which will contribute to the urban character and economic potential of the entire Valley. Venues that would not operate with a viable legacy, like some of the hockey venues and the basketball arena, will be removed and temporary structures will be decommissioned. Permanent venues, the parklands and large pieces of infrastructure such as bridges will remain to form the catalyst for new developments. Venues like the aquatics centre, Olympic stadium and velopark will be modified to suit the future elite training as well as community use, forming the focal points of new mixed-use neighbourhoods which will be developed around them. The Olympic stadium will go from 80,000 seats to around 25,000 seats in the legacy mode. Although the stadium was proposed to a number of football teams, the best legacy the organisers could find was a training centre for athletics. The Olympic village will be transformed into a new city district providing new homes. It will form part of the new Stratford City development including the international station which will become a new prominent gateway for London.

Leaving a positive post-Olympic legacy is easy to promise, but hard to deliver. Legacy itself is kind of a dubious term, a political spin put on by people who aren’t going to be there when the legacy mode is developed after the Games (Iain Sinclair, BBC Four 2006). Even the site in the Lea Valley is proving problematic, businesses have to surrender to purchase orders and there are doubts about the appropriateness of the area. Successful Olympics always have been integrated into the fabric of where people really lived, but the Lea Valley was populated by dirty industry. Perhaps the new Olympic park will be too heavy and dramatic for the surrounding areas. The computer generated version of the legacy park will be stunning, but what will the underlying reality look like? London already has a failed legacy in terms of the Millennium Dome, designed by Richard Rogers. In the case of the dome, everybody talked about legacy in terms of new stations and transport facilities. But after the millennium, there simply wasn’t a proper new function for it. But the dome wasn’t the only disaster of recent years. Delays in the construction of the new Wembley stadium by Norman Foster, forced the Football Association to move the 2006 Cup final to Cardiff. Then there was Picketts Lock, it won the competition for hosting the World Athletics Championships of 2005, but in the end London could not construct it in time. The only legacy use in Britain that really worked was the City of Manchester stadium. Originally built for the Commonwealth Games, it was transformed into a modern football arena afterwards.

During my visit to the park, some of the above concerns were already visible. Starting with the guided tour at the Bromley-by-Bow underground station, at the far end of the Olympic Greenway (a central axis developed for the Olympics), the first impressions are that of a deprived area. Everything surrounding the station is old and perished, the industrial character is everywhere in forms of small pilots and outdoor storage space. When entering the main Greenway this feeling is somewhat differentiated by the feeling of possibility and space. The Greenway took me through the development park, straight to the main Olympic stadium. To reach the main park area, where the aquatics centre, velopark and basketball arena are also situated, we had to pass some of the old Stratford housing areas. These houses were characterised by the small size and vast amount of backyard rubbish. Barbwire could be seen everywhere in the neighbourhood. Graffiti and waste are not uncommon in the Stratford
area. The Olympic Village which was almost completed during this time was contrasting the original apartments on the other side of the Greenway, not helping to create an Olympic atmosphere. When eventually reaching the main venues, the vast scale becomes clearer. The road perpendicular to the main Greenway gives an impression of what it becomes in 2012. The park already was shaped but the greenery wasn’t there yet. I can imagine this part of the Olympic masterplan to work properly during the Olympics and in the legacy mode. Even the existing housing and offices are far more promising. Because the main international station is located here, the majority of Olympic visitors are not confronted by the deprived south side area. I honestly think the legacy possibilities are present in the area, but the Olympic pitfalls are not far away. The area of Stratford is somewhat confusing. Certainly London will not become the new Athens, but for a working legacy time is also a key factor. It will take at least a decade before we will know if the Olympic development strategy of London 2012 has worked.

The previous examples are all Olympic situations. Unfortunately not only Olympic hosts are suffering from failed legacy. One case is so shameful it is worthwhile mentioning it. The World Championship football 2010 in South Africa was almost the greatest ever for Dutch spectators, but what was left behind is far from great.

1.5. General legacy
The financial heritage of the World Championship is a large problem for the city of Cape Town. The stadium of 500 million euro will only cost money in the years after the World Cup, almost 1 million euro every month. The tenant of the Greenpoint stadium withdrew after the World Cup, leaving the maintenance cost entirely for the city of Cape Town. The city of Cape Town already knew before the event that such a stadium could not exist without a permanent user. For a football club like Ajax Cape Town it is not natural to draw enormous amounts of spectators. Normally about 6000 fans will watch a football match of an South African club, but the stadium has a capacity of more than 60.000. Cape Town simply cannot afford such a stadium, more strikingly it is built in the wrong place. It is located far away from the local communities where the football enthusiasts live. Secondly there are too little large events in Cape Town to attract large crowds (NOS 2010). Cape Town has 2 stadiums which could have served as World Cup venues: Newlands with a capacity of 55.000 and Athlone with a capacity of 30.000. But FIFA really wanted to have a new stadium between the mountain and the sea, so the townships wouldn’t be part of the general TV footage. All these factors made the Greenpoint stadium a classic white elephant.

These examples showed creating a legacy isn’t that simple. The lingering question of course is whether the impact of hosting the Olympic Games or other Major sporting events such as the Word Cup justify the enormous costs. Isn’t there a way of rethinking these enormous
events completely, where legacy is part of the central architectural question. The Rotterdam 2028 Olympic Games should be about more than just an event, preventing white elephants to occur. The previous examples showed some interesting legacy questions for the graduation design. These questions exist on multiple levels, from the larger masterplan towards the final architectural detail.

1.6 Raising Questions for Rotterdam 2028
The post-Olympic stadium will be an important aspect of this graduation research. We first have to think about the benefits for a city like Rotterdam before an Olympic stadium design can be developed. The stadium legacy situation will be investigated throughout all aspects of the design project. The main focus of this research is on the technical- and spatial feasibility of a floating post-Olympic residential stadium. There are no real precedents of residential buildings with Olympic origin. Perhaps this is due to the architectural complexity or simply because there has been no need for it. There are no architectural guidelines for designing a stadium with a post-Olympic residential usage. To suit the Rotterdam Delta Games theme the focus is also on floating stadium structures. This research therefor focuses also on the generic and specific conditions necessary for a large floating structure. The leading research question will be:

How can you reuse different stadium elements after the Olympic Games into a floating residential quarter?

One of the characteristics of a floating post-Olympic residential stadium, compared to previous Olympic stadiums, it its setting. The post-Olympic setting is just as important as the Olympic setting. The Rotterdam South harbour area will be developed into a mixed residential and working area. The departure of the harbour related industry will result into new architectural possibilities. Where most Olympic stadiums are located at the edges of cities and neighbourhoods, one of the aimed strengths of the stadium fleet will be its implementation into the urban (residential) context.

What impact can the Olympics have on the development of the urban context in Rotterdam South?

Apart from its enormous scale, an Olympic stadium communicates a certain statement. The Olympic Games are much more than just a sporting event. It is a change for a country and city to present itself on a global level. Hosting the Olympic can be a catalyst for different types of development, like the public space and tourism of Barcelona 1992, the environmental statement of Sydney 2000 and the sustainable legacy of London 2012. Focussing on the harbour area of Rotterdam and Dutch Delta Games Olympic theme:

What influence can the Olympic Games have on the image of Rotterdam and the engineering focus of the Dutch Delta?

When designing a hybrid stadium with stadium and residential usage components it is also a route with multiple junctions. The stadium and the residential requirements will be difficult to merge without having to give one of them a higher priority. It is a question of balancing both worlds without compromising on one of the building specific aspects. The stadium should look like a real Olympic venue without the loss of space and dynamic caused by the residential post-Olympic usage and visa versa. Another aspect is the floating boundaries which are influencing both the stadium and the residential usage. These floating boundaries should be incorporated into the overall design without degrading the overall architectural perception. The floating capabilities of different structures will be investigated throughout the design process. The adjustments and influences due to this floating character will be described and processed. Even so, the elements of Reduce, Reuse and Recycle, could help the design to be a sustainable solution for rethinking Olympic and temporary structures. These themes will guide the design from large scale structure to the level of the final detailing.

Can you make a floating stadium with permanent and temporary components where the question of sustainability is incorporated from the overall design to the final detail, minimising the adjustments necessary for the post-Olympic usage?
In 2006 the NOC*NSF decided to begin researching the possibilities of organising the Olympic and Paralympic Games in the Netherlands. The Olympic ambition for 2028 was born, 100 years after the 1928 Games of Amsterdam. The plan can be a source of inspiration for the Dutch sport orientated population, increasing the width of the sport as well as the top sport environment. Big events set high standard for mobility and accessibility, the Olympic Games can be a catalyst for spatial projects where 2028 is a hard deadline. The construction of sporting venues is an unique opportunity for the realisation of existing ideas like the Dutch Floating Games or Dutch Water Games, harvesting extra international attention comparable with the Dutch Delta Works. The Olympic impact, the sustainable aspects and the first Dutch and Rotterdam spatial plans are creating a context for the graduation design.

2.1. Olympic impact
The large scale of the Olympic Games becomes clear by the size of the needed area. The complete Olympic program covers a maximum of 600 hectare of ground, this is as large as an area of 2.5 by 2.5 kilometre. The area is about the same size as the complete city centre of Amsterdam or 100 times the size of the Binnenhof. Although there have been large development areas in the Netherlands the past years, the combination of scale and deadline makes every comparison unreliable. The sporting map of the Netherlands does not include the Olympic big five: an Olympic stadium, the athletes village, a large indoor venue, the main press centre and the international broadcast centre. These five have to be built new, housed in other accommodations or being accomplished entirely different (Bouw 2010). The winning Olympic bids of the previous Games all had these five built in one concentrated urban region. The maximal time-distance between these five can be approximately 40 minutes according to IOC guidelines. With the present infrastructure in the Netherlands, without traffic jams, this can be the distance between Amsterdam-Zuid and the Kralingse Plas in Rotterdam, or the distance between the Binnenhof and the city of Breda.

The social carrying capacity within one urban region in the Netherlands is certainly limited, because the country is relatively small and the cities are spread out. The Netherlands is missing the urban mass, which is present at other metropolitan areas abroad. The Randstad does not operate as one closed urban system for its inhabitants. This is noticeable in the strong local and regional character of the labour and housing markets, limiting the possibility of a profitable concentrated distribution of Olympic program. This does not mean that finding the necessary space for a new Olympic village or new sporting venues is a major problem, the real problem is finding the carrying capacity within one urban region. The biggest challenge for the Netherlands is balancing the delivered efforts and the legacy profits, closely linked with the concentration and distribution of the Olympic program (Bouw 2010).

The problem solving capacity of a concentrated program can be very large perhaps, like the London 2012 upgrading of a deprived area. Then again it is also attractive having larger areas of the Netherlands profit from the Olympic investments, but as a result the change of dilution will increase. The Dutch configuration of small cities with relatively large distances have their possibilities and impossibilities. The small scale, vulnerable system of the Dutch Delta with its dense water management systems will make large interventions even more radical and expensive. Finally the infrastructure network has its own characteristics. Because of the low density in the Randstad, the network of roads and rail tracks can not be compared to the ones of some other metropolis. According to IOC guidelines, a city should be name the organisation of the Olympic Games. Amsterdam and Rotterdam are willing to play the role of candidate city. But before different models for a Dutch Olympic structure are compared, it is important to know the environmental influences and sustainable impact for the total 2028 bid. The sustainable impact of the Olympics can be described with the size of the carbon footprint and the amount of energy necessary for hosting the Games.

2.2. Sustainable impact
Sustainability is one of the knock-out criteria for every Olympic bid, since the environmental protest against the Lillehammer 1994 Winter Games. Sydney even presented the Green Games theme. In Beijing it was necessary to implement green solution for creating conditions
which were suitable for sport without health risks (Ministerie van VROM 2008). With an average sustainability plan a hosting city cannot distinguish itself. A Dutch Olympic bid should therefore be innovative in the way sustainability is incorporated into the entire plan. At this moment the Netherlands is no forerunner in the realisation of sustainable objectives. By making the Olympic ambition sustainable in relation to, transport solutions, infrastructure, energy management, water management, materials, building and innovation, an extra step forward can be made, presenting the Netherlands on the international map.

Not only is the Olympic impact determined by the size of the event, also the environmental impact is enormous. Sport stadia are huge pieces of infrastructure. When it comes to sustainable design, their use of energy is a major issue. The industry must learn to reduce the energy used in their initial construction, the so-called embodied energy, and to later reuse the building materials in future projects (Populous 2010). In office buildings, most of the energy usage is in operational energy. When it comes to stadia, operational energy is on a much lower scale. The embodied energy far outweighs the operational energy used over its lifetime. Most stadiums are designed to last 50 years, but are used for only 18 months of those 50 years. Once they reach the end of their useful lives, they require huge amounts of energy for demolition too. In a stadium, one steel beam can have an embodied energy of 158 tonnes. This is the equivalent of burning 4000 light bulbs at 20 watts non-stop for a year and a half. This is why the lean design of stadia and the considered materials in construction or refurbishment are so important (Populous 2010).

The London 2012 reference footprint is estimated to be 3.4 million tonnes of carbon dioxide equivalents. Most of the carbon emissions will occur before the Games. These arise from the construction of venues, the delivery of transport infrastructure, and the fitting out and dressing of the venues and Olympic park. Most of the remaining activities and emissions are caused by spectators during the Games. The venues alone are responsible for a carbon footprint of 1.728 kilo tonnes carbon dioxide, 129 of these tonnes is caused by the 2012 Olympic stadium (London Organising Committee 2010).

The amount of carbon emissions can be decreased by developing lightweight structures and make use of materials that produce less carbon dioxide during their manufacture. This both reduced the embodied energy and the financial costs. The less material and the simpler the designs, the more you save in energy and money. The building materials with the greatest amount of embodied energy in them are aluminium and stainless steel, even six times more than reinforced concrete. When it comes to carbon dioxide reduction, stainless steel and aluminium are being avoided. Despite containing less embodied energy, concrete is not always the obvious choose since it is much heavier than a steel structure with similar strength. By far the greatest amount of embodied energy is in the foundations and superstructure, rather than in the cladding, so its important for designers and engineers to use as little steel and concrete in these areas (Populous 2010). Increased use of considered recycled materials is essential.
to reduce the embodied energy in building fabric. The transportation of building materials from source construction to site is often overlooked. Shipping timber by sea from Canada across the Atlantic Ocean to the Netherlands, uses less embodied energy than transporting timber over a short distance by road from Germany to the Netherlands. Sea freight uses the least amount of embodied energy, while air freight uses the most. It is important to make use of the existing topography of the construction site as much as possible. Most importantly no embodied energy is necessary for construction of Olympic venues when venues are used which are already existing in the Netherlands. Permanent structures should only be made when a long-term use after the Games is guaranteed, otherwise the best solution is using temporary structures.

In the reference footprint of London 2012, the largest single source of emissions attributable to the Games is linked to the activities of spectators. The total spectator reference footprint is estimated to be 670 kilo tonnes of carbon dioxide. London 2012 estimates that about 30% of all spectators will arrive from overseas. Travel predominates, making up two-third of the total spectator impact, in particular overseas flights. Air travel will take 52% of all embodied energy attributable to spectators. The footprints of spectator accommodation, catering and merchandise are smaller but also significant. In the reference chart, only transport to and from London is included, not travel within London (London Organising Committee 2010). The journeys to events outside of London were also taken into account. Travel plays an important role for the total carbon footprint of such an event. When considering having multiple hosting cities in the Randstad area, the travel footprint becomes even more important. Sustainable transport, for instance transport over water, can therefore be an important aspect of an Olympic bid. The concentration of the main Olympic venues will limit transportation and thus positively influence the carbon dioxide reference footprint.

An large event such as the Olympic Games, consumes a lot a energy. EDF energy, Britain’s largest electricity generator, estimated the venue energy use of the London 2012 Olympic Games. The energy usage of the big five is highlighted: the Olympic stadium and warm-up track is estimated to use 2,400 MWh of electricity and 165,000 m³ of gas, the athletes village is estimated to use 4,300 MWh of electricity and 170,000 m³ of gas, the largest indoor venue (basketball arena) is estimated to use 1,100 MWh of electricity and 60,000 m³ of gas, the main press centre is estimated to use 1,250 MWh of electricity and 75,000 m³ of gas and the international broadcast centre is estimated to use 5,000 MWh of electricity and 200,000 m³ of gas (London Organising Committee 2010). In total the big five is estimated to use 14,050 MWh of electricity and 670,000 m³ of gas. London 2012 made these estimations for every venue, by adding all the estimates the total Olympic energy use can be found. For London 2012 this will be an estimate of 24,481 MWh of electricity and 1,955,985 m³ of gas. Vancouver 2010 was valued because of its energy saving solutions. Although Vancouver hosted the Winter Games, it was the first time in history that nine key venues and sites where monitored and energy consumption was publicly reported during the Games. By monitoring energy usage real-time, instant adjustments could be made. The total energy savings recorded by the venue energy tracker were 906 MWh (www.venueenergytracker.com).

Perhaps it is presumable that in 2028 environmental solutions, sustainable energy, water management and material use are common. The Olympic Games could be the driver for trying to raise the standards. The real Dutch points of application are within the area of water management, climate-proof water dwellings, environmental logistics and energy solutions implementing with wind and water. The choose of Olympic location can create the conditions suitable for environmental solutions. The real ambitions concerning sustainability will eventually be expressed in the arrangement of the Olympic site itself and the construction of the venues and accommodations (Ministerie van VROM 2008).

2.3. The Dutch Olympic scenario’s
With the model ‘three times a city’, different scenarios’ are given for presenting the 2028 Olympic Games (Bouw 2010). The first scenario’s are presenting the Olympic program within one urban area (Amsterdam or Rotterdam), the other scenario presents is combining the forces of Amsterdam and Rotterdam creating a larger legacy for the Netherlands. These scenario’s are giving potential locations for the big five. Development areas of the region can be linked to the Olympic program. Different flexible structures can be linked, the overlaps of the different structures give the gravitational centers of the scenario. The structures can be linked by social drivers like: water Games, international Games and urban Games. The infrastructure problems and developments are taken into account for every scenario. Before the scenario’s
The Dutch Sport Map

* The venue and accommodation distribution and concentration is plotted on the scale of the Netherlands. Although the big five does not exist in the Netherlands, a great promises in capacity are already existing in the preparation for an Olympic event. These venues are only suitable for the Olympic Games when the capacity is inspected. The availability of training fields and media facilities is not taken into account.

are compared the total Dutch Sport Map is developed, giving insight in the concentrations of existing sporting venues and accommodations for the larger sports such as: football, cycling, sailing and large indoor sports. Big locations such as the Amsterdam Rai, the Jaarbeurshallen of Utrecht and Rotterdam Ahoy are also added to the existing sporting locations. The concentrations of existing sport venues are the most dense at the Amsterdam and Rotterdam region. Both regions have offshoots towards other cities. The offshoot of Rotterdam includes Den Haag and the surrounding region. The offshoot of Amsterdam includes Utrecht and the coastal region. In the rest of the Netherlands, the large existing venues are scattered, making it harder to include these venues in an Olympic plan.

Every possible location for the Olympic Games in the Netherlands is divided in a number of structures where Olympic locations can be placed. Within the cohesion of these places in combination with spatial quality, social drivers can be found. Some structures can be linked to the theme ‘water’, while the urban density can be a driver for other structures. The overlapping of these structures can form the centre for the Olympic Games, this way the distribution and concentration of possible Olympic locations can be reviewed.

Amsterdam

Within the region of Amsterdam, there are a number of spacial cases which can be linked to the Olympic Games: Zuid-as, RAAM (Rijksbesluiten Amsterdam Almere Markemeer) and Zaan IJ. The Zuid-as and RAAM cases are already attached to the existing infrastructure of Amsterdam and the Netherlands. The Zuid-as and the centre of Amsterdam are the center points of the Olympic locations. In the Amsterdam region, three structures are making the total scenario: the Water Games, the International Games and the City Games (Bouw 2010).

The Water Games are linked to the large developments surrounding the IJmeer and the sides of the Zaan-IJ, connected to the dynamic of the Zuid-as. A new rail connection towards Almere is one driver of this structure. The legacy is the economic progress of Almere and the iconic driver of this structure are the water of the IJ, the harbour and canals. The International Games are making the link between Schiphol and the Zuid-as, reaching further to Duivendrecht. The result will be a wide international zone where connection is the theme and legacy. The City Games are using central urban area’s as possible Olympic locations. The Zaan-IJ, Zuid-as,
Duivendrecht and the Jaarbeurs in Utrecht are linked. Urban quality will be the driver of this structure, the main challenge will be making connections on a relatively small scale.

The Water Games have potentially 270 percent of the maximum area needed for hosting the Games (maximum is around 600 Ha). The International Games have 340 percent and the City Games have only 70 percent of the area needed. This means that the City Games structure cannot exist alone.

Rotterdam
In the area of Rotterdam there are a large number of spatial cases which can be linked to the Olympic Games: Stadshavens, the Stadionpark en the Hart van Zuid. These areas are creating the centre of overlapping structures between Den Haag and Dordrecht. Rotterdam can choose different directions, benefitting the focus of spatial developments. The accessibility of Rotterdam is improved over the last years. The high speed train will take you to Schiphol within 25 minutes and Antwerpen is 30 minutes away. The connection with Den Haag is also improved with the new Randstadrail. The future of the accessibility by road however is less bright. Without large investments these roads will be jammed by traffic in 2020, one of the main Rotterdam challenges. With the plans for the renewed Stadionpark, the refurbishment of the area surrounding Ahoy, Hart van Zuid and the large developments of the Stadhavens, the centre of the Rotterdam Olympics should be located on the south side of the Maas. The transformation of the harbour areas will be an important link within the infrastructure of Rotterdam. The social and economic renew of the area are the large drivers of these developments. The clear focus of the Rotterdam case makes is a hard and interconnected puzzle. The freedom of movement and flexibility are relatively limited for the future. Solving the Rotterdam puzzle can be an enormous challenge for Olympic developments. With infrastructural investments, the sporting city of Rotterdam can grow to Olympic levels. The space available on the Rotterdam hotspot (Stadshavens Zuid), will make it an even more suitable location for the 2028 Olympic Games.

The Rotterdam structures are: the City Games, The Delta Games and the South Wing Games. The City Games are focussing on the larger locations of the Rotterdam urban area with a possible link to the Rotterdam-The Hague airport. The space required for the Olympic Games

*The Amsterdam scenario
*The three structures: Water Games, International Games and City Games are overlapping in the Zuid-as area. The potential Olympic locations are marked with yellow.
The Rotterdam scenario

* The three structures: City Games, Delta Games, South Wing Games are overlapping in the Stadshavens area. The amount of potential Olympic areas is large.

can be realised within this structure. The Delta Games are making the link between Rotterdam and Dordrecht and the in-between Deltapoort. The South Wing Games are reaching over Rotterdam and Den Haag, involving the area of Scheveningen, Binckhorst, Vlietzone and Midden Delftland, improvements the metropolitan development of the region. This structure can give a bit more flexibility and room to the planning process (Bouw 2010).

The City Games have potentially 170 percent of the maximum area needed for hosting the Games. The Delta Games have 185 percent and the South Wing Games have 380 percent of the area needed. All Rotterdam structures have more than enough potential area.

Promising increased scale
The Randstad does not make optimal use of its four large cities, in practice it is a non-integrated urban functional system. The Olympic Games can improve the intern accessibility of the Randstad and give a strong impulse to the development of a coherent Randstad urban system. The opposite is also true, connecting the south and north wing of the Randstad will improve market conditions for making sporting accommodations and venues. Urban densification and social-economic renewing can be a mutual legacy driver for the larger cities when organising the Games. The possible locations for the Olympic site will be the same as for Amsterdam or Rotterdam alone. The Olympic legacy can also be engaged on a higher level, meaning the improvement of the total Randstad system (Bouw 2010). The focus will be on internal links and international connections. The promising increased scale can be structures by: the Mainport Games and the G4-Games (Big Four Cities).

The Mainport Games have potentially 225 percent of the maximum area needed for hosting the Games. The G4-Games have 211 percent. Both structures have enough potential area.

2.4. The Dutch Delta Games
In this graduation project the Rotterdam scenario is further explored, with a focus on the Rotterdam Stadshavens area. As the centre of the delta region, Rotterdam and Den Haag have an unique international position and reputation which should be exploited to have the best possible opportunity for hosting the Olympic Games (Stichting Rotterdam Topsport 2011). The economic significance of the water industry in the Netherlands is estimated to be
around 7.5 billion euro a year. For the international world, the Netherlands is synonymous for water. The Netherlands is frontrunner in the area of water innovation and water management, delivering high employment opportunities. The concept of floating Olympic Games is an ideal starting point to put the international spotlight on the Dutch water qualities, immortalising the role of Holland as ‘benchmark’ for future water management and engineering (OeverZaaijer 2011). The Olympic Games will become a showcase for the Dutch Delta industry, a follow-up of the Dutch Deltaworks (Maeslant barrier), the next chapter of Dutch Delta Engineering and a Delta legacy for future generations.

Promising increased scale
* This scenario can act as the Mainport Games with the Schiphol area and the Rotterdam harbour area. Also the Four largest cities of the Netherlands can play a role: Amsterdam, Rotterdam, Den Haag and Utrecht.

Dutch Delta Engineering
* Modern and old examples of the Dutch engineering tradition: the Maeslant barrier, Traditional mills and dike, What is the next chapter?
The proposed area for the Dutch 2028 Olympics will be Rotterdam Stadshavens for this design project. The area is closely related to the inner city of Rotterdam but yet it is an distinctive harbour area. With the new harbour development at the shore of the Netherlands these harbour area’s close to the city will disappear in the future, maybe already by 2028.

3.1. Moving to the west

Part of the harbour related activities will leave the city of Rotterdam towards the 2nd Maasvlakte area. Redeveloping will give new opportunities for existing harbour activities which will not leave the area and completely new developments. Almost 1600 hectares within the inner city of Rotterdam will be ready for redevelopment. An area which is closely linked to the city of Rotterdam and connected to different international streams. The city of Rotterdam have set 2 goals; strengthening the economic structure and creating attractive high-value work and living environments.

The redevelopment of the stadshavens area will take place on multiple areas. The city of Rotterdam and the Rotterdam harbour have created 5 different strategies for the area. These strategies are developed for different time spans. The shortest time span aims for the year 2015. The intermediate time span aims for the year of 2025 and the largest time span aims for 2040.
The five different strategies for the future are:

- re-inventing deltatechnology,
- volume & value
- crossing borders
- floating communities
- sustainable mobility.

For the Rotterdam Olympic Games, the most important strategies are re-inventing delta technology and floating communities.

Rotterdam is frontrunner on the area of water management and energy transition. The stadshavens area is an unique testing ground for experiencing new forms of energy and innovations in the area of water safety and water management. The re-inventing deltatechnology strategy is ideal for experimental Olympic stadium design and engineering. The Rotterdam 2028 Olympic stadium can be the first fully floating and reusable stadium in the world. The reusability of the stadium can be seen in the second strategy used in this case, the floating communities. Rotterdam will be investing and developing new ways for living and working on the water surface, creating entire communities. The Rotterdam Olympic stadium can become just such an community after the Games leave town. The stadium will become the backbone for a newly developed community. Parts of the infrastructure of the stadium will become the foundation for the new living and working environment. The sustainable mobility strategy will increase the connections of the old harbour area with then inner city of Rotterdam. An extra light rail connects a large number of areas within the stadshavens region. An extra connection between the South and North bank of the Maas is developed the same time. Also the metro network is extended with a new line between the area of Pendrecht on the south bank

Vision of future structure Stadshavens 2011
The city of Rotterdam developed this vision for the structure of the entire stadshavens area.
of the Maas and Marconiplein of the north bank of the Maas. Extra stops are added for the different Olympic area’s (Zuiderpark and Waalhaven).

The industrial part of the stadshavens area is decreased (pink) and the space for living and working is increased (beige), extra green boulevard are connecting the Zuiderpark area with the new Olympic Park. And finally an extra floating community is added on the end of Waalheven island; the Olympic stadium community.

Adjusting the structure for the Olympic Games
For the Olympic Games the structure is redesigned to suit the needs of such an mega event.

Olympic connections and floating communities
The “Big Five” can be located on and around the Waalhaven area. The International Broadcast Centre and Media & Press Centre can be located on the Heijplaat area on the left of the Waalhaven. The Olympic Stadium can be located in the water of the Waalhaven. The large indoor arena is located in the Zuiderpark (ahoy), and finally the Olympic village can be located on the North bank of the Maas.

3.2. Waalhaven Olympic Redevelopment
The Waalhaven area is redeveloped into an Olympic Park. Two main green park boulevards are opened up to make room for the stadium arms in the center of the Olympic plan. The arms grab the stadium and support its infrastructural use. Furthermore on the north side of the plan room is made for a temporary and a permanent stadium. The west side of the Rotterdam south area is redeveloped into a new front, connecting the older area of Rotterdam with the new Stadium Park. In the central axis a permanent complex is located and on the south side of the park an extra temporary facility can be located. The training ground for the athletes is located next to the stadium on the central island. Athletes can reach the stadium.
by a floating connection which will guide them underneath the eastern arm towards the stadium entrance.

After the Olympics, the temporary venues are dismantled and room is made free for the construction of extra housing and high-end office space. A large part of the stadium will be disassembled and taken to other locations. Extra floating homes can connect to the former stadium grid to form a new floating community retaining the stadium feel. The Olympic park is redeveloped with urban villa’s, larger apartment complexes in a natural environment.
Sustainable design can be defined as smart design; searching for spatial solutions which are efficient and effective. Efficient as in costs, space, material- and energy use and effective as in economy, environment and utility value. Technical solutions are expensive and provide relatively little in comparison with the profits of a well designed building in the first place. The most important themes for effective and efficient buildings are: life-cycle of buildings, material use, energy and water, interior environment (Grouls 2009). In this chapter the focus is mainly on the first two themes. Life-cycle sustainability is a form of smart design. This means not just extending the life-cycle of a building, but also to be conscious about the life and flexibility of buildings and building elements. A lot of times buildings with a short life-cycle are made of materials with a long technical life-cycle. How can we adjust the material use to the life-cycle of buildings in a effective and efficient way?

Scenarios and strategies can be assessed within the framework of economy, environment and utility value. With every scenario the sustainable accent will be positioned on a different place within the assessment framework. The methodology can be used in different stages of the design process. It can be used for defining the real design task, but also for the chooses of material and building elements. We will discuss the environmental loads by building materials and not so much the energy efficiency one thinks about first when discussing sustainability. The scenario’s in this chapter are generic solutions which can be used for all sorts of buildings: housing, offices, schools and shops. The strategies are specifically focussed on stadium design and engineering.

4.1. Life-cycle design
A building will be demolished or replaced if the technical, economical and functional life-cycle of a building are not matched to each other. It will cost a lot of energy to process these building into construction waste. Building will be different when an area is influenced by social changes. With these social changes we mean social-economical changes in the area of policy and regulations. Next to this social dynamic there is also a dynamic relocation behaviour in the offices and housing sectors. Entrepreneurs are averagely moving after 5 till 30 years. In the housing sector tenants are already moving after 7 years.

The environmental load of a building will be determined largely by the building materials in the first decade (Dobbelsteen 2004). This part of the environmental-costs is larger compared to the energy usage part. After 20-30 years both parts are equal and after this period the environmental load is mainly determined by the energy consumption. When we look at the total amount of building materials, 60-70% of the environmental load is caused by the support structure. The high environmental loads of office buildings are mostly due to the large number of transformations within the buildings. When offices are not consciously dealing with building materials this can cause a high environmental load. A conscious choose has to be made between offices with a long term usage with surplus and a short therm usage with demountable capabilities (Dobbelsteen 2004).

In the past there have been multiple researches about adjustable housing. A difference has to be made between buildings with a long life-cycle and demountable buildings. In the 60’s the foundation was made by Habraken’s concept of support structure and build in structure. It was followed by the movement of the Open Building in the 80’s with the realisation of some projects based on the concept of Habraken. The Solid concept is the modern variant where permanent timeless structures are kept separate of the build-in structures. According to the solid concept the change for long term survival of the building will increase in this way. The foundations of demountable buildings were made by the IFD build movement (industrial, flexible and demountable). Possibilities for change within a building are realized by composed structures of industrial manufactured demountable building components. Because of this flexibility, the desires and demands of users are more easy to achieve which results in the extension of the life-cycle. A differentiation of IFD building is the concept of Slimbouwen (smart buildings). The physical and organisational detachment of installation wires is seen as the key to an efficient and economical building process. Besides this, the concept strives for a construction as slim as possible to limit the amount of materials.
The solution for life-cycle sustainability is not unambiguous. For this reason we should not focus on one single concept, but on a methodology where flexibility and life-span are being matched to the design task (Grouls 2009). Optimising the balance between life-span, building elements and the use of materials can decrease the environmental load substantial. Materials with a large life-span are used in places where they are really necessary. Demountable components or materials with a short life-span are used when the life expectancy of the building is short.

Often buildings should be able to be adjusted during the phase of use as a consequence of the external forces. Different responses are distinguished: adjusting the outside appearance, adjusting the technology, conversion and reuse. These responses could extend the life-span of the building. Most important changes are: physical contexts changes, pressure on location changes, location stability, technological changes, climatological changes, cultural changes, changing trends and social context changes. When a location is instable, a building should be easy to demount. By change in the physical context a building can become attractive for different functions. By change in the location pressure, the building can be attractive for conversion (office to housing). Changes in the social structure of the location can cause the building to be attractive for a different function. Cultural changes can make the building attractive for a different target group. Changes of trends can cause changes in the demands for facade appearance and interior. One can choose to change the building through time or one could choose a timeless image. Because of climatological changes, requirements of installations and facades can change. Requirements of installation technology can change by technological progress.

4.2. Durability & flexibility
The durability of a building can be extended by making a building more flexible. A distinction has been made between different life-cycles, which differ in length and cycle:
- **Structural durability** (ST). The building structure will have the longest life-cycle. The structural durability will be longer compared to the economical durability.
- **Economical durability** (Ec). This is the period in which the building is financial profitable. The cycle depends on the type of owner, market situation and location.
- **Functional durability** (Fu). This is the period in which the building suits its function. The cycle depends on the type of function and user.
- **Installation durability** (IT). This is the period in which the building meets the requirements for the technological installations. The life-span of this cycle is short due to the rapid developments in this sector with increasing efficiency. Also the demands for comfort and energy efficiency are ever changing.
- **Aesthetical durability** (Es). This is the period in which the building meets the wishes and demands for the appearance. This life-cycle is very short, especially for the interior due to rapid changes in architectural trends. By designing without trend sensitive interiors and exteriors the life-span can be extended.

The separate elements of a building have their own life-cycle. A distinction has to be made between structure, openings, facade, installation and build-in components. When a building is flexible and building elements are easily adjustable, the life-cycles of the building elements will differ. Material is used efficient when it is adjusted to the usable time of a building element.

To extend the life-span of a building a building can be designed to be flexible. Flexibility means that a building can easily be adjusted without radical rebuilds. Diversity is the exact opposite of flexibility, since diverse spaces are created. Users can find a place within the building meeting their requirements. For the adaptability of a building a distinction can be made between extending, rebuilding and polyvalent use (Leupen 2002). Polyvalent use means having multiple possibilities for use without structural adjustments. Flexibility can act on different levels: building, unit and space. The most flexible solution is adaptability at the building level. This can be achieved by smart grid lines, within which multiple function can find their place. At the level of unit, the adaptability can be increased by having a surplus of space. Adaptability on the level of space is the least flexible. Just minor changes, like replacing power-sockets and dividing spaces.

4.3. Methodology & assessment
Effective solutions for architecture are an assessment of economy, environment and value of use (Grouls 2009). Sometimes a solution is focussed more on value of use, other times a solution can be located between environment and economy. The assessment triangle used by Grouls is a variant of: People, Planet, Prosperity, with which environmental assessment can be made. The triangle can be used for assessing design choices and raising design questions.
With the assessment of environment we mean: non-living elements (water, fossil fuels, raw material), ecosystems, air, light and water. The focus on environment is especially important for building with a short life-cycle. With environment the focus is on: preventing the exhaustion of raw materials, preventing the exhaustion of finite energy sources, preventing the exhaustion of the water supply, preventing the degradation of the human health (smog, sound) and preventing the degradation of ecosystems.

With the assessment of economy the costs and profits are the central topics. The focus on economy can be important for short-term and long-term buildings. For short-term buildings it is important to limit the construction costs, for long-term buildings it is important to limit the operating costs. Sometimes bigger investments result in lower operating costs. This is mainly likeable for flexible buildings with a long life-cycle. With economy the focus is on: limiting the construction costs, reducing the operating costs, reducing the risk of depopulation of the building and increasing the market- and selling value.

With the value of use assessment the human being is the central topic. The focus is on the user and the surrounding of the building. The value of use is especially important for buildings with a large life-span, by means of increasing their chance of survival. With the value of use the focus is on: increasing functionality, increasing the experience value, increasing flexibility, increasing the identity within its surrounding and limiting the management and maintenance of the building.

The methodology for efficient and effective design chooses consists of 3 steps: first the scenario is determined, next the position within the assessment frame work is determined and finally the strategy for separate building components is determined to create a design (Grols 2009). An essential part of this methodology is the assessment frame work, where the focus of the project will be decided. The architectural expression can be a result of this assessment. The scenario’s are determined by investigating the expected life-span and degree of flexibility. The assessment framework is determined by the themes: environment, economy and value of use. The strategies are determined for each building component (structure, openings, facade, installation and build-in components). Each of the building components will have their own life-cycle which differs for every single scenario. In a specific building all life-cycles are as long as the overall life-cycle.

This methodology will change for the life-cycle of stadiums. The third step will be splitted into 2 parts: component strategy and stadium strategy. The component strategy is for the component level of the design. Stadium strategy will be an extension of the scenario from step 1, but with strategy similarities. One of the reasons this is done is the fact stadiums are being engineered with more than one aspect of the scenario’s at step 1, for instance scenario combinations and conversions. The stadium strategies are divided in; temporary structures, extensions, modular structures, multipurpose structures, conversions. The strategy of floating structures finally is a special type. For floating structures the assessment is more difficult due to the fact environment, economy and value of use are not behaving static but dynamic. Therefore strategies can change when the location of the floating structure changes. The third step of the stadium design methodology will become:
4.4. Scenario’s

The scenario’s from the first step are clarified by life-span and flexibility on both axes. The difference between short-term and long-term is about 25 years. At this border situation, energy costs will be more important compared to building materials. This is also the critical point of the building: modifying or demolishing. Specific and flexible are located on the other axis. A building is specifically designed for one function or it is flexible. The properties of the different scenario’s are further explained and compared, so a choice can be made.

Specific short-term

The life-span of this scenario is shorter than 25 years. It is specifically designed for one function, where little adjustments can be made to extend the life-span. If the life-span of the building is expired, the building will be demolished. This scenario is ideal for locations subjected to a lot of changes, a function with little flexibility and little build budget. Also for single-events demanding specific temporary buildings this is a good scenario. These buildings are slim and light in material- and energy-use. Most building parts will be recycled, composted or burned. These buildings can be qualified as disposable buildings. The gravitational center in the assessment framework will be located at environment and economy.

Flexible short-term

The life-span of this scenario is shorter than 25 years. It is designed with a flexible structure and can easily be adjusted to new requirements and demands. The building can be demolished after its life-span. This scenario is especially useful for dynamitic locations, flexible functions and for clients who can overlook only a short period of time. These buildings are also useful for returning events demanding temporary buildings (beach pavilions). During the life-span of these buildings they can be rebuild and extended with units. When a building is demolished, or in this situation disassembled, large parts of the building can be reused. Multiple configurations can be imagined. The gravitational center in the assessment framework will be located at environment and value of use.

Specific long-term

The life-span of this scenario is longer than 25 years. The building is specifically designed for its purpose and will be demolished after its life-span. This scenario is useful for stable locations, specific functions and larger budgets. These buildings will not be adjusted to the user, but the user should adjust to the building. Flexibility is limited to adjusting installations, partition walls and window framing. Decreasing the cost for energy-use and maintenance are important for these kind of building designs. The gravitational center in the assessment framework will be located at value of use and economy.

Flexible long-term

The life-span of this scenario is longer than 25 years. This scenario is capable to cope with most changes: not only can panels, build-in components and installations easily be replaced, also lots of parts can be reused. Buildings from this scenario are build with permanent structures and temporary elements. This scenario is useful for stable locations, functions of change and clients who can overlook a larger period and want to invest in a solid permanent structure (hospitals and universities). By investing in a good permanent structure, with a lot of flexibility, the change of survival will increase. The temporary building elements have a low

The different scenario’s

3. Herzog & de Meuron, Prada Store, Tokyo 2003, Specific long-term building.
4. Yositaka Udida, Next 21 Housing, Osaka 1994, Permanent structure with flexible facade system.
environmental load. The gravitational center in the assessment framework will be located at all themes, because all previous scenarios are combined in this flexible long-term scenario.

4.5. Building strategies

The strategies for the different building elements can be determined. A distinction is made between, structure, openings, facade, installations and build-in components. Using the right materials for the building elements will increase the efficiency and effectiveness of the scenario. All strategies strive for reusability. Reusability can be achieved on different levels: reusability of the building itself, reusability of building components and recycling. Reusing a building structure is the most profitable for the environmental loads. A new structure will be responsible for 60-70% of the total environmental loads by building materials.

Specific short-term

When the life-span of a building is over, building elements can be burned, recycled or composted. When demount is taken into account in the design process of the building, the chance for qualitative good recycling is the largest. The best quality can be achieved with the recycling of pure material, not mixed with any other material. The materials are lightweight so production, transport, and built are limited. Demountable dry connections make sure that materials can be separated from each other, so the materials can be independently recycled. Although flexibility is not a topic in this strategy, a slim and light frame construction is preferred. Because of the low accumulation capacity of lightweight structures extra installations are often necessary for heating and cooling, although installations should be limited because of the short life-span. Natural and simple installations preferable. Often the facade will take over the function of installations (passive heating by large south-side windows and small north-side windows, use of rainwater and natural ventilation). Lightweight renewable (infinit) materials which can be burned or composted. Material examples are FSC Wood, bamboo, cardboard, loam, straw and textiles. Recyclable plastics are also suitable. Chipboard can be used instead of plasterboard for partition walls. Other options are textile, cardboard or cork.

Flexible short-term

Building elements used in flexible short-term buildings are lightweight and demountable: they can easily be moved, replaced or extended. Building systems are not only saving time during construction, but adjustments during the use phase are also simple. The technical life-span of the used materials is often longer compared to the operational life-span: materials have an extra life-span elsewhere. The degree of flexibility is depending of the assignment. Installations (equipment and infrastructure) have to be limited because of the short life-span. The interior climate is regulated by the facade as much as possible. Declutching and organizing large quantities of wires and pipes to integrate them into the design process is very important. The construction is often a grid or wall structure. Hollow floors with the possibility for imbedded pipes can be used (Infra++, Slimline or Holcom). Also wood systems are often used because of the lower environmental load. Reusing steel profiles is a good option. Almost 49% of all steel profiles is already reused and 45% of all steel is recycled worldwide. Recycling will use 45% less energy compared to making new steel from iron ore (Grouls 2009). Paneling is used for the facade, so adjustments and extensions can easily be made. Multiple small vertical ducts are preferred to increase flexibility and overview. The duct should also be easily reachable for flexibility. The build-in components are often made from wood elements. Gyproc Cable Stud gives the possibility for flexible electric plugs and installations. The connections are demountable (preferably dry), so the used systems can be loosened from the facade or structure.

Specific long-term

A specific building is made to be a comfortable energy efficient building which suits the user, orientation is therefore a key factor. The life-span of the separate building elements are approximately the same. The solutions for building elements are focussed on increasing the value of use and limiting the operational costs. The technical life-span of building materials is long. There is a surplus in the structure (grid and strength) and diversity in spaces. The installations are high-quality and can be replaced (limiting operational costs). The facade is focussed on good thermal qualities and soundproofing. The building elements like floors are meeting higher requirements for future demands. Materials like steel and concrete are often used although the environmental material loads are larger. On the other hand, concrete has a great heat accumulating capacity. The facade is permanent and high-quality. Future adjustments can be expensive, therefore should the facade have the right orientation and openings in the right places (daylight & passive solar energy). Increasing the insulation value
beyond the requirements will have a positive effect of the total life-span. The most important factor for the choose of material is the technical life-span. Stone-like materials like brickwork, natural stone and slates. A surplus in duct is also recommended for future installations and adjustments.

Flexible long-term
These buildings are made out of elements, some with a short life-span and some with a large life span, making the total building very flexible. The temporary building elements are adjustable, while the permanent structure remains the same. These buildings are the most flexible because during their life-span they have to coop with multiple adjustments. The life-span of the different building elements is various. Which building elements are permanent and which are temporary varies for every case. The permanent structure focuses on increasing the value of use and decreasing the operational costs. Technical quality, surplus in grid sizes en floor height, bigger floor loads, good orientation and energy efficiency will increase the chance of survival. The temporary structure focuses on limiting the environmental loads. For the adaptability on building level a column structure is a good possibility (horizontal merging and splitting). An open-plan facade will make the structure even more flexible. Using hollow floors can increase the adaptability. Double floors in combination with demountable in-between floors are also an option. Having an oversize in the foundation and the roof will increase the adaptability, because peak-ups are now possible. Materials used for the permanent structure will be the same as in specific long-term strategy. Materials used for the temporary structure will be the same as in the short-term strategies. Surplus in space will increase the possibility of merging and dividing rooms. The facade system is often a combination of permanent and temporary parts, like permanent structures and temporary system-elements. Temporary panelling can be replaced depending on the user, trends and energy requirements. A good permanent facade structure is crucial for these type of buildings. For the adaptability of the building level, a second-skin facade can be an option. The thermal skin will be permanent and the second skin can be replaced or adjusted to the needs of the user. A surplus in duct size and number is also important. A larger number of ducts will decrease the size of the ducts and increase the possibility of hiding the ducts from the user. High-quality installations (low operational costs) with the possibility for easy adjustments are preferred.

Different building strategies can be used for life-cycle engineering. But these strategies apply to general buildings. What will happen if a building is specifically designed for one function like a stadium? Different specific strategies will occur and some of the building strategies can be adjusted or extended. So how does the stadium as building fit the life-cycle analysis?

4.6. Stadium strategies
When planning a new stadium, the first thing to investigate is whether an existing building can be reused, refurbished or even given a radical redesign (Populous 2010). Many existing sports venues are not suitable for refurbishment because structural or physical problems. Poor sight-lines or terrace tread depths, may mean that a stadium can never become a 21st century sports facility. Other solutions, such as temporary structures or venues can be disassembled and later reassembled elsewhere, are potential strategies. Reusable structures are particularly useful for cities staging one-off sports events such as the Olympic Games. Stadium strategies are more specific compared to the general building strategies. In this report, only the flexible long-term and short-term stadium strategies are being investigated as well as the and specific short-term stadium strategies. For the specific long-term strategies, one can apply the general building strategies given in section 4.5. A distinction is made between: temporary structures, temporary extensions, modular structures, multipurpose structures, conversions and floating structures.

Temporary structures
Temporary structures can be dismantled and used several times, and are lighter in weight than permanent buildings, they save enormous amounts of energy in both construction and transportation (Populous 2010). Sydney’s 2000 Olympic beach volleyball stadium at Bondi Beach, Salt Lake City’s 2002 Olympic ski venues and Formula 1 grandstands in Monaco and Valencia are just some applications of temporary venues. In terms of the overlay, an interesting perspective is to look at how we might be able to design venues that can almost be recreated elsewhere in an alternative location. Reusing these venues, or their parts, would certainly boost their financial sustainability as well. In the United Kingdom for example, the Olympic Games are hosted in 2012, the Commonwealth Games in 2014 and the Rugby World Cup in 2015. These events will give opportunities to share venues and facilities between multiple
events, increasing the savings of the temporary venue versus the permanent one (Avison 2011). Temporary structures can also be reused into multiple smaller structures. One of the competition showpieces for the FIFA World Cup in Qatar, the 45,000-seat Port of Doha Stadium, will be dismantled and transported to other destinations in the Middle East and Asia. The reused seats, materials and structures will be carved up to for five smaller sporting facilities (Avison 2011). Where a permanent facility will become a legacy, it is the right decision to built if it will be used regularly, but if not, temporary and semi-permanent structures bridge the gap.

The number of temporary structures will increase in future Olympic Developments as well as the size of the venues. The 12,000-seat Basketball Arena, designed by Wilkinson Eyre, will become the fourth largest sporting venue in the London 2012 Olympic Park (Avison 2011). The Olympic Delivery Authority is responsible for delivering the infrastructure for the 2012 London Olympics and has calculated that there will be a threefold increase in the temporary seats compared to either Athens 2004 or Beijing 2008, and almost four times the gross floor area of temporary buildings (Stevens 2009). According to Nussli International, the largest supplier of temporary venues, it is possible to put up temporary buildings with roofs up to 85 meter wide without supporting pillars. This means that, for example, even a temporary cycling stadium measuring 85 x 120 meter can be erected or dismantled in a relatively short space of time (Buel 2006). Temporary stadiums up to 50,000 seats have already been built.

For events like the Bavaria City Racing in Rotterdam, the Monaco Formula 1 or the Valencia Formula 1, complete temporary grandstand systems are often rented. A system similar to scaffolding will form the base of the stands, providing the possibility of different sizes and shapes with the same material. Different infill pieces will provide the seating or standing areas. These standardised stands go from simple bench stands to completely covered stands with bucket seats. Most of these standardised stands are built up with elements of 1.5 meter wide and multiplied length of 0.8 meter (depth of single tread).

An other advantage of temporary venues is the fact they can be build on places unreachable for permanent venues. During the Olympic Games, city marketing is a mayor issue for a long lasting legacy. Temporary venues in London 2012 for example are being build in Greenwich Park,
which is a World Heritage Site, and Horse Guards Parade, which has a lot of listed buildings and is an important historic site. During the FIFA World Cup of 2006 in Germany, a temporary scale model of the Olympic Stadium was built in front of the Reichstag building in Berlin. On this historic site, World Cup sponsor Adidas ordered a 10,000 seat stadium, constructed for spectators to follow the World Cup matches on big television screens. The Adidas World of Football did not only act as a magnet for visitors to Berlin, but live broadcasting the day before the matches gave TV viewers the opportunity to see the stadium as a spectacular backdrop (Buel 2006). Permanent venues would never get building permission. Temporary venues however can be built on these sites and be taken away afterwards. It is a case of city marketing with limited impacts on the grounds of important city sites (Avison 2011).

Finally, there can be many benefits when choosing and planning the use of temporary facilities, seating and equipment. A distinction can be made between economic, environmental and social benefits (Chernushenko 2002):
- Avoided capital and maintenance costs (a temporary facility can be up to a third of the price of a permanent facility)
- Additional revenue from infill seating in existing facilities
- Adaptations during operation are feasible at short notice, and thus allow for multiple use and subsequent requirements (fast conversion times)
- Reduced overall site footprint
- Overall waste created and energy consumed in construction or erection
- Near perfect reuse and recycling of materials and equipment
- No residual impact on the host community
- No long-term debt or operating expenses for the taxpayer

Choosing for temporary structures may not always be the best one, however. Problems can arise through inadequate understanding, planning or implementation (Chernushenko 2002):
- The absence of industry-wide standards (size, quality and so on) can obstruct true competitive bidding and require additional time and expense for design work
- The limited number of qualified suppliers in some parts of the world adds additional transportation costs and reduces competition
- High energy use to transport equipment from one continent to the next
- Harm to fragile sites if facilities are rapidly erected and dismantled without the same precautions as for permanent construction
- Temporary facilities can be aesthetically obstructive, create traffic problems or in other ways disrupt local communities
- Providing a similar quality of experience for users as a permanent facility can be harder (seating comfort, visual performance, warmth and feel)
Temporary structures are specific short-term buildings, the gravitational center in the assessment framework will therefore be located at environment and economy.

Temporary extensions
Temporary modular grandstand extensions added to an existing sports venue can provide a one-off influx of spectators. The 2012 London Olympic Stadium, for example, will hold 80,000 spectators during the Games, and will have a reduced capacity of 25,000 spectators afterwards. Just like in London, the main stadium for the 2014 Asian Games in the South Korean city of Incheon will hold 70,000 spectators, before shrinking to a capacity of 30,000 spectators afterwards and becoming a park for the local community (Populous 2010).

The ANZ Stadium in Sydney featured temporary stands for the 2000 Olympic Games increasing the total capacity to 115,000 spectators, making it the largest Olympic stadium ever constructed. The stadium was reduced to 80,000 spectators after the Games, and the gaps in the stadium bowl and roof were filled in (Populous 2010). Not only stadiums with a successful legacy are using temporary extensions. For the FIFA World Cup 2010 in South Africa, the stadiums in Durban and Cape Town also used these extensions. However, these extensions were somewhat less visual. The Third trier of the Durban Stadium was completely temporary but at the same time integrated in the overall design, extending the stadium from 54,000 to 70,000 seats. The Green Point Stadium in Cape Town was extended from 52,000 to 65,000 seats. The Cape Town extensions were infill pieces of the highest trier with the same architectural look and feel of the legacy stadium (Avison 2009).

The temporary extensions can be reused elsewhere after a one-off event is finished. The temporary extension of the Sydney International Aquatic Centre for the 2000 Olympic Games, for example, was later reconstructed as part of the Wollongong Showground, just south of Sydney (BHP Steel 2009). The Zaha Hadid Aquatic Centre for the 2012 Olympic Games in London follows similar design principles, the Aquatic Centre is extended by two temporary stands which will be dismounted after the Games. By making the Aquatic Centre construction span in the longitudinal direction, extensions can simply be placed to both sides without compromising on the sightlines for the Olympic event.

Temporary extensions are also useful when dealing with monumental structures, like the Olympic Stadium of Amsterdam. For the European Championships Athletics 2014 bid, Amsterdam investigated the possibility of extending the 1918 Olympic Stadium to meet the capacity increase by 12,500 seat requirements of such an event. This can be done entirely by rentable extension systems or rentable systems combined with one steel structure. Some modular stadium extensions where designed by Tom Bergevoet and Na-Ma architecture, as
well as a completely temporary ring around the whole stadium. This way, the monumental stadium was left untouched by the stadium extensions. After the European Athletics event, the extensions would be dismantled and brought back to the supplier or build up elsewhere (Bergevoet 2008).

These stadiums are a combination of specific long-term buildings with specific short-term extensions, the gravitational center in the assessment framework will therefore be located at environment and value of use.

Modular structures
Many sporting clubs have opted for a modular stadium expansion or a completely temporary stadium in the recent years. This can be in order to increase spectator capacity during promotion into a higher league for an indefinite time period, or to renovate the home stadium. The Vancouver Whitecaps and BC Lions played in a 27,500-seat modular stadium during the renovation of the home stadium BC Place. Fortuna Dusseldorf played in a 20,000-seat modular stadium when the Eurovision Song Contest was scheduled to be hosted in its home ground, the Espirit Arena. Installation speed is one of the great advantages of modular structures based on steel construction. It is possible, for example, to implement a new grandstand facility including planning, production and installation during the summer or winter breaks. The temporary modular stadium in Dusseldorf, for example, was built in a period of only eight weeks. A further benefit is the price, suppliers offer complete grandstands, for purchase or as a leasing model. When the stadium is not longer necessary, the different dismantled parts go back to the supplier (Avison 2011).

In Amsterdam, different types of extension models are possible within the development of a repeatable, universal “extension-unit” with a capacity of approximately 1500 seats. The main benefit of such extension-units is the fact they spare the monumentality (characteristic lights, scoreboard and existing roof structure) of the existing stadium. With these extension-units the stadium can be customised to different demands. By using these units, the stadium can gradually extend by 1500 seats per unit. By making the elements out of standardised, lightweight and easily demountable building products, reusability after sport events is a valid scenario. The units can be reused for small scale projects. The extension ring scenario will increase the capacity of the stadium from 20,000 seats to approximately 55,000 till 60,000 seats (Bergevoet 2008). Modular stadium construction can also be useful for growing stadiums from small scale to larger structures. When sporting achievements improve, a stadium can be extended to attract larger crowds of spectators. A modular stadium can be extended without losing the overall architectural impact. These extensions can be integrated in the total construction and are fast to erect and dismantle.
These stadiums can be specific modular long-term buildings or specific modular short-term buildings or extensions, the gravitational center in the assessment framework will therefore be located at environment and value of use for the short-term buildings. For long-term buildings it will be located at economy and value of use.

**Multipurpose structures**

Multipurpose utilization is one of the fundamental features of a modern sport and event venue. Open-air concerts for example, have been integrated into stadium plans for years. To be competitive on the vent market, minimum capacity is set at 50,000 people. The subsequent loss of backstage seats needs to be considered (Nixdorf 2008). Nowadays, large arena structures will expand hosting events beyond the standard utilization for sports and concerts. The Arena AufSchalke in Gelsenkirchen is hosting a broad range of events. With its movable grass surface and closing roof, the complex guarantees instant re-use by providing a playable central area and ensuring independence for weather conditions. Indoor biathlon championships or motocross races are taking place outside the regular football matches of FC Schalke 04. The layout of the grandstands may be altered by setting up temporary spectator areas, responding to the reduced dimensions of handball events, for example. After moving out the turf tray, the lower trier, by folding down several rows, can also be pushed back and stored 15 meter underneath the bridge-like structure of the south stand. The usable interior area is therefor expanded and the erection of the stage facilitated (Nixdorf 2008). The high investment and operating costs of a movable field have to be evaluated in the financial concept. This solution is only economically viable if the regenerative effects for the turf, when outside, can be combined with a simultaneous utilization of the empty stadium interior.

Sometimes stadiums are being built to house multiple sports which can operate alongside each other. In the Stade de France was built for the FIFA World Cup 1998 in Paris, Saint-Denis, as a new national stadium featuring 3 triers. The configuration of the stadium is interchangeable from football or rugby venue to athletics venue by the use of movable stands. A hydraulic gantry, which was specially adapted, is needed to move the stands back to allow the athletics track to appear. The 500 tons stands can be moved over a length of 15 meter, rolling on a cushion of air and steel and Teflon rollers. Another 32 slabs of 100 tons have to be lowered by telescopic lifts to make room for the movement of the lower stands. The whole process can take place within a time of only 4 days. The system enables the spectator to be as close as possible to a particular event, optimising visibility. The lower stands hold 25,000 seats, making the Stade de France the largest modifiable stadium in the world (Gravelaine 1997).

Different sports are sometimes more difficult to combine into one venue, a triangular shape of a baseball playing field is harder to combine with a rectangular football pitch. The Sapporo
STADIUM FLEET

Dome in Japan is such a multipurpose arena, completed in 2001 for the FIFA World Cup 2002 in Korea and Japan. The central element of the complex is a movable grass pitch, which can be slided in or out, depending on the demand or weather situation. When a football match takes place inside the stadium, the pitch slides into the dome on air-cushion and, once pitch is located in the centre it turns 180 degrees. Accordingly, over a width of 90 meter, the seating rows of the lower trier stand can be folded back and then moved tangentially. The 2 crescent-shaped elements of the lower trier can be moved in such a way as to create a baseball ground shape. The entire manoeuvre last around 2 hours. When the Sapporo Dome is converted into a football stadium, it provides accommodation for 42,000 people, placing them as close to the pitch as possible (Nixdorf 2008). The Three Rivers Stadium in Pittsburgh, first erected in 1970, has a similar conversion method from football to baseball and the other way around, although this stadium has no movable pitch.

Perhaps the most striking example of moving stadium parts is the Saitama Super Arena. The arena is located in the suburbs of Tokyo where the land is extremely precious. The design team was therefore faced with making an arena that could be used year-round. This arena has a complete movable grandstand block, a gigantic structure of 15,000 tons and 41.5 meter high, capable of moving horizontally over a distance of 70 meter. The moving block moves 9,200 seats, almost a third of the building, along with rest rooms, concessions, hallways and even parts of the ceiling, making the arena feel as natural as possible. In about 20 minutes, the Saitama Super Arena converts from an intimate concert venue to a fully equipped stadium accommodating up to 37,000 spectators. An automatic flexile utility regulation system starts up as the 64 base points travel over their steel rails. Electric cables wind up and release from their reels. Plumbing and air-conditioning supplies cut and reconnect (Becket 2000).

The shifting of a third of the building allows for the naturally lit negative space created by the move to be used for small-scale exhibitions, community events and flea markets on a daily basis. Through the use of rolling partitions and curtains it is possible to convert the arena space into a theatre. The multipurpose capability is further enhanced with a vertically moving floor, movable partitions and movable ceiling panels that all work together to make each space feel appropriate for the event taking place. Due to the flexible floor, the highest quality sightlines for each event can be achieved. Ceiling panels can be added and removed to create the best possible acoustics (Heineman 2003). The Saitama Super Arena has the functional diversity and flexibility of a Swiss Army Knife with a wide range of features and combinations.

The Jean Nouvel competition entry for the Stade de France has similar moving grandstands. All grandstands are capable of sliding, making room for the athletics modus. The proposed radical solution for the angle of view onto the playing field ensures optimal field lighting.
The stadium is not partly modifiable, it is 100% flexible. An extra flexibility is the sliding roof structure which maximizes sunshine on the field and shades the stands in during the summer. The stadium will house between 25,000 and 80,000 spectators, depending on the engaged modus (Marquez 1995).

Multipurpose stadiums will play an important role in the context of building modern sports and events venues of the third generation. The concept of adaptability plays a vital role into the conversion between different modus. Horizontal and vertical movement of different stadium parts, sliding grandstands, movable seating, telescopic stands, movable pitches and roofs will be some of the technical multipurpose characteristics of this building type. Multipurpose stadium structures are flexible long-term buildings, the gravitational center in the assessment framework will therefore be located at economy and value of use.

Conversions
When a stadium is being built for the housing of one single-event like the Olympic Games, Commonwealth Games or Word Cups, multipurpose characteristics are different. The stadium structure can be converted into its final form after the single-event is finished. The conversion only takes place once. Different similarities with the previous stadium strategies can occur. The City of Manchester stadium is such an converted structure. After the Commonwealth Games, the Manchester City Football Club moved to the new stadium as tenants. A long-term sustainable future was guaranteed. A design was made so that the stadium would be ready to stage athletics for the Commonwealth Games and then be converted for football. The Games capacity was to be 38,000, rising to 48,000 after conversion by removal of the athletics track and addition of extra seating.

Athletics and football can only occupy the same stadium at the same level if the football spectators are seated a long way from the pitch. At Manchester this would have meant a million spectators per annum for 60 years having to accept poorer viewing positions because of a 10-day event in 2002. This was unacceptable, so the football pitch was created 6 meter lower than the athletics field. Almost 90,000 cubic meter of fill would be removed, the pitch laid, and the temporary 13,000-seater stands were replaced with permanent structure in time for the 2003-2004 football season (Austin 2003).

Stadiums can also play an important role in their urban context. The discussion for demolishing older stadiums can therefore be replaced by the discussion of converting the stadium into something complementing the urban context. In the case of the Arsenal Football Club stadium, Highbury Park, the discussion was taken to convert the important example of a British football stadium into a residential community. The conversion design preserves the nature and memory of the original stadium, while developing a new residential typology which contributed to the local area and streets. It nestled behind rows of small Victorian terraced houses, making it a remarkable structure in this residential area.

The design retains the art-deco facades of the stadium’s listed East stand and West stand and converts them into residential blocks, using the existing four metre structural grid to create apartments. It then adds new, shallower blocks with internal residential courtyards to
the remaining two sides of the football pitch, which is transformed into a landscaped garden. The design retains the size and sense of the sports arena, but embeds it into a smaller scale context. The developed garden gives the impression of a football pitch, a simple rectilinear space (Mullin 2010).

It is to mush to say this is a total stadium conversion due to the fact that only a number of features where preserved. The old stadium was actually dismantled and for the most part the new apartments are simply put into or attached to the historic facade and key stadium elements like the roof. The grandstands at both ends of the playing field where completely demolished. The only sign left of the tilted stand shape is the triangular window in the facades on both sides. On one moment during construction only the two monumental facades where left standing.

The Highbury Square residential community is the only built example of a stadium converted into housing. Further examples can be found in competition and student designs. For the 3rd Advanced Architecture Contest 2009, the self-sufficient city, Adrian Garcia designed the massive urban recycling-plastered stadium. The project is about the recycling of the Jalisco Stadium to create a micro city, a contained ecosystem, with cyclical ecological processes. The Jalisco Stadium in Guadalajara is the third largest of Mexico and participated in the 1970 and 1986 World Cup soccer. Nowadays the stadium is at the end of its evolution process within the city’s time-line, leaving a huge hole on the city volume. The project urbanizes the stadium, using the otherwise useless architecture, giving it a second chance.

Another livable stadium was designed by Joeri van Ommeren for his architecture graduation project at the Technical University of Delft in 2010. The designed Olympic Stadium should act as the counterpart of the more regional oriented Amsterdam Arena and will be a livable post-Olympic stadium after the 2028 Amsterdam Olympic Games. The so-called ‘BijmerOase’ will have a more practical use as a public park with residential facilities. The gravel of the athletics track will be replaced with a chalk line track of grass and the public accessible Olympic site will house public and commercial allotment gardens, parks, play- and sport equipment. The former warming up areas close to the field are converted into shallow water basins for water management and ice skating in the winter. The stadium should act as a catalyst for the whole Bijlmermeer area. At the west side towards the Bijlmermeer center, the stadium is 35 meters deep, at the east side 25 meters. An entrance on the urban scale is added. After the Olympics, the stadium opens up at this side, connecting the housing areas to the public domain.

The separation of technical, programmatic and image determining structure preserves the image of the stadium during the different stages. All structural building parts are detailed in such a way that all stadium scenario’s are backwards transformable. The 2028 Olympic scenario has room for 100,000 spectators. The majority of the first ring will be removed in the post-Olympics scenario. The Bijlmermeer orientated levels will become residential and the levels below ground will maintain stadium, with public facilities underneath the main stand. Each household has a personalized stand, connected to the main green facilities. The grandstand is connected to office spaces, which guaranty activity during day time. The building cores divide the building in a known scale of building blocks. A public route is added in the roof structure, connection all collective areas to the cores. In the residential modus, the stadium consists of a functional 27,000 seats, 270 households and 35,000 square meter of public facilities. The roof structure is part of the post-Olympic plan. After removing the glare and rain protection foil, the steel geometry optically unifies the residential areas and maintains the stadium image. In the most extreme density housing scenario a total of 900 households can be implemented in the stadium structure (Ommeren 2010).
The combination of a stadium and a residential community can form a new building typology, the livable stadium or stadium housing, with its own characteristics. The impact of the development of a livable stadium can be seen as a foundation for residential developments. Most stadiums are located in the outer parts of urban context, while residential blocks are located within this urban context. The implementation of a 60,000-seater stadium within an existing urban context is difficult in terms of scale and mass. For the embedment of a livable stadium, the aspects of mass, logistics and security are crucial. A stadium typology can either be applied in an open context, or the design solutions should be found for the connecting of the stadium with the public domain. The scale of the stadium will determine the urban character. A large stadium will be more introvert while a smaller stadium is easier to connect with its urban surroundings.

Most aspects of the building typology are determined by usage, building code and technical aspects. The main compositional structure of a livable stadium is determined by the spectator distribution demands and bowl entry points. In the stadium geometry there is need for bigger open spaces, resulting in huge spans an construction height, while in the residential geometry smaller spaces are desirable. These differences can be taken into account in a more flexible and adjustable stadium structure, or the German model of outside zones can be adapted. In the 2006 German World Cup, fan zones were located outside the Berlin stadium to leave the monumental structure of the stadium intact. This idea is also adapted in the 2012 Olympic stadium of London. A big advantage of bigger spaces is the supply of daylight to the inner stadium structure. The huge width of a stadium ring will automatically ask for innovative solutions concerning the daylight entry to the residential units. For a stadium geometry the optimal sun orientation only suits less than half the ring. The north and south housing solutions therefore should considered to be different. When designing a livable stadium on the forehand instead of transforming an existing stadium, grid adjustments can help the residential scale and infill in the post-Olympic usage. The immense scale of a livable stadium dictates the need of sufficient parking space. When this will take place inside the building, it should be considered in the grid size.

The three example stadium of this section all have different ways of dealing with the somewhat dictating geometry when converting it into housing. The Highbury conversion almost completely neglect the geometry of the grandstand and only reuses visual aspects of the facade and the roof. The Jalisco stadium conversion leaves the Grandstand bowl intact and places the new residential units on top of this bowl. The Bijlmermeer stadium is placing an combined residential ring around a stadium structure, somewhat like a residential stadium facade. All three examples reuse the sporting field as a park structure. In Highbury Square and Jalisco it is only a visual park whereas in the Bijlmermeer it is also used as allotment gardens.
When designing a residential stadium on forehand instead of transforming an existing stadium, transforming known residential typologies into a stadium is also a possibility. Terraced housing typologies and tilted residential volumes can be converted into a stadium geometry. When designing the terraced housing of tilted volumes the most important aspect is the slope of the roof, which should be capable of attaching the grandstand. The gravitational center of stadium conversions will be located at economy and environment.

Floating structures
In 1964, an early example of a floating stadium was proposed for the city of San Diego in Mission Bay. Hosting football, major league baseball and aquatic events, the stadium would have place for 50,000 fans. The stadium would consist of three huge sections. The center section, a 13,000 seat grandstand, would be landlocked. Two wings, 20,000 seats each, would float on pontoons and could be manoeuvred into various configurations to give the opportunity for different sports. For baseball, the two wings would be attached to the center grandstand. For football, the wings would be disengaged and floated over to cover both sides of a separate playing field. With other configurations fans could watch water sports on the bay. Unfortunately the stadium has never been built, instead a conventional multipurpose facility was approved and finished in 1967 (Crawford 2010).
The Israeli professor, Michael Burt, suggests putting mega-events which attract massive
audiences on floating stadiums. Today we already have massive rafts with power stations and
floating drilling platforms. The US military is developing a three kilometre long floating landing
strip for aeroplanes. The corner stone for the Olympic Games will be an Olympic stadium with
room for 150,000 spectators. Depending on existing facilities within the host city this main
arena can be surrounded by several smaller modules with facilities for different types of sport,
living quarters for athletes or hotels. It would be cheaper to built a traditional stadium, but with
a floating stadium you do not have to buy the land to built it on (Kristensen 2006).

Floating stadium are already been built, or in this case a floating pitches. The Marina Bay
Floating Platform in Singapore is the largest floating stage in the world. Made entirely of steel
the platform measures 120 metres long and 83 metres wide. The platform can bear up to 1,070
tonnes, equivalent of 9,000 people. The floating platform is made out of smaller pontoons, 15
pontoons interlock like a jigsaw puzzle. Six pylons fixed into the seabed act as the foundation
structure. Heavy duty rubber rollers were used to gently guide the stage vertically. Three links,
which connect the floating platform to the land, have special integrated joints to keep them
steady. The gallery at the stadium has a seating capacity of 30,000 people. The stadium will
be the venue for events on the waters of Marina Bay, including sports, concerts, exhibitions
and cultural performances.

The question of floating capabilities of entire stadiums will perhaps be answered in 2022.
A Floating Offshore Stadium is designed for the FIFA World Cup 2022 in Qatar. It is a fully
mobile structure which can be moved to seaside venues worldwide after the World Cup,
maximizing the utilization future. A rib structure of vertical frames and horizontal slabs form the
supporting structure. A floating baseplate carries the stadium bowl. The floating body under
water has separated floats which allow the nivellment of the whole stadium. Next to this
utilization future, sporting teams which move along with their owners, can also profit from this
floating characteristics. Bigfoot was a 1997 ideas competition to design a football stadium in
order to entice teams back to Los Angeles which had been deserted by two football teams.
The proposed design was a football ship to address the increasing mobility of the teams. The
form of the ship is derived from a supertanker into which a football stadium for 80,000 has
been inserted. The possibilities of floating sport structures are endless, off course the greatest
pitfall of floating structures are the investment costs. Floating structures are more expensive
and somewhat experimental, but the benefits of reusability also have to be taken into account.
Floating structures are flexible long-term buildings, the gravitational center in the assessment
framework will be located at environment and value of use.

4.7. Rotterdam 2028 stadium strategy
For the Rotterdam 2028 stadium, different strategies are combined into one primary concept.
The scenarios of the completely temporary stadium and the multipurpose stadium will not
be used in the Rotterdam case. The completely temporary stadium isn’t suitable for an main
Olympic stadium, because of the scale and prestige of such a project. The multipurpose
stadium strategy is the most expensive strategy to be used for a stadium situation and is
primarily used when their is a clear view of the combined functions. Multipurpose stadiums are
moreover used in area’s where space is limited.

For the Rotterdam 2028 stadium, the concept of floating is exploited by making not just one
large floating stadium that can be relocated, but making an entire fleet of floating pieces which
can be relocated and converted for different purposes. This will increase the value of reuse
and possibilities in the after life of the stadium.
In this chapter the creation of the stadium is explained step by step. Through a series of schemes the stadium is developed out of multiple elements.

1. The athletics track and field is placed on a floating pontoon
2. A number of stadium rings is placed around the field
3. The stadium is modified to comply with the viewing angle demands
4. The stadium is cut into multiple pieces
5. Multiple stadium pieces
6. The stadium facade is skewed to lower the center of gravity
The elements are modelled for housing purposes. The smallest volume is modelled so a single sided apartment is always within the reach of 8 meter from the facade and the double volumes are double sided due to the access ways in the center of the block.

The temporary spectator stands are connecting all the volumes an completing the two lower stadium rings. These spectator stands are completely modular, so after the Games these can also be reused for smaller scale stadiums and events such as Bavaria City Racing Rotterdam or a beach volleyball stadium at the shore of Scheveningen. Finally the design is finished with the landscape from the Waalhaven area. Two massive arms will incline the stadium, making

7 The elements are modelled for housing purposes

8 The elements are connected by a spectators ring

10 The head volumes (4) are connected and used for larger functions

11 The smaller volumes are used for residential purposes

12 The double volumes can be used for simple residential purposes

14 The stadium capacity is enlarged by adding forelocks
it accessible from the Olympic Park. One arm is located on the spectator ring level and the other arm is located higher, to make way for the athletes arriving from the training grounds at the left side of the stadium (see chapter 3). From these arms, simple pivoting bridges are connecting the stadium with the Stadium Park. At the waterside of the stadium these arms are floating, making an access way for people arriving by boat.
Because of the nature of a stadium design, the housing elements are different compared to ordinary landward housing developments. Because of the stadium shape, the lower apartments are stretched over the length of the block, the higher apartments are smaller due to the narrowing of the skewed sides. 14 apartments are located in the smallest stadium unit. 2 of them are mirrored and the rest is almost unique.

All apartments have outdoor space, 4 of them have a terrace which will be visible after the games. During the Games these terraces are located below the spectator seating level. The grandstand will have wooden in-fills at these places. The apartments in the head volume have panoramic views. The penthouse apartment will be developed after the Games have left. During the Games these apartments function as food corner and restaurants.

The stadium volumes are supported by a concrete pontoon. In this pontoon the supporting structure is elongated towards the first level of the building to carry the temporary stands in between the different elements. On the second level and outrigger is placed on these supporting structures to connect and sideways support the load structure of the temporary stands. Because of the nature of a stadium, the head volume is cantilevering over the spectator ring to make more room for the stadium spectators. This cantilevering will be supported by trusses on level 5. at this level the apartments are linked to the structure and are not that flexible. on the two levels
below, an extra supporting structure is made to carry these trusses (blue). The elevator cores and the back structure (pink) of the apartments will provide for the overall stability of a single volume. The panoramical apartments are hung on these trusses limiting the number of columns.

The roof structure of the stadium is placed outside the spectator rings on concrete pillars. The roof consists of a textile tension system. The inner ring is carried by extra columns on the outside of the stadium. These pillars are connected to each other by a large steel ring. In the inner ring room is made for the television screen and stadium lights. The inner ring will overlap the difference between the athletics ring and outer ring, therefore the shape is somewhat oval. The inner ring is covered by plastic material to provide for extra daylight onto the playing field.
After the Games all stadium parts can be reused in the Rotterdam area or elsewhere where there is open water available. The contrast between the different situations can be seen on the pictures of these two pages.
Reusing stadium elements for different purposes like housing or flood shelters
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In this section the forces on floating buildings are explained. Floating buildings can be seen as objects founded on liquid. A liquid can only be loaded with pressure. Shear forces and tensile forces cannot be founded, resulting in some specific contractual problems. To understand floating structures different load cases are gradually explained.

1. Evenly distributed vertical loads

**Immersion**

An object will sink to some extend in liquid depending on the mass of the object. Archimedes law describes how far an object will sink in liquid:

*The upward force applied to a floating object equals the weight of the moved liquid by this object*

Because a floating object is in equilibrium the upward force is equal to the gravitational force on the object, So Archimedes law can be rewritten:

*The weight of the moved liquid equals the gravitational force on the object*

With this law the immersion of different floating bodies can be calculated.

Rectangular floating body

\[ d = \frac{F_z}{10b \cdot l} \]

Triangular floating body

\[ d = \frac{F_z}{\sqrt{10 \cdot l \cdot \tan \beta}} \]

Cylindrical floating body

\[ d = \frac{1}{2} r^2 l (2\varphi - \sin 2\varphi) \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>immersion of floating body (m)</td>
</tr>
<tr>
<td>l</td>
<td>length of floating body (m)</td>
</tr>
<tr>
<td>b</td>
<td>width of floating body (m)</td>
</tr>
<tr>
<td>Fz</td>
<td>upward force (kN)</td>
</tr>
<tr>
<td>\beta</td>
<td>half the angle of the triangle top</td>
</tr>
<tr>
<td>r</td>
<td>radius (m)</td>
</tr>
<tr>
<td>\varphi</td>
<td>central angle</td>
</tr>
</tbody>
</table>

**Water pressure**

The vertical component of the water pressure equals the gravitational force. The horizontal component of the water pressure equals itself

\[ p = \gamma_w \cdot d \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>water pressure (kN/m³)</td>
</tr>
<tr>
<td>\gamma_w</td>
<td>density of water (kN/m³)</td>
</tr>
</tbody>
</table>

(for water inland: 10 kN/m³)

**Modulus of subgrade reaction**

The modulus of subgrade reaction describes the link between deformation en the vertical load. This modulus is used for foundations on weak soil. The modulus for a foundation on steel can be calculated by loading the foundation with a force F:

\[ k = \frac{F}{l \cdot b \cdot u} \]
The modulus of subgrade reaction varies between \( k = 10,000 \text{ kN/m}^3 \) and \( k = 50,000 \text{ kN/m}^3 \). The modulus of subgrade reaction for a pontoon foundation matches the modulus for a foundation on steel. The settlement \( u \) is replaced by the immersion \( d \).

\[
k = \frac{F}{l \cdot b \cdot d}
\]

For a rectangular pontoon construction this means \( k = 10 \text{ kN/m}^3 \) (substituting the immersion \( d \) for a rectangular floating body in the formula above). A floating foundation is thus at least a thousand times weaker compared to a foundation on sandy soil.

If you have a triangular floating body, the water displacement for the same immersion is exactly half of the water displacement of a rectangular floating body. When applying the same loads the settlement of a triangular body will be twice the settlement of a rectangular body (\( A_{\text{triangular}} = \frac{1}{2} A_{\text{rectangular}} \)). A triangular floating body is thus twice as weak. \( k = 5 \text{ kN/m}^3 \)

**Center of buoyancy**

The center of buoyancy is the center of gravity of a displaced volume of water. The center of buoyancy is significant because the resulting upward force engages here. The position of this center of buoyancy can be calculated for a rectangular, triangular and cylindrical floating body:

\[
B_{\text{rectangular}} = \frac{1}{2} d
\]

\[
B_{\text{triangular}} = \frac{1}{3} d
\]

\[
B_{\text{cylindrical}} = \frac{4r}{3\pi} \approx 0.42r
\]

\( B = \) center of buoyancy from water surface (m)

The center of buoyancy of a triangular floating body is closest to the water surface. The center of buoyancy of a rectangular floating body is the furthest to the water surface.

**2. Bending moment and eccentric loads**

**Rotation**

If a floating body is loaded by an eccentric force, the pontoon will rotate. When rotation by an angle \( \alpha \) we can calculate the minimal and maximal immersion of the floating body:

\[
d_{\text{min}} = (d - \delta) \cos \alpha
\]

\[
d_{\text{max}} = (d + \delta) \cos \alpha
\]

\[
\delta = \frac{1}{2} b \tan \alpha
\]

The maximal a minimal water pressure at the bottom plate will become:

\[
p_{\text{min}} = 10(d - \delta) \cos \alpha
\]

\[
p_{\text{max}} = 10(d + \delta) \cos \alpha
\]

**Righting moment**

If a floating body starts rotating, the water pressure on the bottom plate starts to be unevenly distributed. The consequence of this uneven distribution is a righting moment counterbalancing the imposed force on top of the floating body; a new state of equilibrium. In the following steps we assume that the pontoon is rotating around its keel (A).
Step 1  The consequence of the skewed pontoon is an unevenly distributed water pressure at the bottom plate and the sides of the pontoon.

Step 2  The vertical part of the righting moment at the bottom plate of the floating body is split in two triangles: triangle 1 and triangle 2.

\[ M_1 = \frac{b^2 \cdot l \cdot 10(d - \delta) \cos \alpha}{12} \]
\[ M_2 = \frac{b^2 \cdot l \cdot 10(d + \delta) \cos \alpha}{12} \]

Step 3  With M1 and M2 we can calculate the total vertical component of the righting moment, Mvert.

\[ M_{vert} = \frac{b^2 \cdot l \cdot 10 - \delta \cos \alpha}{6} \]

Step 4  The water pressure at the sides of the floating body result in an extra moment, again split up in two triangles.

\[ M_3 = -\frac{10 \cdot l(d - \delta)^3 \cos \alpha}{6} \]
\[ M_4 = -\frac{10 \cdot l(d + \delta)^3 \cos \alpha}{6} \]

Step 5  With M3 and M4 we can calculate the total horizontal component of the righting moment, Mhor.

\[ M_{hor} = \frac{10 \cdot l(6d^2 \delta + 2 \delta^3) \cos \alpha}{6} \]

Step 6  With Mvert and Mhor we can calculate the total righting moment, Mright. Mvert and Mhor equal Mext.

\[ M_{right} = M_{vert} + M_{hor} \]

\[ M_{right} = F \sin \alpha \left( \frac{b^2}{12d} + \frac{1}{2} d + \frac{b^3 (\tan \alpha)^3}{24d} \right) \]

If the center of gravity of a floating body is higher compared to the keel point, a different formula should be used to calculate the righting moment.

**Spring rate**  
The spring rate of a floating body describes the link between the size of the righting moment and the rotation angle of the foundation. Because a floating body can only rotate a maximum of 5° in UGT the contribution of the angle \( \alpha \) is so small it can be neglected.

\[ C = \frac{M}{\alpha} = F \cdot \left( \frac{b^2}{12d} + \frac{1}{2} d \right) \]

\[ C = \text{spring rate (kNm/rad)} \]
\[ \alpha = \text{angle of rotation (rad)} \]
3. Second order effect

In the previous section we assumed that the load will be applied at the keel on the floating body. However, this assumption will not work in practice. The gravitational force should be applied in the center of gravity of the total construction. The influence of the height of this point will be investigated in this section. If the gravitational force is applied at a higher point, the consequences will be greater in case of horizontal movement.

If the center of gravity is positioned higher compared to the keel, the following will happen: as a consequence of the horizontal force the building will rotate, resulting in a displacement of the gravitational force $F_z$, resulting in an extra moment. This moment will increase if the height of the center of gravity will increase, because the length of the arm will increase.

A resilient foundation with an infinite clamped bar.

To understand the behaviour of a floating building we will first look at an infinite bar with the length $l$ clamped in a resilient foundation with a spring rate $C$. The bar is vertically loaded with a force $F$ in the center and horizontally loaded with a force $H$.

Step 1. The foundation is loaded with a moment. A rotation over an angle $α$ is a consequence of this moment.

$$α = \frac{M}{C}$$

Step 2. A consequence of the rotation is a displacement of the top part of the bar by $w$:

$$w = l \cdot \sin α \approx l \cdot α$$

This displacement results in an extra moment:

$$δ \cdot M_1 = F \cdot w$$

Step 3. The consequence of this extra moment is an increased angle of rotation.

$$δ \cdot α_1 = \frac{δ \cdot M_1}{C}$$

The increasing angle of rotation will increase the displacement by:

$$δ \cdot w_1 = l \cdot δ \cdot α_1$$

Step 4. This process will continue until the structure will fail or until $δ \cdot w_2$ is infinitely small.

$$δ \cdot M_2 = F \cdot w_1$$

$$δ \cdot w_2 = l \cdot δ \cdot α_2$$

$$δ \cdot M_3 = F \cdot w_2$$

$$δ \cdot w_3 = l \cdot δ \cdot α_3$$

To check if the structure will fail as a consequence of the second order effect, the ratio between $w$ and $δ \cdot w_1$ is defined as $n$.

$$δ \cdot w_1 = \frac{w}{n}$$

There are three situations imaginable:

- $n < 1$: The moment will increase by smaller steps
- $n = 1$: The moment will increase by the same steps
- $n > 1$: The moment will increase by larger steps
n=1 is a critical situation. The growth of the moment will be at a constant rate, so eventually the construction will fail. If n<1, the moment will grow to a certain value which can be approached. If the total structure can coop with this moment, the structure is stable.

\[ M_{tot} = \frac{n}{n-1} M_0 \]

The term n/n-1 is called the enlargement ratio. When n=1, the structure will fail so the critical length and critical force can be calculated:

\[ l_{crit} = \frac{C}{F} \]

\[ F_{crit} = \frac{C}{l} \]

\[ n = \frac{C}{F \cdot l} = \frac{F_{crit}}{F} = \frac{l_{crit}}{l} \]

The second order effect at pontoon structures.
The spring ratio of a floating object is much smaller compared to the ratio of a conventional founded building. The building is standing on an extreme weak foundation. Consequently the second order effect will be mainly determined by the rotation of the floating body. The deformations of the top building can usually be neglected, because they are really small compared to the floating body.

The distance l in the previous section can be seen as the distance between center of gravity of the total building and the center of rotation of the floating body.

\[ l_{crit} = \frac{C}{F} = \left( \frac{b^2}{12d} + \frac{1}{2}d \right) \]

From this formula we can see that l_{crit} is depending on the depth and width of the floating body. The width of the floating body is influencing the critical length quadratic. When l_{crit} is known we can calculate the value of n and subsequently the value of M_{tot}.

4. Static stability
Static stability is about (long-term) horizontal or eccentric vertical loads. If a building is statically stable, it means the building will not capsize of fail under the influence of the expected loads. Dynamic stability is all about the motion of the water surface which can put the building in motion. If a building is dynamically stable it will not be resonated by the influence of waves.

Stability and skew
A floating building is balanced when it meets the following demands: \( \Sigma F_{hor}=0 \), \( \Sigma F_{vert}=0 \), \( \Sigma M=0 \). When this equilibrium is disturbed, three reactions are possible:

1. The building will return to it equilibrium state (stable equilibrium)
2. The building will not return to its equilibrium state (labile equilibrium)
3. The building will return to an equilibrium state in a displaced state (indifferent equilibrium)

If a floating building is stable, it can be skewed as a consequence of the loads, but will not capsize. The building will return to its original equilibrium when these loads will be removed. Skew is a concept which describes the rotation under a certain load, stability is a concept which describes if a floating building can coop certain loads.

Center of gravity, center of buoyancy and metacenter.
If we position an external moment on the structure, the structure will rotate. The center of gravity and the center of buoyancy will displace due to this moment. However, the center of buoyancy will be displaced over a larger distance compared to the center of gravity. This means \( F_z \) and \( F_{right} \) will form a couple, providing a righting moment. This moment \( M_{right} \) will be finding a new equilibrium.
the opposite of the external moment $M_{\text{ext}}$, making equilibrium. When the center of gravity is placed at the position of the keel, $M_{\text{right}}$ can be calculated with:

$$M_{\text{right}} = F \sin \alpha \cdot \left( \frac{b^2}{12d} + \frac{1}{2} d + \frac{b^2 (\tan \alpha)^2}{24d} \right)$$

When the center of gravity is placed at the rightful position (no longer at the keel position), $M_{\text{right}}$ can be calculated with:

$$M_{\text{right}} = F_z \cdot a = F_z \cdot \sin \alpha \cdot h_m$$

The intersection between the working line of the righting force and the symmetry-axis is called the metacenter $M$. The distance between the center of gravity $Z$ and the metacenter $M$ is called $h_m$.

If a floating building will increase in height, the center of gravity will be higher. If the height of the building will increase until the center of gravity and the metacenter are in the same position, the couple $F_z$ and $F_{\text{right}}$ will be eliminated, resulting in an indifferent balance. If we add more additional layers to a floating building, the center of gravity will be located above the metacenter. The couple $F_z$ and $F_{\text{right}}$ will now be helping the external moment $M_{\text{ext}}$. This means the structure will capsise. If the center of gravity is positioned above the metacenter the value of $h_m$ is negative.

The most important conclusions from the previous section are:

1. For a stable structure, the metacenter $M$ should be positioned above the center of gravity $Z$.
2. If the distance $h_m$ becomes larger, it is harder to rotate the floating body and the skew shall be smaller at a certain moment $M_{\text{ext}}$.
3. A higher metacenter and a lower center of gravity result in a higher value of $h_m$, which is favourable for the stability.

*The height of the metacenter.*

The metacenter can be described as the critical height of the center of gravity. In the center of
gravity is above the metacenter the structure will capsize.

\[
 l_{\text{crit}} = \frac{C}{F} = \left( \frac{b^2}{12d} + \frac{1}{2}d \right) = KM
\]

The distance between center of gravity \( Z \) and the metacenter \( M \) is called \( h_m \), so the distance between the keel \( K \) and \( M \) is called \( h_k \).

\[
 h_k = \frac{b^2}{12d} + \frac{1}{2}d
\]

\[
 h_m = \frac{b^2}{12d} + \frac{1}{2}d - h_z
\]

\[
 h_z = h_k - h_m
\]

The above formulas are direction dependant. In case the width and length of a floating body are different, the height of the metacenter will be different for the \( x \) and \( y \)-direction.

**The height of the metacenter for different geometry.**

Know we know the position of the metacenter for a rectangular floating body, we can calculate the metacenter for other floating bodies:

**Triangle:**

\[
 h_{m \, \text{triangle} \, x} = \frac{2d(\tan \beta)^2}{3} + \frac{2}{3}d - h_z
\]

\[
 h_{m \, \text{triangle} \, y} = \frac{l^2}{6d} + \frac{2}{3}d - h_z
\]

**Cylinder:**

\[
 h_{m \, \text{cylinder} \, x} = \frac{4r(\sin \varphi)^3}{3(2\varphi - \sin 2\varphi)} + 0.58r - h_z
\]

\[
 h_{m \, \text{cylinder} \, y} = \frac{\sin \varphi \cdot l^2}{3r(2\varphi - \sin 2\varphi)} + 0.58r - h_z
\]

**Catamaran:**

If a floating body consist of multiple parts, like for instance a catamaran body, we have to use the quadratic surface moment of the floating body:

\[
 BM = \frac{J_u}{\nabla}
\]

\[
 \nabla = b_{\text{tot}} \cdot d \cdot l
\]

\( B_{\text{tot}} = \) total width of the floating body

(in this particular case: \( b_{\text{tot}}=2b_1 \))

\[
 J_{u \, \text{tot}} = J_{u \, \text{body1}} + a_1^2 \cdot A_{\text{body1}} + J_{u \, \text{body2}} + a_2^2 \cdot A_{\text{body2}}
\]

\( a_1 = \) distance between the center of gravity of the total body an the center of gravity of floating body 1

\( A_{\text{body1}} = \) surface area of the water cross-section

In this case body 1 and body 2 are the same volumes so:

\[
 J_{u \, \text{tot}} = 2J_{u \, \text{body1}} + 2(a_1^2 \cdot A_{\text{body1}})\]
The width is influencing the shape-stability

Types of static stability.
The degree of stability becomes visible in the height of the metacenter $h_m$ and the distance between $M$ and $Z$. The height of the metacenter is influenced by: the width of the floating body, the immersion and the position of the center of gravity. We can distinguish shape-stability and weight-stability.

Shape-stability
If a floating body is rotating, the center of buoyancy is shifting.
The degree, in which this is occurring, is depending on the width of the floating body.
If the floating body gets wider, the center of buoyancy will shift by a larger degree.
This shifting is important for the form-stability because the arm of the couple $F_z$ and $F_{right}$ will increase. A building with a wide floating body has a large starting stability, but when the moment is increasing the rotation will increase as well.

Weight-stability
The arm of the couple $F_z$ and $F_{right}$ will increase when the floating body is wider, but this arm will also increase when the center of gravity is lower. In case of a lower center of gravity, the arm will increase at a slower rate, though this increasing arm will extinguish at a slower rate. When there are only small rotations, the couple is also small. When there are larger rotations, the couple is also larger due to the increasing arm. Weight-stability is not so important at the start of the rotation (the first couple of degrees are effortless), but the region covered by weight-stability is large. When the rotations get larger the structure is acting like a dip switch (bobber), because the center of gravity is relatively low compared to the metacenter.

\[
h_{m \text{ catamaran } x} = KM - h_z = BM + \frac{1}{2} d - h_z = \frac{h_z^2 + 12a_z^2}{12d} + \frac{1}{2} d - h_z
\]

\[
h_{m \text{ catamaran } y} = \frac{I_z^2}{12d} + \frac{1}{2} d - h_z
\]

* In the above chart, the difference between shape-stability and weight-stability is plotted. Shape-stability is important for the first couple degrees of rotation, weight-stability is more effective for larger rotations.
**Weight-stability**

- Rotation: 0°  
  - Increase: +0%  
  - Length increase: +100%  

- Rotation: 3°  
  - Increase: 3°  
  - Length increase: +50%  

- Rotation: 6°  
  - Increase: 3°  
  - Length increase: +34%  

- Rotation: 9°  
  - Increase: 3°  
  - Length increase: +26%  

**Form-stability**

- Rotation: 0°  
  - Increase: 1°  
  - Length increase: +1%  

- Rotation: 3°  
  - Increase: 2°  
  - Length increase: +161%  

- Rotation: 6°  
  - Increase: 3°  
  - Length increase: +102%  

- Rotation: 9°  
  - Increase: 3°  
  - Length increase: +50%  

- Rotation: 12°  
  - Increase: 3°  
  - Length increase: +41%  

- Rotation: 15°  
  - Increase: 3°  
  - Length increase: +2%  

- Rotation: 3°  
  - Increase: 3°  
  - Length increase: +2%  

- Rotation: 6°  
  - Increase: 3°  
  - Length increase: +100%  

- Rotation: 9°  
  - Increase: 3°  
  - Length increase: +41%  

- Rotation: 12°  
  - Increase: 3°  
  - Length increase: +161%  

- Rotation: 15°  
  - Increase: 3°  
  - Length increase: +100%
In the design of a floating stadium, it is important to know what boundary conditions are important for floating design. The most important boundary conditions are technical conditions, like immersion, surface area, skew and freeboard.

1. Technical boundary conditions
In the Netherlands there are no general regulations concerning floating buildings. The builder will imagine the demands the building should meet. The Dutch regulation focuses on mainland buildings, therefore there are no regulations concerning the problems specifically related to floating buildings. In Canada however, there are regulations developed for floating buildings. Some of these guidelines will be used as boundary conditions for the design.

Immersion
According to Canadian regulations the immersions should at least be 0.6 m. This is important for the water quality around the floating body. Small resulting immersion can lead to flow reduction. The oxygenated water will have troubles mixing with the hypoxic water underneath the floating body (also depending on day lighting and flora), which can lead to unpleasant smells.

Built surface area
You can only use 40% of the total water surface for buildings. This is also due to the water quality. The ecological equilibrium should be maintained.

Freeboard
The difference between the maximum flow line and the top of the bank or structure should be at least 0.3 m; this distance is called the freeboard. For buildings with a larger overall height this freeboard should be around 0.4 m.

Skew
As a consequence of the horizontal or non-centric vertical loads a floating building can become skewed. The maximal permissible skew is not totally clear in the regulations.

- NEN 6702 uses for mainland buildings the demand of 1/300 per storey. The maximum divergence of the total building can be 1/500 of the total building height.
- The Canadian regulations define the maximal permissible skew to be lower then 5°, or 50% of the freeboard.
- The group of Aqua Struenda uses a maximal permissible skew of 2°.

The maximal permissible skew of NEN 6702 is recognized to be too rigorous. If one should use the demand of 1/300, the maximal angle of rotation will be 2°. Generally residents of a floating building will accept larger amounts of swell and skew compared to residents of mainland buildings because this phenomenon is natural for floating buildings.

To determine the acceptable skew of a floating building it is useful to make a distinction between the maximal rotation in the ultimate limit state (UGT) and the maximal rotation in the usefulness limit state (BGT). In the UGT one should account for extreme load conditions which in practice rarely occur. In the BGT one should look at the desirable conditions for the use of the building. In the UGT a skew of 5° is permissible and in the BGT a skew of 1° is permissible.

Stability
The most important stability criterion for a floating building is the height of the metacenter. In the naval industry a minimal height of 0.15 m is used for the metacenter, although this is somewhat depending on the type of vessel. For pontoon constructions a minimal height of 0.5 m is recommended. The natural frequency of the floating building should always be different from the expected wave frequency. All other demands of strength and rigidity are the same for floating buildings as they are for mainland buildings.

2. Other boundary conditions
In this section some aspects of floating building to take in account are discussed. One should think for example of juridical and environmental boundary conditions for floating buildings.
The most important boundary conditions are:

- Mortgage lenders and insurance agencies classify floating buildings like they classify vessels and ships. This means a floating building is, because of its sinking capabilities, significantly more expensive. A mortgage is also more difficult to obtain. The unsinkability of a floating building is therefore an important design aspect.
- The water quality below and besides the building should be guaranteed. For example one should prevent the growing of algae and the unpleasant smell of decaying vegetation.
- The floating body should be materialised to prevent harmful substances for the surface water. For instance leaching of metals should be limited.
Appendix III: Hydrostatic calculation

All stadium units are calculated to determine the sizes of the different components. The smallest single-unit is used for these calculations to meet the demands for stability and rotation. The single-unit is tested with and without extra additions (wings, catamaran). Also the largest single-unit is tested to know the differences. All hydrostatic calculations can be explored further by using the Excel worksheets included in this report.

1. The smallest single-unit without extra additions

The different units are investigated to get a sense of size and stability. The first situation which is investigated is the single-unit without extra additions.

1.1. Static stability

In this section the floating body is evaluated. The floating part of the design is calculated, to determine if the design is stable and the skew is within the regulations. All surface areas are derived from the Rhino model to be as accurate as possible.

1. Load calculation for BGT and UGT

In the following table a small summary is given of the different loads in the BGT and UGT situation:

<table>
<thead>
<tr>
<th>Surface area top Building (m²)</th>
<th>Section</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor</td>
<td></td>
<td>1427.80</td>
<td>472.44</td>
<td>391.00</td>
<td>1242.20</td>
</tr>
<tr>
<td>facade</td>
<td></td>
<td>815.79</td>
<td>97.84</td>
<td>403.44</td>
<td>805.45</td>
</tr>
<tr>
<td>stands</td>
<td></td>
<td>273.77</td>
<td>0.00</td>
<td>220.28</td>
<td>54.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loads top building (kN)</th>
<th>Load type</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>permanent</td>
<td></td>
<td>4049.81</td>
<td>855.43</td>
<td>1742.37</td>
<td>3208.79</td>
</tr>
<tr>
<td>changing</td>
<td></td>
<td>2126.96</td>
<td>590.55</td>
<td>764.10</td>
<td>2517.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface area floating body (m²)</th>
<th>Section</th>
<th>floor</th>
<th>partition walls</th>
<th>walls</th>
<th>bottom plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>front</td>
<td></td>
<td>2072.02</td>
<td>1184.16</td>
<td>843.54</td>
<td>690.67</td>
</tr>
<tr>
<td>rear</td>
<td></td>
<td>1739.01</td>
<td>433.44</td>
<td>853.94</td>
<td>579.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load type</th>
<th>Total loads top building (kN)</th>
<th>Total loads floating body (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>permanent</td>
<td>BGT</td>
<td>UGT</td>
</tr>
<tr>
<td>changing</td>
<td>9856.39</td>
<td>78788.60</td>
</tr>
<tr>
<td></td>
<td>5998.91</td>
<td>7145.87</td>
</tr>
</tbody>
</table>

2. Determining the center of gravity of the floating body

The first step in the calculation of the floating body is to determine the center of gravity. Because of the shape of the stadium elements is a composition of different individual parts, the center of gravity has to be determined by the composed gravitational centres of these individual parts.

\[
z_x = \frac{\sum S_x}{A_{tot}}
\]

\[
z_x = \frac{(A_1 \cdot y_1) + (A_2 \cdot y_2) + (A_3 \cdot y_3) + (A_4 \cdot y_4)}{A_1 + A_2 + A_3 + A_4}
\]
\[ z_y = \frac{(A_1 \cdot x_1) + (A_2 \cdot x_2) + (A_3 \cdot x_3) + (A_4 \cdot x_4)}{A_1 + A_2 + A_3 + A_4} \]

\[ z_x = 11.83 \text{ m} \]
\[ z_y = 36.99 \text{ m} \]

\[ y_1 = \text{distance between the center of gravity of volume } A_1 \text{ and the center of gravity of the total volume in the direction } y \text{ (m)}. \]
\[ A_1 = \text{surface area (m}^2\text{)}. \]

3. Metacenter in the longitudinal x-direction (for moment, \( M_y \))

To find the metacenter for the x-direction the rule of Steiner has to be used because the total shape of the floating body is composed out of 4 main elements. With this rule we can find the distance between the center of buoyancy and the metacenter:

\[ BM_x = \frac{J_y}{\nabla} \]

\[ J_{y \text{ tot}} = J_{y \text{ body}_1} + a_1^2 \cdot A_{\text{body}_1} + J_{y \text{ body}_2} + a_2^2 \cdot A_{\text{body}_2} + J_{y \text{ body}_3} + a_3^2 \cdot A_{\text{body}_3} + \]
\[ J_{y \text{ body}_4} + a_4^2 \cdot A_{\text{body}_4} \]

\[ J_{y \text{ triangle}} = \frac{1}{36} \cdot b \cdot h^3 \quad J_{y \text{ rectangle}} = \frac{1}{12} \cdot b \cdot h^3 \]

\[ \nabla = A_{\text{tot}} \cdot d - 0.5 = \text{total immersed volume of floating body (m}^3\text{)} \]

\[ BM_{x} = \frac{1}{12} b_{\text{tot}} l_2^3 + a_1^2 \cdot A_{1} + \frac{1}{12} b_{\text{tot}} l_1^3 + a_2^2 \cdot A_{2} + \frac{1}{36} b_{\text{tot}} l_1^3 + a_3^2 \cdot A_{3} + \frac{1}{36} b_{\text{tot}} l_1^3 + a_4^2 \cdot A_{4} \]

\[ BM_{x} = 37.96 \text{ m} \]

4. Metacenter in the transverse y-direction (for moment, \( M_x \))

For determining the metacenter in the y-direction we are using the same formulas. Only the length and width are now used different:

\[ BM_{y} = \frac{1}{12} l_{\text{tot}} b_{\text{tot}}^3 + a_1^2 \cdot A_{1} + \frac{1}{12} l_{1} b_{\text{tot}}^3 + a_2^2 \cdot A_{2} + \frac{1}{36} l_{1} b_{1}^3 + a_3^2 \cdot A_{3} + \frac{1}{36} l_{1} b_{2}^3 + a_4^2 \cdot A_{4} \]

\[ BM_{y} = 4.27 \text{ m} \]

5. Determining the center of gravity for the building on top of the floating body

First the center of gravity of the top building has to be known to determine the length of \( h_m \) for both directions. The top building is part of the stadium and its geometry can’t be changed in this case. Due to the complicated geometry of the stadium buildings, computer software is used to find the center of gravity. Using the software Rhinoceros the center of gravity is found.
First the stadium model is simplified in 4 different volumetric parts (V1-V4). From these parts, Rhino can calculate the Volume Centroid. The following values for the separate volumetric elements can be found:

<table>
<thead>
<tr>
<th>Direction</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>25.78</td>
<td>53.55</td>
<td>35.29</td>
<td>51.57</td>
</tr>
<tr>
<td>z</td>
<td>3.94</td>
<td>0.74</td>
<td>12.36</td>
<td>16.42</td>
</tr>
</tbody>
</table>

The center of gravity of the total top volume can be found graphically by unifying all separate volumes to one large volume in Rhinoceros. The total center of gravity becomes:

\[
\begin{align*}
  x_{tot} &= 37.99 \text{ m} \\
  z_{tot} &= 9.10 \text{ m}
\end{align*}
\]

The center of gravity for the total top volume can be found numerical by using the rule of Steiner the same way as in the floating body. The main difference in this calculation is the fact the volume is used instead of the surface area (V1 in m³). This way the center of gravity can be a function of l2:

\[
\begin{align*}
  x_{tot} &= 37.99 \text{ m} \\
  z_{tot} &= 9.10 \text{ m}
\end{align*}
\]

The center of gravity of the top building is known, the length of hm can be determined (for the Rhinoceros situation and the calculated Excel situation):

\[
\begin{align*}
  h_m &= h_k - h_z \\
  h_{xm} &= 37.99 \text{ m} \\
  h_{ym} &= -0.58 \text{ m}
\end{align*}
\]

One of the boundary conditions for the stability of the building is the fact that hm should be at least 0.5 m. This is no problem in the x-direction, but for the y-direction extra measures should be taken to reach 0.5 m. In this situation the center of gravity is located above the metacenter. A couple of forces will occur, contributing to the external moment. The stadium element will capsize over the x-axis.

### 1.2. Sense of rotation

In this section the building is validated on the sensitivity for rotation when dealing with wind loads or eccentric variable loads.

1. **Eccentric loads caused by the unsymmetrical geometry in the x-direction**

Because the floating object has been part of a stadium ring, the geometry of the building is causing an unevenly distributed load on the floating body in the x-direction. Counterbalancing this load is possible by extending the floating body over l2. The other length, l1, is always the same due to the connectivity of the stadium. The smallest stadium unit is almost counterbalancing it self, but the center of gravity of the total top building is not positioned directly below V3 but more towards the far end of the head volume V4.

In the most unfavourable situation, the head of the top volume contains the largest live load. Imagine the following unfavourable situation: the whole top ring of the stadium is full of...
spectators, but the lower rings are completely empty (extreme loads on the top floor and instantaneous loads on the rest of the floors). In this situation the external moment on the floating body will be the largest. This will determine the size of the structure.

\[ a = \sum \frac{F_i \cdot a_i}{F} \quad \alpha = \frac{n}{n-1} \cdot \frac{M}{C} \quad C = F \cdot h_k \quad n = \frac{l_{\text{crit}}}{l} = \frac{h_k}{a} \]

Calculating the rotation for BGT and UGT

The stadium construction will be skewed in its neutral situation, although this skew is within the norms \((0.30^\circ<1^\circ \text{ and } 0.32^\circ<5^\circ)\). This skew can be prevented by adjusting the length of \(l_2\).

If \(l_2\) is lengthened to 26.76 m, the \(\alpha_y\) becomes 0 degrees. This means the floating body of the original design has to lengthened by 2.26 m (=2 times the arm of the righting moment) in this particular case.

2. Eccentric loads caused by wind in the x-direction

The influence of the wind in the x-direction is determined. The structure is simplified in a number of surfaces so the pressure, friction and suction can be calculated. Although the x-direction is not the size determining direction, it gives some insight in the skew of the construction in case of wind in this direction. In the following section the volume \(V_2\) and the floating body are already extended to 26.76 m.

\[ F_w = \frac{p_w}{\sin A} \cdot C_{\text{dim}} \cdot C_{\text{ex}} \cdot \varphi_t \cdot A \]

\[ F_{w, \text{pressure}} = p_w \cdot C_{\text{pe}} \cdot C_{\text{dim}} \cdot C_{\text{ex}} \cdot \varphi_t \cdot A_{\text{front façade}} \]

\[ F_{w, \text{suction}} = p_w \cdot C_{\text{pe}} \cdot C_{\text{dim}} \cdot C_{\text{ex}} \cdot \varphi_t \cdot A_{\text{rear façade}} \]

\[ F_{w, \text{friction façades}} = p_w \cdot C_{\text{fr}} \cdot C_{\text{dim}} \cdot C_{\text{ex}} \cdot \varphi_t \cdot A_{\text{side façades}} \]

\[ F_{w, \text{friction roof}} = p_w \cdot C_{\text{fr}} \cdot C_{\text{dim}} \cdot C_{\text{ex}} \cdot \varphi_t \cdot A_{\text{roof}} \]

\[ F_w = F_{w, \text{pressure}} + F_{w, \text{suction}} + F_{w, \text{friction façades}} + F_{w, \text{friction roof}} \]

\[ M_w = \frac{1}{2} \cdot h \left( F_{w, \text{pressure}} + F_{w, \text{suction}} + F_{w, \text{friction façades}} \right) + h \cdot F_{w, \text{friction roof}} \]

\[ P_w = 1.1 \text{ kN/m}^2 \]
\[ C_{\text{pe}} = 0.4 \text{ for friction and 0.8 for pressure} \]
\[ C_{\text{dim}} = 0.92 \]
\[ C_{\text{fr}} = 0.04 \text{ for façades with protrusions larger than 40 mm} \]
\[ C_{\text{ex}} = 1 \]
\[ \varphi_t = 1 \]

\[ v_{\text{min}} = v - \left( \tan \alpha \cdot \frac{1}{2} \cdot b \right) \quad v_{\text{max}} = v + \left( \tan \alpha \cdot \frac{1}{2} \cdot b \right) \]
Now the rotations can be calculated and the amount of freeboard in the BGT and UGT load situation:

<table>
<thead>
<tr>
<th>Rotation BGT</th>
<th>Rotation UGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$</td>
<td>88682.05</td>
</tr>
<tr>
<td>$M_w$</td>
<td>9353.36</td>
</tr>
<tr>
<td>$d$</td>
<td>6.60</td>
</tr>
<tr>
<td>$v$</td>
<td>2.20</td>
</tr>
<tr>
<td>$a$</td>
<td>6.67</td>
</tr>
<tr>
<td>$h_k$</td>
<td>44.75</td>
</tr>
<tr>
<td>$C$</td>
<td>3968193</td>
</tr>
<tr>
<td>$n$</td>
<td>6.71</td>
</tr>
<tr>
<td>$\alpha_y$</td>
<td>0.16</td>
</tr>
<tr>
<td>$v_{min}$</td>
<td>2.21</td>
</tr>
<tr>
<td>$v_{max}$</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Rotation and freeboard for BGT and UGT

The rotations are smaller than the maximal allowed rotations for both BGT and UGT conditions ($0.22^\circ<1^\circ$ and $0.27^\circ<5^\circ$).

In the other direction it is a whole different situation. The same way these rotations are calculated. As said before the metacenter is located lower compared to the center of gravity. The rotations in the $y$-direction become:

<table>
<thead>
<tr>
<th>Rotation BGT</th>
<th>Rotation UGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_y$</td>
<td>4.45</td>
</tr>
</tbody>
</table>

Extra additions to the structure are necessary to overcome these rotations.

3. **Eccentric loads caused by users in the $x$-direction**

Imagine the following situation: during a special event, 150 overweight people gather at the front deck. The average weight of these people is around 120 kg. The total force of these people will be 180 kN. If the people are spread out evenly over the surface of $V_2$, they cause an extra moment $M_x$ of 2968 kNm. The following rotation will occur as a consequence of these people.

<table>
<thead>
<tr>
<th>Rotation BGT</th>
<th>Rotation UGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_x$</td>
<td>83717.75</td>
</tr>
<tr>
<td>$F_x$</td>
<td>180</td>
</tr>
<tr>
<td>$M_x$</td>
<td>2968.00</td>
</tr>
<tr>
<td>$z_y$</td>
<td>16.49</td>
</tr>
<tr>
<td>$h_k$</td>
<td>44.75</td>
</tr>
<tr>
<td>$a$</td>
<td>7.06</td>
</tr>
<tr>
<td>$C$</td>
<td>3968193</td>
</tr>
<tr>
<td>$n$</td>
<td>6.33</td>
</tr>
<tr>
<td>$\alpha_y$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Rotations for BGT and UGT

The rotations are smaller than the maximal allowed rotations for both BGT and UGT conditions ($0.05^\circ<1^\circ$ and $0.06^\circ<5^\circ$).

Note: the 180 kN of 150 overweight people can be compared with 20 cars in the parking garage only parking in part $V_2$ and not parking in part $V_1$ of the garage (20 cars of 1000 kg will give 200kN).

2. **The smallest single-unit with extra wings**

The extra additions to the floating body will cause different loads, center of gravity and metacenter. In this section these differences are examined.
2.1. Static stability
In this section we determine if the design is stable and the skew is within the regulations.

1. Load calculation for BGT and UGT
The load calculation for the single unit with extra wings is almost the same as the single-unit without wings. In the following table a small summary is given of the different loads in the BGT and UGT situation:

<table>
<thead>
<tr>
<th>Surface area top Building (m²)</th>
<th>Section</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor</td>
<td></td>
<td>1427.80</td>
<td>472.44</td>
<td>391.00</td>
<td>1242.20</td>
</tr>
<tr>
<td>facade</td>
<td></td>
<td>815.79</td>
<td>97.84</td>
<td>403.44</td>
<td>805.45</td>
</tr>
<tr>
<td>stands</td>
<td></td>
<td>273.77</td>
<td>0.00</td>
<td>220.28</td>
<td>54.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loads top building (kN)</th>
<th>Load type</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>permanent</td>
<td></td>
<td>4049.81</td>
<td>855.43</td>
<td>1742.37</td>
<td>3208.79</td>
</tr>
<tr>
<td>changing</td>
<td></td>
<td>2126.96</td>
<td>590.55</td>
<td>764.10</td>
<td>2517.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface area floating body (m²)</th>
<th>Section</th>
<th>floor</th>
<th>partition walls</th>
<th>walls</th>
<th>bottom plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>front</td>
<td></td>
<td>2072.02</td>
<td>1184.16</td>
<td>843.54</td>
<td>690.67</td>
</tr>
<tr>
<td>rear</td>
<td></td>
<td>1899.42</td>
<td>453.78</td>
<td>694.62</td>
<td>633.14</td>
</tr>
<tr>
<td>single-wing</td>
<td></td>
<td>100.35</td>
<td>22.50</td>
<td>85.14</td>
<td>200.70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load type</th>
<th>Total loads top building (kN)</th>
<th>Total loads floating body (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BGT</td>
<td>UGT</td>
</tr>
<tr>
<td>permanent</td>
<td>9856.39</td>
<td>11827.67</td>
</tr>
<tr>
<td>changing</td>
<td>5998.91</td>
<td>85789.25</td>
</tr>
</tbody>
</table>

2. The consequences of the wings geometry
As described, the metacenter of the floating body for the y-direction is located below the center of gravity. The structure will capsize at the slightest load. To prevent this capsizing, the geometry of the floating body will be adjusted to prevent this. The first improvement can be to make balancing wings over the length of l₂. Volume 2 will get extra additions, V₅ and V₆, to improve the shape stability of the floating body. The adjustments for the y-direction are also influencing the x-direction. The center of gravity of the floating body will shift towards Volume 2. The y-direction will be the size determining direction. In other words, the y-direction is the most unstable direction of the floating building.

In the rule of Steiner, the volumes of the floating body are used instead of surface areas like in the case without additions, so the depth is also taken into account. The center of gravity can be found the same way as before only with two extra parts, making the total center of gravity:

\[ z_x = 19.33 \text{ m} \]
\[ z_y = 38.66 \text{ m} \]

Now also the metacenter can be found, but the total immersed volume has to be calculated different. The length of the center of buoyancy to the metacenter can be found in the same way:

\[ V = (A_{L-4} \cdot d_1 - 0.5) + (A_{S-6} \cdot d_2 - 0.5) \]

\[ B_{Mx} = 40.53 \text{ m} \]
\[ B_{My} = 8.33 \text{ m} \]

The length of hₖ and hₘ can now be determined. The top volume will not change, only the floating body will change. The position of the center of gravity for the top building will thus be
the same as in the previous sections.

<table>
<thead>
<tr>
<th></th>
<th>hk x-direction</th>
<th>h m x-direction</th>
<th>hk y-direction</th>
<th>h m y-direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>44.91 m</td>
<td>35.87 m</td>
<td>12.70 m</td>
<td>3.66 m</td>
</tr>
</tbody>
</table>

One of the boundary conditions for the stability of the building is the fact that \( h_m \) should be at least 0.5 m. This was a problem in the \( y \)-direction before, but with the extra side volumes the problem is solved. So the stadium element will not capsize due to its own geometry.

Because of the extra floating side-wings, the center of gravity of the top building and the center of gravity of the floating body are not aligned anymore. The lengths of \( l_2 \) and \( l_3 \) have to be adjusted in this case. Only now we first analyse the \( y \)-direction, because this is the size determining direction in this case (metacenter is lower, causing a higher change of instability).

### 2.2. Sense of rotation

The additions are causing the units to be more stable in the \( y \)-direction. In this section the size and rotation with the additions is investigated.

#### 1. Eccentric loads caused by wind in the \( y \)-direction

The influence of the wind in the \( y \)-direction is determined. The \( y \)-direction is the size determining direction for the stability because of the larger façade surface and the limited width of the floating body. In the BGT situation extra ballast is used to lower the center of gravity. A layer of 0.5 m of water is positioned over the bottom plate floor.

<table>
<thead>
<tr>
<th>Rotation BGT</th>
<th>F_2</th>
<th>98929.56 kN</th>
<th>M_w</th>
<th>13093.56 kNm</th>
<th>d</th>
<th>6.49 m</th>
<th>v</th>
<th>2.51 m</th>
<th>a</th>
<th>6.14 m</th>
<th>h_k x-direction</th>
<th>12.70 m</th>
<th>C</th>
<th>1256803 kNm</th>
<th>n</th>
<th>2.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation UGT</td>
<td>F_2</td>
<td>114061.72 kN</td>
<td>M_w</td>
<td>19640.35 kNm</td>
<td>d</td>
<td>7.48 m</td>
<td>v</td>
<td>1.52 m</td>
<td>a</td>
<td>6.68 m</td>
<td>h_k x-direction</td>
<td>12.70 m</td>
<td>C</td>
<td>1449040 kNm</td>
<td>n</td>
<td>1.90</td>
</tr>
</tbody>
</table>

**Rotation and freeboard for BGT and UGT**

The rotation in the UGT is smaller than the maximal allowed rotation (1.637°<5°). The rotation in the BGT is larger than the maximal allowed rotation (1.156°>1°). Extra ballast is also being added in this situation, but the rotation is still larger than allowed.

The wing additions are limited in the \( y \)-direction to a maximum of 8 m because of the stadium geometry (space between elements is 8 m). For the \( y \)-direction other measures should be taken to limit the rotations. The rotations due to the geometry of the floating body in the \( x \)-direction are within limits. The center of gravity will shift a little, but the rotations due to this shifting are 0.12° and 0.13° for BGT and UGT. Other measures can be introducing catamaran wings, these wings should extend after the unit is no longer a stadium segment. So the arm of the stabilizing elements can be larger than 8 m. An other option is extra additions to the stabilizing wings or catamaran wings, meaning the normal wings are maximal 4 m and should have extension units to reach a length of more than 8 m.

### 3. The smallest single-unit with catamaran additions

Catamaran additions have the advantage to increase the quadratic surface moment due to the larger arm without adding a large weight to the total construction.

#### 3.1. Static stability

The arm of the catamaran is quadratic related to the height of the metacenter, so a catamaran construction should be ideal for the rotation decrease in the \( y \)-direction. The catamaran additions can also be made from a different material, making them a lightweight construction.
1. Load calculation for BGT and UGT

The load calculation for the catamaran unit is almost the same as for the single-unit with wings, only the floating body is a bit different. In the following table a small summary is given of the different loads in the BGT and UGT situation:

<table>
<thead>
<tr>
<th>Surface area top Building (m²)</th>
<th>Section</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor</td>
<td></td>
<td>1427.80</td>
<td>472.44</td>
<td>391.00</td>
<td>1242.20</td>
</tr>
<tr>
<td>facade</td>
<td></td>
<td>815.79</td>
<td>97.84</td>
<td>403.44</td>
<td>805.45</td>
</tr>
<tr>
<td>stands</td>
<td></td>
<td>273.77</td>
<td>0.00</td>
<td>220.28</td>
<td>54.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loads top building (kN)</th>
<th>Load type</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>permanent</td>
<td>permanent</td>
<td>4049.81</td>
<td>856.43</td>
<td>1742.37</td>
<td>3208.79</td>
</tr>
<tr>
<td>changing</td>
<td>changing</td>
<td>2126.96</td>
<td>590.55</td>
<td>764.10</td>
<td>2517.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface area floating body (m²)</th>
<th>Section</th>
<th>floor</th>
<th>partition walls</th>
<th>walls</th>
<th>bottom plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>front</td>
<td></td>
<td>2072.02</td>
<td>1184.16</td>
<td>843.54</td>
<td>690.67</td>
</tr>
<tr>
<td>rear</td>
<td></td>
<td>1899.42</td>
<td>453.78</td>
<td>694.62</td>
<td>633.14</td>
</tr>
<tr>
<td>catamaran</td>
<td></td>
<td>66.90</td>
<td>30.00</td>
<td>175.56</td>
<td>133.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load type</th>
<th>Total loads top building (kN)</th>
<th>Total loads floating body (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BGT</td>
<td>UGT</td>
</tr>
<tr>
<td></td>
<td>permanent</td>
<td>9856.39</td>
</tr>
<tr>
<td></td>
<td>changing</td>
<td>5998.91</td>
</tr>
</tbody>
</table>

2. The consequences of the catamaran geometry

The extra wing additions in the previous section are making the design heavy in weight and sense. Another unfavourable aspect of these wing adjustments is the amount of surface area above water level. The building loses its sense of floating. Perhaps when using catamaran additions this sense is kept intact. The surface area of the catamaran wings is far smaller compared to the wing additions. When the stadium is transformed into a living quarter and the single-units will be positioned elsewhere, the catamaran legs should be able to extend, so the 8 m is not limiting the overall stability. Also in this case, the y-direction will be the size determining direction.

Extra length and width are added, so the influence of the open space, for example the space between A1 and A5, can be taken in account. The center of gravity can be found the same way as before only with two extra parts, making the total center of gravity:

\[ z_x = 24.33 \text{ m} \]
\[ z_y = 38.72 \text{ m} \]

Now also the metacenter can be found, but the total immerged volume has to be calculated different. The length of the center of buoyancy to the metacenter can be found in the same way:

\[ V = (A_{1-4} \cdot d_1 - 0.5) + (A_{5-6} \cdot d_2 - 0.5) \]

\[ BM_x = 46.38 \text{ m} \]
\[ BM_y = 10.30 \text{ m} \]

The length of \( h_k \) and \( h_m \) can now be determined. The top volume will not change, only the floating body will change. The position of the center of gravity for the top building will thus be the same as in the previous sections.

\[ h_k \text{ x-direction} = 50.72 \text{ m} \]
\[ h_m \text{ x-direction} = 41.68 \text{ m} \]
One of the boundary conditions for the stability of the building is the fact that \( h_m \) should be at least 0.5 m. This was a problem in the y-direction in the single-unit without additions, but with the extra side catamaran volumes the problem is solved. So the stadium element will not capsize due to its own geometry.

### 3.2. Sense of rotation

The catamaran additions are causing the units to be more stable in the y-direction. In this section the rotation of the building is examined.

#### 1. Eccentric loads caused by wind in the y-direction

The influence of the wind in the y-direction is determined. The y-direction is the size determining direction for the stability because of the larger facade surface and the limited width of the floating body, although this width is wider compared to the original building situation due to the catamaran additions. In this case ballast water is used as extra weight for lowering the center of gravity.

<table>
<thead>
<tr>
<th>Rotation BGT</th>
<th>Rotation UGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_z )</td>
<td>98929.56 kN</td>
</tr>
<tr>
<td>( M_w )</td>
<td>13093.56 kNm</td>
</tr>
<tr>
<td>( d )</td>
<td>6.49 m</td>
</tr>
<tr>
<td>( v )</td>
<td>2.51 m</td>
</tr>
<tr>
<td>( a )</td>
<td>6.14 m</td>
</tr>
<tr>
<td>( h_k ; \text{x-direction} )</td>
<td>12.70 m</td>
</tr>
<tr>
<td>( C )</td>
<td>1256803 kN</td>
</tr>
<tr>
<td>( n )</td>
<td>2.07</td>
</tr>
<tr>
<td>ballast water</td>
<td>6619.06 kN</td>
</tr>
<tr>
<td>( \alpha_y )</td>
<td>1.156 deg</td>
</tr>
<tr>
<td>( \nu_{\min} )</td>
<td>2.12 m</td>
</tr>
<tr>
<td>( \nu_{\max} )</td>
<td>2.90 m</td>
</tr>
</tbody>
</table>

#### 2. Eccentric loads caused by users in the y-direction

Imagine the following situation: everybody on the west side of the building is celebrating a birthday. An average of 30 people attends a single birthday. If the 9 west side apartments are full of 30 people, the total of people on the west side will become 270. The average weight of these people is around 100 kg. These people cause an extra moment \( M_x \) of 3194.10 kNm.

The following rotation will occur as a consequence of these people:

<table>
<thead>
<tr>
<th>Rotation BGT</th>
<th>Rotation UGT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_z )</td>
<td>91220.06 kN</td>
</tr>
<tr>
<td>( F_y )</td>
<td>270.00 kN</td>
</tr>
<tr>
<td>( M_y )</td>
<td>3194.10 kNm</td>
</tr>
<tr>
<td>( z_x )</td>
<td>11.83 m</td>
</tr>
<tr>
<td>( h_k ; \text{y-direction} )</td>
<td>14.64 m</td>
</tr>
<tr>
<td>( a )</td>
<td>6.99 m</td>
</tr>
<tr>
<td>( C )</td>
<td>1335176 kNm</td>
</tr>
<tr>
<td>( n )</td>
<td>2.09</td>
</tr>
<tr>
<td>( \alpha_y )</td>
<td>0.26 deg</td>
</tr>
</tbody>
</table>

Rotations for BGT and UGT
The rotations are smaller than the maximal allowed rotations for both BGT and UGT conditions (0.26°<1° and 0.33°<5°)

4. The largest single-unit with catamaran additions
The largest-unit can be examined and compared to the smallest-single unit with catamaran additions.

4.1. Static stability
The increase in height will have a number of consequences for the construction; in this section the different loads and the position of the metacenter are examined.

1. Load calculation for BGT and UGT
The load calculation for the largest-unit is almost the same as for the smallest-unit, only the surface areas and lengths will increase. In the following table a small summary is given of the different loads in the BGT and UGT situation:

<table>
<thead>
<tr>
<th>Surface area top Building (m²)</th>
<th>Section</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>floor</td>
<td>1427.80</td>
<td>609.40</td>
<td>391.00</td>
<td>2058.00</td>
<td></td>
</tr>
<tr>
<td>facade</td>
<td>815.79</td>
<td>97.84</td>
<td>403.44</td>
<td>1216.94</td>
<td></td>
</tr>
<tr>
<td>stands</td>
<td>273.77</td>
<td>0.00</td>
<td>220.28</td>
<td>139.81</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Loads top building (kN)</th>
<th>Load type</th>
<th>V₁</th>
<th>V₂</th>
<th>V₃</th>
<th>V₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>permanent</td>
<td>4049.81</td>
<td>1060.87</td>
<td>1742.37</td>
<td>5261.93</td>
<td></td>
</tr>
<tr>
<td>changing</td>
<td>2126.96</td>
<td>761.75</td>
<td>764.10</td>
<td>3945.05</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface area floating body (m²)</th>
<th>Section</th>
<th>floor partition walls walls bottom plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>front</td>
<td>2072.01</td>
<td>1184.16 843.54 690.67</td>
</tr>
<tr>
<td>rear</td>
<td>1899.42</td>
<td>453.78 633.14 633.14</td>
</tr>
<tr>
<td>catamaran</td>
<td>66.90</td>
<td>30.00 175.56 133.80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load type</th>
<th>Total loads top building (kN)</th>
<th>Total loads floating body (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGT</td>
<td>UGT</td>
<td>BGT</td>
</tr>
<tr>
<td>permanent</td>
<td>12114.97</td>
<td>14537.96</td>
</tr>
<tr>
<td>changing</td>
<td>7597.86</td>
<td>11396.79</td>
</tr>
</tbody>
</table>

The size of the floating body is exactly the same as for the smallest single-unit to make it easy to compare the large-unit and small-units. Adjustments will be made after the large-unit is tested.

2. Metacenter for both directions
The center of gravity can be found the same way as before, making the total center of gravity:
\[
\begin{align*}
  z_x &= 24.33 \text{ m} \\
  z_y &= 38.72 \text{ m}
\end{align*}
\]

Now also the metacenter can be found, but the total immersed volume has to be calculated different. The length of the center of buoyancy to the metacenter can be found in the same way:
\[
V = (A_{L-4} \cdot d_1 - 0.5) + (A_{S-6} \cdot d_2 - 0.5)
\]
\[
BM_x = 46.38 \text{ m}
\]
\[
BM_y = 10.30 \text{ m}
\]

The length of \( h_k \) and \( h_m \) can now be determined. The top volume is changed. The position of the center of gravity for the top building will be different from the previous sections, the length
of \( h_m \) will change. The length of \( h_k \) is depending on the dimensions of the floating body, so the length will not change:

\[
\begin{align*}
\text{hk x-direction} &= 50.72 \text{ m} & \text{hm x-direction} &= 40.01 \text{ m} \\
\text{hk y-direction} &= 14.64 \text{ m} & \text{hm y-direction} &= 3.93 \text{ m}
\end{align*}
\]

One of the boundary conditions for the stability of the building is the fact that \( h_m \) should be at least 0.5 m. This was a problem in the y-direction in the single-unit without additions, but with the extra side catamaran volumes the problem is solved. So the stadium element will not capsize due to its own geometry.

### 4.2. Sense of rotation

The catamaran additions are causing the units to be more stable in the y-direction, the arm of the catamaran units will quadratically influence the surface moment of the total floating body. In this section the size of the additions is examined.

1. **Eccentric loads caused by wind in the y-direction**

The y-direction is the size determining direction for the stability because of the larger façade surface and the limited width, especially with the larger volume V4 extra wind loads are inevitable:

\[
\begin{align*}
\text{Rotation BGT} & \\
F_2 &= 101696.65 \text{ kN} & M_w &= 15938.41 \text{ kNm} \\
d &= 6.98 \text{ m} & v &= 2.02 \text{ m} & a &= 6.94 \text{ m} \\
h_k x\text{-direction} &= 14.64 \text{ m} & C &= 1488521 \text{ kNm} & n &= 2.11 \\
\text{balast water} &= 6619.06 \text{ kN} & \alpha_y &= 1.166 \text{ deg} \\
{\text{v}}_{\text{min}} &= 1.58 \text{ m} & {\text{v}}_{\text{max}} &= 2.47 \text{ m}
\end{align*}
\]

\[
\begin{align*}
\text{Rotation UGT} & \\
F_2 &= 117861.75 \text{ kN} & M_w &= 23907.62 \text{ kNm} \\
d &= 8.09 \text{ m} & v &= 0.91 \text{ m} & a &= 7.56 \text{ m} \\
h_k x\text{-direction} &= 14.64 \text{ m} & C &= 1725127 \text{ kNm} & n &= 1.94 \\
\text{balast water} &= 6619.06 \text{ kN} & \alpha_y &= 1.643 \text{ deg} \\
{\text{v}}_{\text{min}} &= 0.29 \text{ m} & {\text{v}}_{\text{max}} &= 1.54 \text{ m}
\end{align*}
\]

**Rotation and freeboard for BGT and UGT**

The rotation in the BGT is larger than the maximal allowed (1.166\(^\circ\) > 1\(^\circ\)). The rotation in the UGT is smaller than the maximal allowed rotation (1.643\(^\circ\) < 1\(^\circ\)). The design has to be adjusted to meet the requirements for the BGT rotation. Compared to the rotations of the smallest-unit, the increase in rotation is not very large (in BGT situation: 1.166\(^\circ\) compared to 0.905\(^\circ\) and in UGT situation: 1.643\(^\circ\) compared to 1.258\(^\circ\)).

The rotations due to the geometry of the floating body in the x-direction are within limits. The center of gravity will shift a quite a bit, but the rotations due to this shifting are 0.97\(^\circ\) and 1.04\(^\circ\) for BGT and UGT. It is possible to adjust the design by altering the length, \( l_2 \) so this gravitational shifting is countered. The rotations due to wind in the x-direction are within limits 0.13\(^\circ\) for BGT and 0.18\(^\circ\) for UGT.

2. **Adjusting the catamaran design**

The following adjustments are made to meet the requirements: \( l_2 \) and \( l_3 \) are lengthened from 26.76 to 34.40. The width and arm of the catamaran construction (b4 and b5) will stay the same. By increasing the length to 34.40, the rotation due to the geometry will be 0.00\(^\circ\). The rotation due to wind in the y-direction will be:

\[
\begin{align*}
\text{Rotation BGT} & \\
\alpha_y &= 0.988 \text{ deg} \\
\text{Rotation UGT} & \\
\alpha_y &= 1.373 \text{ deg}
\end{align*}
\]

**Rotations for BGT and UGT**

The design meets the requirements (0.988\(^\circ\) < 1\(^\circ\) and 1.373\(^\circ\) < 5\(^\circ\)). The total increase of \( l_2 \) and \( l_3 \) is 34.40-26.76=7.64 m.
5. The floating body construction
Now the static stability of the building is sorted, the construction of the floating body can be verified. The floating body is not only loaded by the loads of the top building, the water pressure will also influence the strength and rigidity of the floating body construction. In this chapter we are using the smallest-unit.

5.1. Calculation of the concrete floor
The building has to be in the water for a long period without maintenance. The forces on the concrete floating body can be calculated. It is important for the floating body to stay without ruptures for a long period, so water has no access to the construction.

Calculation data

<table>
<thead>
<tr>
<th></th>
<th>upward water pressure</th>
<th>downwards permanent load on floor</th>
<th>resulting load</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_w$</td>
<td>8.5*10</td>
<td>1.2<em>0.3</em>24</td>
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<tr>
<td>$p_d$</td>
<td>85.00</td>
<td>8.64</td>
<td>76.36</td>
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</table>

Load calculation
The floor is reinforced by multiple ribs in two directions. The largest floor area will be 7.2 * 9.8 m². With VBC table 18 (NEN 6720, 1995) and $l_y/l_x=9.8/7.2=1.36$ we find the moments in the field edge with scheme VB and the in-between field with scheme IVB. The calculated moment with this table are calculated elastically so they can be redistributed. The supporting moments are maximal in the field edge, these moments can be redistributed to: $M_{sx}=0.8*Msx$. The supporting moments in the in-between fields are smaller compared to the supporting moments in the field edge, so it is economical to reduce the moment maximal in the field edge, $Msx=0.8*Msx=0.8*423.56=338.85$ kNm. This supporting moment is still larger than the supporting moment in the in-between field ($Msx=316.68$). Because this reduction, the field moment in the field edge will increase by: $M_{sx}=M_{sx}+\frac{1}{2}(Msx-0.8Msx)$.

Calculation of the floor reinforcement
The height of the concrete floor 300mm, rebar FeB500, $f_s=435$ N/mm², $B_{ss}$, minimal reinforcement: $A_{min}=0.18*300*1000/100=540$ mm²

Top moist environment, environment class 2, $c=25$ mm, rebar diameter $\phi=8$ mm, $h=300$ mm, $d=h-c-\phi_{bg}-\frac{1}{2}\phi_{hw}=300-25-8-4=263$ mm. $\phi_{bg}$=diameter rebar braces, $\phi_{hw}$=diameter main rebar

Needed rebar for the top:

$$A_s = \frac{M_{sx}}{z \cdot f_s} = \frac{248.20*106}{0.9*263*435} = 2410.54 \text{ mm}^2 \quad \phi=16-80, A_s=2513 \text{ mm}^2$$

Bottom moist environment, weakly aggressive, environment class 3, $c=30$ mm, rebar diameter $\phi=8$ mm, $h=300$ mm, $d=h-c-\phi_{bg}-\frac{1}{2}\phi_{hw}=300-30-8-4=258$ mm

Needed rebar for the bottom:

$$A_s = \frac{M_{sx}}{z \cdot f_s} = \frac{338.85*106}{0.9*258*435} = 3354.72 \text{ mm}^2 \quad \phi=20-90, A_s=3491 \text{ mm}^2$$

The size of $A_s$ is determined with the following table:
5.2. Calculation of the sidewalls

The sidewalls can be calculated the same way as the bottom plate. The sidewalls are 9.0 m high, and supported by 3 floors. Because the parking is half immersed at the start, the maximal height of a part of the wall is $3.0 + 1.5 = 4.5$ m. The load on the wall is maximal $p_d = 8.5 \times 10 = 85$ kN/m². The moment caused by this load equals: $M_d = \frac{1}{2} \times 85 \times 8.5 \times \frac{8.5}{7.2} = 426.48$ kNm

Moist environment, weakly aggressive, environment class 3, $c = 30$ mm, rebar diameter $d = 8$ mm, $h = 400$ mm, $d = h - c - \frac{1}{2}d_{bw} = 400 - 30 - 8 - 4 = 358$ mm. The wall thickness will be 400 mm, rebar FeB500, $f_s = 435$ N/mm², B35, minimal reinforcement: $A_{min} = 0.18 \times 400 \times 1000 / 100 = 720$ mm²

<table>
<thead>
<tr>
<th>distance c.t.c. Number of bars per m</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
<th>16</th>
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<td>1149</td>
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</table>

5.3. Deformation of the bottom plate

To decrease the deformation of the bottom plate and increase the durability, the favourable construction is a non-ruptured construction. First is examined if the bottom plate will rupture in use state, next the deformation of the floor is examined using: Timoshenko S. and Woinowsky Krieger S., Theory of plates and shells (for the numerical factors). The ratio $0.00705$ is found for $b/a=1.4$ (9.8/7.2=1.36). Because the bottom plate is a fixed plate the ratio becomes $0.00705/2=0.00453$

\[ w = \frac{0.0453 \cdot p \cdot l^4}{E \cdot h^3} \]

1. Rupture, long-term loads

The construction will be un-ruptured if the acting bending stresses by long-term loads are smaller than $1.2 \ast (1.6 \cdot h) \ast f_{bm}$. For B35s concrete: $f_{bm}=2.8 \text{ N/mm}^2$, $1.2 \ast (1.6 \cdot 0.3) \ast 2.8=4.37 \text{ N/mm}^2$. Instantaneous load combination: permanent+60% of the instantaneous load. Average immersion is 9.0-0.5=8.5 m. The resulting load can be calculated:
THE DUTCH DELTA GAMES 2028

The maximal moment on the floor plate will be:
$$M_{x} = d \cdot p_{\text{prep}} \cdot b^2 = 0.3 \cdot 77.80 \cdot 7.20^2 = 1209.95 \text{ kNm}$$

Stresses:
$$\sigma = \frac{M_{x}}{W} = \frac{1209.95 \cdot 10^6}{1000 \cdot 300^2 / 9.8} = 131.75 \text{ N/mm}^2$$

131.75 > 4.37 N/mm², so the floor will rupture. Adjustments should be made to cope with these stresses and prevent the ruptures. The floor is doubled in height, 600 mm. Also B65 concrete is used instead of B35 concrete: \( f_{\text{bm}} = 4.3 \text{ N/mm}^2 \), \( 1.2 \cdot (1.6-0.6) \cdot 4.3 = 5.16 \text{ N/mm}^2 \)

The maximal moment on the floor plate will be:
$$M_{x} = d \cdot p_{\text{prep}} \cdot b^2 = 0.6 \cdot 70.60 \cdot 7.20^2 = 2195.94 \text{ kNm}$$

Stresses:
$$\sigma = \frac{M_{x}}{W} = \frac{2195.94 \cdot 10^6}{1000 \cdot 600^2 / 9.8} = 59.78 \text{ N/mm}^2$$

59.78 > 5.16 N/mm², so the floor will rupture. Adjustments should be made to cope with these stresses and prevent the ruptures. This time 4 extra supporting beams are added to shorten the length of the loaded floor plate. The length of 9.8 becomes 9.8/4 = 2.45 m, so the floor plate will span in the opposite direction. Because the floor in this case will have the same thickness as in the previous case, the calculation data stays the same.

The maximal moment on the floor plate will be:
$$M_{x} = d \cdot p_{\text{prep}} \cdot b^2 = 0.6 \cdot 70.60 \cdot 2.45^2 = 254.27 \text{ kNm}$$
Stresses: \[ \sigma = \frac{M_{\text{rep}}}{W} = \frac{254.27 \times 106/1000 \times 600^2/7.2}{5.09} = 5.09 \text{ N/mm}^2 \]

5.09 < 5.16 N/mm², so the floor will be non-ruptured. The extra supporting beams are necessary for a floating body with a large immersion.

2. Deflection of bottom plate
The modulus of elasticity of B65 concrete equals: \( E_b = 38500 \text{ N/mm}^2 \). The permanent load on the bottom plate is: \( p_{\text{rep}} = 70.60 \text{ kN/m}^2 \). Creep moist environment \( \phi = 1.8 \).

\[ E'_b = \frac{38500}{1 + 0.75 \cdot \phi} = \frac{38500}{1 + 0.75 \cdot 1.8} = 16382.98 \text{ N/mm}^2 \]

\[ w = \frac{0.00453 \cdot p \cdot I^4}{E_h^2 k^3} = \frac{0.00453 \times 70.60 \times 24504 \times 16382.98 \times 1000 \times 6003}{12} = 0.04 \text{ mm} \]

The acceptable deflection equals: \( w = 0.004 \times l = 0.004 \times 2450 = 9.8 \text{ mm} \). The acting deflection is smaller than the maximal allowed deflection \( 0.04 < 9.8 \), so the construction meets the requirements.

5.4. Conclusion
The construction of the floating body meets the requirements for strength and stability. The construction is calculated to stay non-ruptured; water cannot access the floating body construction. Concrete can rupture when loaded. This phenomenon is not determining the size for structures above the water, but for immersed structures this is an important factor. We have to keep in mind that the resulting load is this large because the structure is 8.5 m immersed. The downward pressure should counter the upward pressure of the water. The ballast which is needed to meet the requirements for the skew is not taken into account for the rupture; normally the resulting load will be smaller because the downward pressure is larger due to the ballast tanks. When one tank is leaking or emptying the concrete floor plate will not rupture due to the decreasing downward pressure; it is an extra safety feature.
In this appendix the C-value calculation sheet from excel is printed. The C-value is a tool for calculating the depth and skew of the spectator stands. For the full calculation and further understanding of this value, the C-value calculation sheet is included on the cd-rom at the back of this report.
The left column on the previous page is for stadium bowls with a parabolic grandstand. These are especially used in the lower areas of a stadium bowl. Also when designing for example a football stadium, the stands are located closer to the field, therefore the increase in height of every thread is higher. For an athletics stadium, the stands are located at a further distance to the field. Therefor the increase is lower. For my athletics stadium, the C-value is calculated with the column on the right of the previous page. This is a less accurate way, but for larger stadiums it gives an insight in the possible stadium skew.

The Rotterdam olympic stadium will be reused for housing possibilities, therefor the C-value is also linked to the vertical and horizontal housing grid. The vertical grid is always 3.2 meters and the horizontal grid is adjustable to suit the C-value. It is shifting for 8 to 7.2 meters. The horizontal and vertical parameters are tested in this C-value calculation sheet.

The value of ring 1 is 6.14 wich is not favourable, but for exceptional buildings the value is within the rules and regulations (minimal of C-value=6). Because the building is floating the height factor is also taken into acound. With a higher C-value comes a higher building, so on ring 1 a compromise is done concering the C-value. For ring 2 and 3 of the stadium the C-value is almost perfect, 11.60 and 11.95 (optimum =12).
Appendix V: Stadium seat calculation

One of the technical requirements for an Olympic Stadium is the gross number of seats. The capacity requirements can be found in the ‘Technical Manual on Venues, Design Standards for Competition Venues’ of the International Olympic Committee. The IOC requires the main stadium to have a seating capacity no less than 60,000 seats. A design calculation is done to make sure this requirement is achieved in the designed Rotterdam Olympic Stadium 2028. First an overview is given of the previous Olympic Stadia capacities.

<table>
<thead>
<tr>
<th>Year</th>
<th>Place</th>
<th>Capacity</th>
<th>Year</th>
<th>Place</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1896</td>
<td>Athens</td>
<td>80,000</td>
<td>1956</td>
<td>Melbourne</td>
<td>100,000</td>
</tr>
<tr>
<td>1900</td>
<td>Antwerp</td>
<td>20,000</td>
<td>1960</td>
<td>Rome</td>
<td>55,000</td>
</tr>
<tr>
<td>1904</td>
<td>St. Louis</td>
<td>19,000</td>
<td>1964</td>
<td>Tokyo</td>
<td>60,000</td>
</tr>
<tr>
<td>1908</td>
<td>London</td>
<td>68,000</td>
<td>1968</td>
<td>Mexico City</td>
<td>58,000</td>
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<tr>
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<td>1972</td>
<td>Munich</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>1976</td>
<td>Montreal</td>
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<tr>
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<td>Antwerp</td>
<td>20,000</td>
<td>1980</td>
<td>Moscow</td>
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<td>Paris</td>
<td>45,000</td>
<td>1984</td>
<td>Los Angeles</td>
<td>76,000</td>
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<tr>
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<td>1988</td>
<td>Seoul</td>
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<td>1992</td>
<td>Barcelona</td>
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<td>1996</td>
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<td>London</td>
<td>80,000</td>
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</table>

Stadium capacity through the time

Of course we have to keep in mind that some stadium were designed with standing places instead of seatings. If we look at the last Olympic period it is clear the requirement of 60,000 seats is really a bare minimum. In order to calculate the total stadium capacity we first have to look at seating dimensions. Different countries have different dimensional standards, an overview of these standards is given in the following table.

<table>
<thead>
<tr>
<th>Country</th>
<th>Seats per row</th>
<th>Minimum seat dimensions</th>
<th>Seating areas People per m² (maximum)</th>
<th>Standing areas People per m² (maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td>28</td>
<td>460 Width 500 Depth</td>
<td>700 People per m² recommended 760</td>
<td>3 People per m² with back 559 seat only</td>
</tr>
<tr>
<td>USA</td>
<td>22</td>
<td>450 Width 500 Depth</td>
<td>762 People per m² recommended 750</td>
<td>3 People per m² with back 559 seat only</td>
</tr>
<tr>
<td>Germany</td>
<td>72</td>
<td>500 Width 450 Depth</td>
<td>800 People per m² recommended 750</td>
<td>2 People per m² with back 559 seat only</td>
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<td>30 m max. bench length</td>
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<td>800 People per m² recommended 750</td>
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<td>600 People per m² recommended 750</td>
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<tr>
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<td>450 Width 450 Depth</td>
<td>750 People per m² recommended 750</td>
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<td>800 People per m² recommended 750</td>
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<tr>
<td>Sweden</td>
<td>40</td>
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<td>800 People per m² recommended 750</td>
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<td>800 People per m² recommended 750</td>
<td>2 People per m² with back 559 seat only</td>
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</tbody>
</table>

Dimensional standards for seat and standing areas

In the calculation the dimensional standards of Germany (also applies to Normay and Sweden) are used. Germany has got the same seat dimensions as the Netherlands. We are calculating with a value of 2.5 people per m². Because the stadium design is cutout at some places, the initial design is checked. In the calculation we assume that 18 percent of the total stadium
bowl is in use as circulation area (stairs and runways). This percent is larger for the designed stadium due to its geometrical division in permanent and temporary parts, making the length of the rows smaller than maximum allowed.

With the extra capacity of the possible additions, the Olympic stadium can easily reach the requirement of 60,000 seats. For a modern Olympic stadium the capacity of seats should be reaching at least 70,000 if we look at the previous Games. Because the height is limited due to the floating capabilities, other ways of extra capacity should be found such as adjusting the radius of the stadium bowl. This means making the distance from the field towards row 1 larger in such a way an extra permanent structure can be added to the chain. In the original design the chain of permanent structures at the short sides of the stadium consists of 8 floating pieces (8-6-8-6 or 8-3-8-3 when counting one catamaran as 1). All permanent structures are designed to be reused after the games as housing, so the dimensions of a single unit cannot change because of an increase in stadium capacity. A big advantage of the geometrical system of the chain of structures is the fact we can calculated the extra distance necessary for the addition of 1 unit at one of both short sides without changing the geometry of the single-units. At the same time the catamaran-units will increase in size as well. The sharper angle of the whole long side will prevent the catamaran-units to increase to much. One extra single-unit will have a capacity increase of 1803 seats, making the total increase at least twice this figure. A total of 3606 seats will be added.

<table>
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<td>2202</td>
</tr>
<tr>
<td>D</td>
<td>563</td>
<td>1154</td>
</tr>
<tr>
<td>E</td>
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<tr>
<td>F</td>
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<td>3058</td>
</tr>
<tr>
<td>G</td>
<td>2199</td>
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Extra stadium capacity
One extra single-unit will mean a smaller angle and a larger radius. First the mathematical relationship between the radius and the number of single units is derived. This way the increase in distance can be found as well.

\[
\beta = \frac{\alpha}{n} \quad r = \frac{B}{2 \sin(0.5\beta)}
\]

The length of \( \Delta r \) gives an impression of the smallest distance to the field. This means that for the number of units larger than 10, the distance will become to large. The distance \( \Delta r \) of 10 units is still reasonable, but for a optimal athletics stadium, 9 units are used in the adjusted design. The distance between the permanent structures is 8 meter, so the ratio 8 \( \cdot \) 9.220 is also a nice side present. A larger capacity can be achieved, but is reducing the athletics feeling and Olympic atmosphere. Now these extra capacity additions are known, the total design can be adjusted to meet the demands of 60.000 seats. This can be done with the following capacity combination:

<table>
<thead>
<tr>
<th>No.</th>
<th>Extra seats</th>
<th>( r ) (m)</th>
<th>( \Delta r ) (m)</th>
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<tr>
<td>8 ID</td>
<td>57.242</td>
<td>2.242</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>57.242 + 3606</td>
<td>57.242 + 64.220</td>
<td>2.242 + 9.220</td>
</tr>
<tr>
<td>10</td>
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<td>11</td>
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<td>57.242 + 78.548</td>
<td>2.242 + 23.548</td>
</tr>
<tr>
<td>12</td>
<td>57.242 + 14424</td>
<td>57.242 + 85.663</td>
<td>2.242 + 30.663</td>
</tr>
</tbody>
</table>

Extra stadium capacity
One of the architectural responsible combinations is ID+A+E+G+9. This combination delivers more than 67,580 seats. The original architectural concept stays intact and the capacity is increased with more than 10,000 seats. Because of the larger radius, extra catamaran seats are also delivered, but these are slightly less important, because of the smaller increase in length (a similar length B for the catamaran units). These seats are not incorporated in this calculation. Also the extra additions A till G are calculated for 8 units. Extra seats for these additions should also be added to the total number of seats. The total number of seats for the ID+A+E+G+9 combination will be somewhere in the area of 70,000. The delta r of this combination is comparable with the field distance of the London 2028 stadium.
Appendix VI: Project sheets
A team of Sinclair Knight Merz, Winkinson Eyre and KSS Design was appointed to design the Basketball Arena for the 2012 Olympic Games. The Basketball Arena will host a variety of sports: Basketball, Handball, Wheelchair Basketball and Wheelchair Rugby. During the Olympic Games the Basketball Arena will have 12,000 seats, during the Paralympic Games it will have a capacity of 10,000 seats. During the Olympic Games there will be a period of 22 hours to transform the venue from the Basketball competition to the Handball competition.
finals. Afterwards, there will be just 12 hours to get ready for Wheelchair Rugby after the Wheelchair Basketball competition finishes. The venue’s ‘back of house’ area will be shared with the Velodrome and BMX Track to make the most efficient use of space and resources.

A key challenge of the project was to create a temporary building which would not only be simple to erect and sustainable in terms of its legacy once the Games are over, but which will provide a world-class sporting venue for some of the most popular Olympic events. The design is such that two-thirds of the materials and elements within the building can be reused or recycled after the Games, allowing other parts of the United Kingdom and other parts of the world to benefit from the project. The Arena will be one of the largest temporary venues built for any Games.

The venue is 35 m high and its 1.000 tonne steel frame structure is wrapped in 20,000 m² of recyclable white PVC membrane, stretched over three variations of arched panels. During the Games this membrane will act as a canvas for different kind of lighting.
This project is a response to the cost of staging the Olympic Games, offering a solution to both experience of stadia construction and waste of their redundancy after the event. Together with lightweight structure specialists, 4 stadia were designed with different capacities which can be transformed in component form to be erected on site. Each stadium is covered by twin skin, fabric envelopes stretched over a series of 80 meter tied steel arches and can be demounted and erected elsewhere after the Games are over.
Adidas Arena, World Of Football

Berlin, Germany

The Adidas Arena is a temporary replica of Berlin’s Olympic stadium on a scale 1:3 at the heart of the 40,000 square meter soccer park in front of the historic Reichstag building. It was made for the 2006 FIFA World Cup in Germany. The stadium has a capacity of 10,000 seats, where fans could watch the World Cup matches live on a giant screen with a authentic atmosphere. Altogether 1,150 tons of material, supplied in 65 truck load, was erected for this event.

Client: Adidas
Architects: Nussli
Completion: 2006
Theme: Temporary
Olympic Stadium
London, United Kingdom

The main stadium for the 2012 Olympics will be one of the centrepieces, hosting the opening and closing ceremonies and the athletics event. The stadium can convert down from a 80,000-seater stadium for the games to a 25,000-seater permanent venue for football, athletics, concerts and community use.

The lower permanent trier has been excavated out on the site. The natural slope of the land is incorporated into the design, with warm-up and changing areas being dug...
into a semi basement position at the lower end. A demountable lightweight steel and concrete upper trier has been build up from the lower bowl to accommodate 55,000 spectators during the Olympic Games.

The cable supported roof structure will cover approximately two third of the stadium’s seating. During the design process the option of no roof at all was also taken into account, but this could invalidate any potential world records set in the stadium. The roof is made from polymer based membranes.

There will be no food outlets inside the arena, which reduces the higher level of fire protection. Instead, the architects have planned party concourses outside the stadium inspired by the 2006 World Cup Germany fan zones, where spectators gathered to eat and drink while watching the action on big screens. The toilet areas are also designed as pods outside the stadium.

On November 2010, it was announced that two bids have been short-listed for the stadium post-Olympics. The football clubs Tottenham Hotspur FC and West Ham United FC have interests of taking over the stadium structure. One would maintain the 80,000 capacity and the other would reduce it to 60,000.
The London Aquatic Centre is designed to have the flexibility to accommodate the size and capacity of the London 2012 Olympic Games whilst also providing the optimum size and capacity for use in Legacy mode after the 2012 Games.

The Aquatic Center can downscale its capacity after the games by removing the temporary stands at both longitudinal sides of the stadium roof. Unveiling the complete fluid wave design of Hadid. The architectural concept of the London Aquatic Centre is
inspired by the fluid geometry of water in motion, creating spaces and a surrounding environment in sympathy with the river landscape of the Olympic Park.

The Aquatic Centre is planned on an orthogonal axis. Three pools are located along this axis. The training pool is located under the bridge whilst the competition and diving pools are within a large volumetric pool hall. The overall strategy is to frame the base of the pool hall as a podium by surrounding it and connecting it into the bridge. This podium element allows for the containment of a variety of differentiated and cellular programmatic elements into a single architectural volume.

A large roof which is arching along the same axis as the pools. Its form is generated by the sightlines for the spectators during the Olympic mode. Double-curvature geometry has been used to create a structure of parabolic arches that create the unique characteristics of the roof. The roof projects beyond the base legacy pool hall envelope to extend the roof covering to the external areas of the cascades and the bridge entrance. The roof projection over the bridge entrance announces the London Aquatic Centre’s presence from the approach from either Stratford City or the Olympic Park. Structurally the roof is grounded at 3 primary positions. Otherwise the opening between the roof and the podium is in-filled with a glass façade.
Populous won the design for the 2014 Asian Games. The stadium will hold 70,000 people for the main event and will reduce down to a single sided grandstand for 30,000 afterwards as a People’s Park for the city of Incheon. The stadium design is based on an asymmetrical configuration with the main facilities located on the permanent Western side for efficient operation and construction. The Eastern side will be the lighter solution, the temporary modular seating will disappear after the Games, and the stadium structure integrates into the local landscape.
The ANZ stadium, the Olympic stadium of Sydney 2000, was originally built to temporarily hold 110,000 spectators, making it the largest stadium ever built. In 2003 reconfiguration work was completed to shorten the North and South wings, reducing the capacity to 83,500 seats. Additional roofing parts were added on the place of the temporary stands. The stadium is environmentally sustainable. Passive design measures include ventilation, natural cooling and heating. Rainwater is recycled from the roof and used to irrigate the pitch.
Temporary Extensions
Olympic Stadium
Amsterdam, The Netherlands

The temporary extension models are part of a feasibility study for the European Championship Athletics 2014, the World Cup Football 2018 and the Olympic games 2028. Different types of extension models are possible within the development of a repeatable, universal “extension-unit” with a capacity of approximately 1500 seats. The main benefit of such extension-units is the fact they spare the monumentality (characteristic lights, scoreboard and existing roof structure) of the existing stadium. With these extension-units the stadium can be

<table>
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<td>Theme</td>
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customised to different demands. By using these units, the stadium can gradually extend by 1500 seats per unit.

Because the Olympic Stadium of Amsterdam is a monument any potential extension will have a temporary nature. This study focuses on the reuse aspects of these temporary units. By making the elements out of standardised, lightweight and easily demountable building products, reusability after sport events is a valid scenario. The units can be used for small scale projects.

The extension ring scenario will increase the capacity of the stadium from 20,000 seats to approximately 55,000 till 60,000 seats. The Marathontower of the original design will cause the extension-ring to be asymmetrical. This extension-ring will be an autonomous structure completely disjointed from the existing stadium structure. The choose of materials will highly contrast the monumental brickwork (fine steel-mesh or fabric). Within the extension-ring there is room for secondary program. Offices, recording-studios and shop will have direct views of the field.

The next extension scenario, the European Championship Athletics is about increasing the capacity by 12,500 seats to meet the requirements set by the Athletics Association. This can be done entirely by rentable extension systems or rentable systems combined with one steel structure.
City Of Manchester Stadium

Manchester, United Kingdom

Client: Manchester City Council
Architects: Arup Associates & KSS Architects
Completion: 2002
Theme: Temporary, Conversion

After the failed attempts to host the 2000 Olympics and have the Millennium stadium in Manchester, the city looked towards a new target, the 2002 Commonwealth Games. The city of Manchester won this bid and could host the Games.

The question of what would happen to the stadium after the Commonwealth Games was solved when a deal was struck between the City Council and Manchester City Football Club, which was moving to the new stadium as tenants after the Games. A long-
term sustainable future was guaranteed. Arup and KSS reworked the design so that the stadium would be ready to stage athletics for the Commonwealth Games and then be converted for football. The Games capacity was to be 38,000, rising to 48,000 after conversion by removal of the athletics track and addition of extra seating.

Athletics and football can only occupy the same stadium at the same level if the football spectators are seated a long way from the pitch. At Manchester this would have meant a million spectators per annum for 60 years having to accept poorer viewing positions because of a 10-day event in 2002.

This was unacceptable, so the football pitch was created 6 m lower than the athletics field. Almost 90,000 m² of fill would be removed, the pitch laid, and the temporary 13,000-seater stand erected on the north side of the venue for the Games were replaced with permanent structure in time for the 2003-2004 football season. Also the shell used for the Games was converted into corporate hospitality, concessions, restaurants, conference areas, shops and kitchens.

The required seating bias dictated a bowl with high sides on the east and west and low ends north and south, allowing a single roof geometry to cover all seatings and leave large open areas in the corners for pitch ventilation and video screens. Simultaneously the low sides would pass into the nearby housing area. Placing the ramps externally makes the structure very distinctive and adds drama.
The organisers of the Stockholm Olympic bid of 2004 had implied that they wished to have an 80,000 seat stadium that could be removed and replaced with a 20,000 seat indoor arena where possible re-using as much of the original stadium. This design can reuse all the original components largely without alteration. The resultant arena is very much an evolved form. By using computers to ‘evolve’ a solution it was possible to fold the stadium closed much like flower petals. Two distinctively different buildings were produced using one set of components.
Olympic Stadium

Stockholm, Sweden

The stadium had to accommodate the needs related to its long-term use. Along each side, cable-braced curving cantilevers hung on central tubular arches formed two spherical segments which were covered by stretched fabric. During the Olympics these segments would shade the open stands. After the Olympics the dynamic segments would rotate towards each other. Central roof glazing would then be added, and the platforms of the elevated stands would pivoted upward to form vertical walls, thus closing the sides to create an indoor arena.
Highbury Square transforms an early an important example of a British football stadium, previously the home of Arsenal Football Club, into a residential community. The Arsenal Football Club has used the stadium for 93 years, but was moving to a more modern Emirates Stadium down the road. The conversion design preserves the nature and memory of the original arena, designed by C.W. Ferrier and William Binnie, while developing a new residential typology which contributed to the local area and streets. It nestled behind rows of

**Client**
Arsenal Football Club

**Architects**
Allies & Morrison

**Completion**
2009

**Theme**
Conversion, Housing

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Highbury Square

London, United Kingdom
small Victorian terraced houses, making it a remarkable structure in this residential area.

The design retains the art-deco facades of the stadium’s listed East stand and West stand and converts them into residential blocks, using the existing four metre structural grid to create apartments. It then adds new, shallower blocks with internal residential courtyards to the remaining two sides of the football pitch, which is transformed into a landscaped garden. The design retains the size and sense of the sports arena, but embeds it into a smaller scale context. The developed garden gives the impression of a football pitch, a simple rectilinear space.

The residential community consists of one, two and three bedroom apartments together with a number of penthouses. Most of the art-deco features where preserved: the facades, sun-burst gable windows and the marble entrance hall.

It is to mush to say this is a total stadium conversion due to the fact that only a number of features where preserved. The old stadium was actually dismantled and for the most part the new apartments are simply put into or attached to the historic facade and key stadium elements like the roof. On one moment during construction only the two monumental facades where standing.
In 1995, the final decision was made on the design for the Stade de France, to host the 1998 World Cup final and become the new national stadium. Choosing between two finalist designs it was decided to go with Michel Macary’s design: the one we now know as the Stade de France. The other finalist design by Jean Nouvel was certainly just as interesting.

The competition entry for the Stade de France by Jean Nouvel is a proposal with a radical solution for the angle of view onto the playing...
field and ensuring optimal field lighting. The stadium is not partly modifiable, it is 100% flexible. An extra flexibility is the sliding roof structure which maximizes sunshine on the field and shades the stands in during the summer. The underside of the grandstands is lined with retractable awnings that hang from the level of the stands. The stadium will house between 25,000 and 80,000 spectators, depending on the engaged modus. Because the stadium is originally design for the World Cup 98, the colours are derived from the french national teams.

The stadium is not only designed to house soccer matches, the stadium can turn in a full Olympic stadium. Nouvel thought it was inconceivable to design a 65,000 seats Olympic minimum capacity. Therefor the stadium will have an Olympic capacity of 85,000 seats. Four large screens will be placed in the four corner openings of the stadium’s Olympic interior.
The Stade de France is located four kilometres north of Paris in Saint-Denis. It is Paris’ main stadium and can accommodate over 80,000 people, making it the fifth largest stadium of Europe. It is used by both the French National football team and French rugby union team for international competition. The stadium was designed by four architects from two firms; Michel Macary, Aymeric Zublena, Michel Regembal and Claude Costantini.

The configuration of the stadium is interchangeable from football or rugby
venue to athletics venue by the use of movable stands. A hydraulic gantry, which was specially adapted, is needed to move the stands back to allow the athletics track to appear. The 500 tons stands can be moved over a length of 15 meter, rolling on a cushion of air and steel and Teflon rollers. Another 32 slabs of 100 tons have to be lowered by telescopic lifts to make room for the movement of the lower stands. The whole process can take place within a time of only 4 days. The system enables the spectator to be as close as possible to a particular event, optimising visibility. The lower stands hold 25,000 seats, making the Stade de France the largest modifiable Olympic stadium in the world.

The roof is another key feature of the Stade de France. With an area of 6 hectares and weight of 13,000 tons it is considered a technical masterpiece. The roof is suspended at a height of 40 meters above ground and supported by 18 soaring steel masts. It was designed to easily protect the 80,000 spectators without covering the playing field.

All technical features, for example lights and speakers, are embedded in the roof to avoid obstructing visibility.
The Sapporo Dome was one of the 10 venues to stage the Soccer World Cup 2002 in Korea and Japan. The idea was to have an easy-to-change grassed playing field that could be used for various purposes regardless of weather conditions. The arena has a domed roof, mechanically variable rows of seating and a movable grass pitch, which can be rolled out into the open air. The complex is used not only for professional sports like soccer and baseball, but also for exhibitions, trade fairs, pop concerts and other major events.
The international competition held for the stadium was won by Hiroshi Hara. He proposed a “double arena” with a figure-of-eight layout. Within the hall, the seating is arranged in triers, whereas the open-air arena is enclosed by an embankment of grass on which spectators can sit. Since an openable roof was out of the question in a region with such heavy snowfall, the architects decided to move the playing field instead.

A special apparatus was designed for the stadium. Set on 34 electrically operated wheels, the playing field can be raised 7.5 centimeter by means of a compressed air system. The 8.300-tonne football pitch can be moved through the 90 meter wide gate of the stadium at a rate of 4 meter a minute. Within only five hours, the structure can be converted from a baseball arena into a football arena.

The artificial turf of the baseball arena is rolled up and the gate is opened. The triers of seating can be pushed under the stands at the sides of the gate. Externally, the playing field is raised and wheeled into the hall, pivoted on its axis by 90 degrees and lowered again. The gate is closed and the seating is pushed back again.

For football matches, the stadium can accommodate 42,000 spectators. By moving the lower seating they enjoy great proximity to the game, whether it is baseball or football.
Saitama Super Arena

Saitama Shintoshin, Japan

Key feature of the Saitama Super Arena is the gigantic movable stand, weighing 15,000 tons and moving 70 meter horizontally. The main arena can transform into a stadium accommodating up to 37,000 spectators. The stadium provides a space for sports, concerts and large scale trade fairs. The main arena is ideal for indoorsports and musical events. The community arena is perfect for small scale sport events, exhibitions and festivals. Partitioning the main arena creates a hall for the holding of concerts or gatherings with high acoustic requirements.
Marina Bay Floating Stadium
Singapore, Malaysia

The Marina Bay Floating Platform is the largest floating stage in the world. Made entirely of steel the platform measures 120 metres long and 83 metres wide. The platform can bear up to 1,070 tonnes, equivalent of 9,000 people. The gallery at the stadium has a seating capacity of 30,000 people. The stadium will be the venue for events on the waters of Marina Bay, including sports, concerts, exhibitions and cultural performances. The venue was the stage for the opening and closing ceremonies of the 2010 Youth Olympics.

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<td>Theme</td>
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The Floating Offshore Stadium is designed for the FIFA World Cup 2022 in Qatar. It is a fully mobile structure which can be moved to seaside venues worldwide after the World Cup, maximizing the utilization future. A rib structure of vertical frames and horizontal slabs form the supporting structure. A floating baseplate carries the stadium bowl. The floating body under water has separated floats which allow the nivellement of the whole stadium. The stadium is eco-efficiently powered by a blend of hybrid energies such as water, wind and solar power.

**Floating Offshore Stadium**

**Doha, Qatar Worldwide**

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Bigfoot was a 1997 ideas competition to design a football stadium in order to entice teams back to Los Angeles which had been deserted by two football teams. The proposed design was a football ship to address the increasing mobility of the teams. The form of the ship is derived from a supertanker into which a football stadium for 80,000 has been inserted. The form of the hull is slightly modified to accommodate the idealized stadium. The space between the stadium and the hull is occupied by service utilities and access ways.
The Beijing Olympic Green Tennis Centre is located on the western edge of the Forest Park, the vast landscape that terminates the axis of the main Olympic site. The centrepiece of the complex is the 17,400 seat stadium, which sit above the terrain like a large opening flower. The balance of the facility is organised around a linear sequence of four giant platforms that step up the sloping park edge and so bring in the surrounding landscape. There is a clear hierarchical and compositional organisation to the site that counters the profile of the main stadium.
The tennis centre is a permanent venue which includes a 17,400 seat centre court, 4,000 and 2,000 seat show courts, seven 200 seat match courts and six practice courts with supported facilities. The venue has to become the home of the Chinese Tennis Federation after the Olympic Games of 2008.

The centre court stadium is composed of twelve segmented raking plates separated by tapered openings, which induce natural ventilation while providing views out of the engagement with the outside. The twelve sided seating bowl provides a clear structural proposition while giving excellent sight-lines and proximity to the field of play. The courts have been specially designed for natural air ventilation to reduce the amount of air pollution entering the courts. It also allows the court to be cooled, reducing court temperatures by five degrees Celsius.

Heroically scaled concrete beams and raking structures define the structure of the court and platforms. The vigorous use of structure and geometry, combined with a robust and minimum use of materials, has provided a venue with an order and clarity rarely seen in sporting venues.
San Nicola Football Stadium

Bari, Italy

The football stadium in Bari, located on the south-eastern outskirt of the city, was built for the World Cup in 1990. The outline of its tiered seating and roof is visible from afar in the flat plains of Apulia. Broad open spaces immediately around the stadium are contrasting its architecture. The 60,000-seater stadium was formed by security concern together with aesthetic and functional considerations.

The stadium is made up of a radial system with 26 axes, each axis corresponding to
an entrance. The lower tiers of seating are sunk into the ground, like an amphitheatre. The main communication corridor, which runs between the lower section and the seating above, is a continuation of space outside the stadium, thus ensuring maximum transparency between the outside of the arena and the pitch below.

The upper part of the tiered seating is raised above ground level and constructed of 312 sickle-shaped precast reinforced concrete compound units. Underneath this section are service facilities, dressing rooms and warm-up halls.
This project was the result of a 1994 competition. A total of 70 apartments are located in 5 buildings on the Gooimeerpromenade in Huizen. Each of the nearly identical blocks tapers towards the water to offer the best unobstructed lake views.

Each floor of the building contains one less apartment, resulting in a configuration that the architects have likened to the form of the sphinx. The sun-oriented back of each sphinx is used for the apartments terraces.
The front of the sphinx is finished with a large panoramic window. The penthouse in each building is slightly different, giving rise to a rhythm of distinctive heads, a striking skyline seen from the shore approach of the Stichtse bridge linking the new polders and the old mainland.

The buildings are clad in unpolished aluminium, playing with the reflective shades of grey of the Dutch water and weather. The buildings have parking facilities below the water level.

Reeds are planted along the sides of the concrete landing platform that link the buildings to their entrances. The reeds serve both as a gentle transition with the shore and a hydrophytic filter for water treatment. Concrete landing stages cut through the reeds to provide access to the sphinxes.

An emphasis has also been placed on public spaces along an esplanade between the buildings that successfully gives way to a look-out bastion, a surf beach, a village square, a wind balcony and a fishing jetty.
The Budenberg Haus Project is a canal-side living complex, providing 215 apartments with lots of outside space, whether that be a private balcony or the private residential garden.

The buildings rise from three to seven stories cantilevering over the canal. The Budenberg Haus maximises the potential of its unique canal-side location and is designed to resonate with the residential character of the adjacent roads. The scheme comprises two new residential blocks, making the transition...
from the low-rise housing on Woodfield Road to the large-scale industrial units on the canal.

The scheme includes 18 different types of apartments, ranging from single level one bedrooms, two bedrooms duplexes, curved corner apartments and three bedroom penthouses. All apartments feature balconies. Their are 315 car-parking spaces contained in a semi-basement garage.

The Budenberg Haus has provided a fantastic opportunity to develop and regenerate a brownfield site in Greater Manchester. The design has created contemporary living space with highly innovative sustainable features on an ideal canal-side setting.