CLIMATE ADAPTATION CONCEPT ON A STADIUM

THE NEW FEYENOORD STADIUM

P5 Report

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ABSTRACT

The practice of almost any sport requires friendly and comfortable environmental conditions, cool temperatures and medium humidity levels, as well as satisfactory lighting and ventilation performance (Torsing et al., 2016). The complex challenge of designing sport infrastructure is likely to become even bigger in the expected future warmer scenario.

This research focuses on the development of a climate adaptation concept for the new Feyenoord Stadium, with the goal to make it adaptable to the future climate scenario, characterized by global warming, which will lead to an increase in temperatures and heat waves.

The focus of the design is mainly on the integration of passive strategies to cool down the stadium and control the indoor temperature to guarantee proper livability to users, thus reducing the need for active cooling.
The research explores mainly possibilities for the design of the envelope, which represents the connection between the stadium and its surroundings. A proper design of the envelope would bring benefits both to the stadium itself and the outdoor environment, by mitigating the urban heat island effect. Indeed, the main question of this research is "how can the envelope of a large-scale stadium be designed to integrate passive strategies to provide cooling in a future warmer scenario and guarantee a comfortable micro-climate to users, while reducing the UHI in the surroundings?"

Based on the literature review, different strategies were explored, and those more likely to make the Stadium adaptable to the climate of Rotterdam have been selected and analyzed in detail to be integrated into the new design.
Through means of calculations and simulations, outcomes were obtained, which show that with a proper design of the envelope and some areas of the stadium, it is possible to control the indoor temperature to avoid overheating, guarantee comfort to users, and reduce the cooling demand of the building.

The ultimate goal of this research is to give guidelines for a replicable design approach to be applied to stadiums around the world to deal with local climate potentials and hazards, and rely on the resources offered by the surroundings.

Keywords

Stadium, climate change, sustainability, climate design, passive design, natural ventilation, daylight, shading, evaporative cooling, energy production, urban heat island effect.

The research is divided into seven main different sections:

1) Introduction
Overview of climate change and its effect at human, building and city scale.

2) Research framework
Description of the methodology adopted to carry out the research. In this section the problem is stated, the research questions are formulated, and the objective is defined.

3) Background knowledge
Introduction to useful information obtained from the literature review regarding climate change, organizations, stadiums around the world and general adaptation measures.

4) Case study: the new Feyenoord Stadium
Overview of the Feyenoord City Project and the Rotterdam context. In this section, the stadium is analyzed to proceed with the design.

5) Final design
Elaboration of the final design proposal with evaluation of the performance by means of validation through calculations and simulations.

6) Conclusions
Direct answers to the previously formulated research questions.

7) Recommendations
Suggestions for future research about the topic or how to improve the quality of work in similar researches.

0 TABLE OF CONTENTS

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1 INTRODUCTION

This research focuses on the development of a climate adaptation concept on a stadium, with the goal to make it adaptable to the future climate scenario, characterized by global warming, which will lead to increase in temperatures and heat waves.

Stadia are atypical building types, where various activities are carried out. This diversity of functions makes hard to control the indoor climate and guarantee the required level of comfort to all the users. This is also enhanced by the way in which stadia are constructed: they can, indeed, be considered semi-outdoor spaces. Whereas other building typologies, such as office buildings or schools, can be seen as "boxes" which can be closed to create the desired indoor micro-climate, in a stadium this is not possible. First, as it is semi-open in most of the cases, it is hard to control the indoor temperature due to many climatic variables. Then, the changing amount of people, which can differ according to the type of event, leads to different heat production scenarios and different requirements.
In addition, stadia are big infrastructures which can have a strong impact on the surroundings. It is important, therefore, to consciously design and develop them so that they can represent a resource to tackle urban heat related issues and not a further cause of vulnerability.

The new Feyenoord stadium is here taken as case study to develop a design approach which can be replicated and adapted to other stadia around the world. Feyenoord is chosen due to its strategic position nearby the Nieuwe Maas river, which can be seen either as a hazard source with the increasing risk of floods, or as a potential for cooling and water collection. Also, the plan for Feyenoord City does not include only the stadium but many facilities and new activities which will attract lots of visitors, thus making the area highly vulnerable in a future warmer scenario. In addition, according the Feyenoord City's construction plans, the stadium is expected to be built by 2023 and be eligible for hosting World Cups' competitions. Being a stadium of the future, the Feyenoord is an optimal case study to design for the climate of the future.

This chapter is about the background information studied to contextualize this project. The context is described to understand the reasons behind this research, highlighting the most challenging aspects.
Climate change data are shown, with consequent issues and hazards which could effect the built environment in a future climate scenario.

1.1 CONTEXT

1.1.1 Climate change

Climate change is one of the greatest environmental threat human beings have ever faced. Dealing with it is a complex challenge, characterized by several issues to tackle. According to the Climate change and global warming data published in the NASA website (n.d.), it has been observed that from 1970s temperatures have relentlessly increased, mainly due to the emission of greenhouse gases from burning fossil fuels, which sees as main cause the anthropogenic activities. Global warming, defined as an increase in combined surface air and sea surface temperatures, is bringing irreversible consequences: from shifting weather patterns, with associated increasing heat waves and droughts periods, as well as extreme events, to rising sea level with effects on the risk of floods. The impacts of climate change are global and of unprecedented scale, as stated in the United Nations website (n.d.).
However, consequences and registered effects may vary at different scales. Although it is true that several organizations studying climate change are providing reliable figures to foresee the future global scenario, it is also true that differences in effects and registered temperatures can vary from place to place. It is, therefore, important to take into account both global and local consequences when designing to face climate change.
Data on climate change and its consequences, with related goals to mitigate them both at global and national scale for the Netherlands are respectively shown in table 1.1.1 and 1.1.2.

CLIMATE CHANGE - GLOBAL	What	Notes	Goal
Temperature (Earth's surface - land+ocean)	14 °C **1,5 °C** 0,7-0,9°C 1,5-1,8 °C 0,5 °C 1,1-5,4 °C 0,9 °C	Today's average surface temperature. Expected by 2030-2052. Increase per century since 1901. Double rate of warming per century since 1975. Expected by 2020 compared to 1986-2005 average. Increase expected by 2100 mainly due to CO2+GHG. Last annual average anomaly (2017).	Global warming should not exceed 1,5 °C; this value must be stabilized, cause if exceeded and then lowered again will bring worse consequences than if it is kept constant.
Heat waves	Increase	Expectation	
Droughts	Increase	Expectation	
UHI	Increase	Expectation	
Sea level rise	3,2 mm/yr 87 (±4) mm	Rate of change - increase. Last measurement (October 2018) compared to 1993.	
Rain	Increase	More intense phenomena	
Flood risks	Increase	Expectation	
CO2	409 ppm 94 ppm	Last measurement (October 2018). Increase since 1958	45% reduction by 2030. Net-zero by 2050

Table 1.1.1: Data on climate change - global
Source: climate.nasa.gov
IPCC (2018)

CLIMATE CHANGE - NETHERLANDS	What	Notes	Goal
Temperature	3-6 °C 2°C	Increase by 2100 compared to 1850 if GHG emissions do not decrease. Increase if drastic measures are adopted to reduce GHG emissions.	1.5 °C max
Heat waves	Increase	Expectation	
Droughts	Increase	Expectation	
UHI	3-7 °C Increase	Today's average in Dutch cities . Expectation.	
Rain	26% 14% 12% 851 mm 5%	Increase 1910-2013. Increase 1951-2013. Increase of rainfall per hour per degree of warming observed. Precipitation 1981-2010. Increase by 2030. The precipitation and extreme precipitation increase in winter; the intensity of extreme rain showers in the summer is increasing. More rain in a short time is expected, with higher chance of thunderstorms with heavy gusts of wind and large hail.	
Flood risks	Increase	Expectation	All flood defence systems must meet the new standards by 2050; 100 km of dykes improved by 2020; 945 km of dykes+468 engineering structures improved by 2050.
CO2	49,3 Gigatonnes eq		20% CO2 emission reduction by 2020 compared to 1990 (EU agreement). 40% CO2 emission reduction by 2030 compared to 1990.

Table 1.1.2: Data on climate change - the Netherlands
Source: "KNMI'14 klimaatscenario's voor Nederland
Delta Program 2019 , KNMI

In addition, the temperature rise trend is shown in figure 1.1.1.

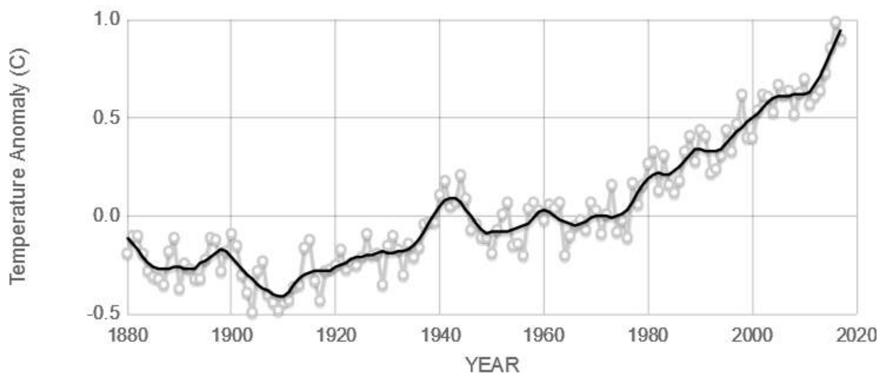

Figure 1.1.1: Temperature anomaly (°C).
From "NASA/GISS", 2018. https://climate.nasa.gov/vital-signs/global-temperature/

1.1.2 Urban Heat Island effect (UHI)

Due to materials properties and buildings density, cities are generally warmer than their surrounding areas (Figure 1.1.2). This phenomenon is called urban heat island effect. There are different types of UHI:

- Surface UHI, which is the difference in surface temperature between the city and the surrounding countryside. It occurs both at day and night, but it is higher during the day due to surfaces absorption properties;
- Atmospheric UHI, which is the difference in air temperature between the city and the surrounding countryside. It occurs mainly at night because the countryside cools down faster than the city.

  The atmospheric UHI can be subdivided into:

  I. Urban Boundary Layer UHI: the intensity depends on the geographical situation of the city, general configuration and morphology;

  II. Urban Canopy Layer UHI: the presence of buildings, street surfacing, trees and water have a direct and noticeable effect on the climate at living level (Climate Proof Cities Consortium, 2014).

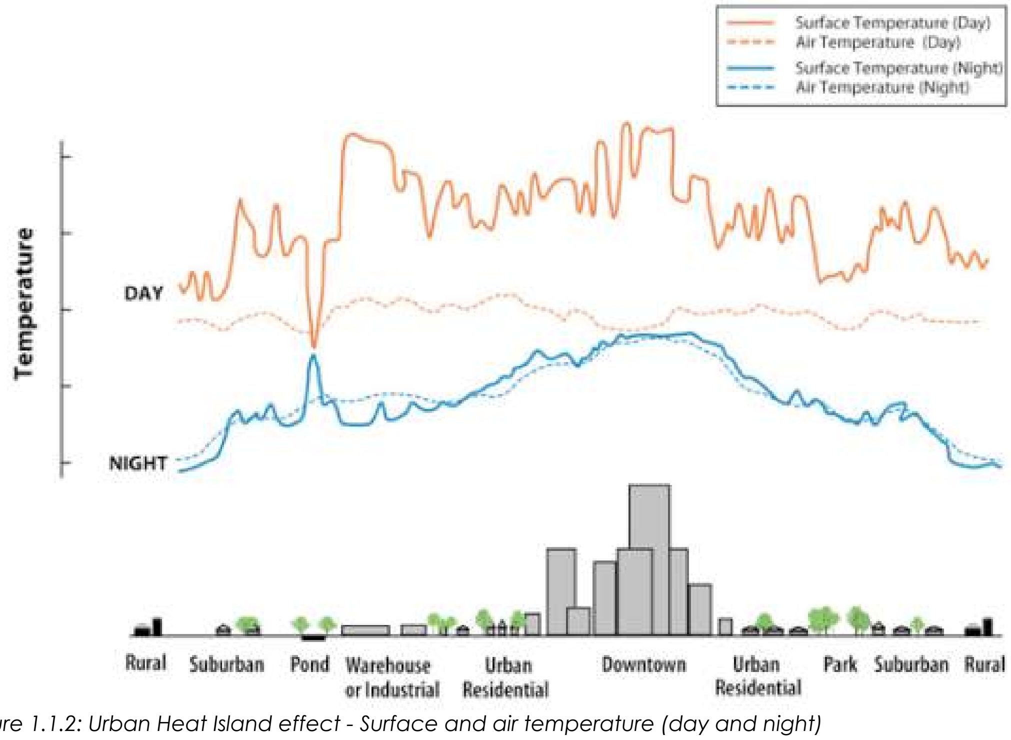

Figure 1.1.2: Urban Heat Island effect - Surface and air temperature (day and night)
From "Epa - United States Environmental Protection Agency", 2019. https://www.epa.gov/heat-islands/learn-about-heat-islands

1.1.3 Thermal comfort and heat stress

Climate change and rising temperature will strongly affect thermal comfort of people, thus increasing the risk of heat stress diseases.
According to the Designing Buildings website (n.d.), thermal comfort is defined as the condition of mind that expresses satisfaction with the thermal environment

and is assessed by subjective evaluation.

Heat stress, instead, is a situation where too much heat is absorbed by a person causing stress, illness or even death. It is manifested by elevated body temperature, hot, dry skin, lack of sweating and neurological symptoms such as paralysis, headache, vertigo and unconsciousness. It can also cause heat cramps, heat exhaustion and heat stroke which may lead to death, as stated in the Dutch website on heat stress (n.d.).

1.1.4 Users' requirements

The main activities carried out in stadia are football matches, events such as concerts, and conferences when dedicated spaces are available. For each activity there are different users and related needs.
In case of a football match, the users are the players and the spectators. In order to carry out this activity it is required to guarantee cooling to avoid health hazards to both the users and good air quality due to the high amount of people. However, players must be able to perform in excellent conditions, whereas comfort requirements of visitors are mainly connected to the protection from rain, wind, but also to the view on the field. In addition, lighting requirements are set by FIFA and UEFA.
When a concert takes place, the users are mainly the spectators. Like in the previous case, good air quality and cooling are required. Next to it, the acoustic performance of the stadium should be optimal.
Last, when the users are the conference attendees, requirements must be met in particular in the rooms where conferences are held. Users' needs, in this case, are related to heating and cooling to guarantee comfort in different seasons.

1.1.5 Vulnerability

Defining the safe boundaries of global warming is hard as the effects of climate change in the future cannot be precisely foreseen but only estimated. However, the Intergovernmental Panel on Climate Change defined as "safe" 1.5 °C global warming (by 2100) above pre-industrial levels. This would reduce challenging impacts on ecosystems, human health and well-being (IPCC, 2018).
Human health is walking into enormous hazards due to climate change. Heat stress risks will increase, leading to increasing number of heat-related death. Exposure to extreme heat can also lead to heat stroke and dehydration, as well as cardiovascular, respiratory, and cerebrovascular disease (United States Environmental Protection Agency, n.d.).
At the same time, buildings and built environment are extremely vulnerable to climate change. Due to the increasing temperatures, extreme events and risk of floods or other phenomena, there might be an increase in the risk of collapse, declining state and significant loss of value. Buildings, indeed, can significantly be deteriorated by these factors and their lifespan reduced (European Climate

Adaptation platform, n.d.).

Local measures should, therefore, be adopted to face the challenges of climate change, in particular the increasing urban heat island effect and the risk of floods at city scale, and the increasing temperature with consequent worst comfort for users in buildings.

1.1.6 Mitigation VS Adaptation

Before defining a possible design strategies in the context of climate change, a clear distinction between mitigation and adaptation must be done.
Mitigation measures look up to the reduction of climate change by avoiding human interference with the climate system and stabilizing greenhouse gases levels in a time-frame sufficient to allow ecosystems to adapt naturally to climate change (IPCC, 2014).
On the other hand, adaptation measures aims to adapt life to climate change to reduce vulnerability to the expected effects and exploit the potentials associated with the consequences of climate change, as mentioned in the NASA website (n.d.).

2 RESEARCH FRAMEWORK

In this chapter, the research methodology is explained step by step.
First, the problem is stated, then research questions are formulated, and aims and objectives defined.
Last, an overview of the phases of the research is given.

2.1 PROBLEM STATEMENT

The practice of almost any sport requires friendly and comfortable environmental conditions, cool temperatures and medium humidity levels, as well as satisfactory lighting and ventilation performance (Torsing et al., 2016).
Whereas buildings, in general, are “boxes” which can be closed to create the desired indoor micro-climate, stadia are atypical building types, which can be seen as semi-outdoor spaces, thus making hard to control the indoor climate due to many climatic variables. Stadia also host various events. This diversity of functions further enhances the challenge due to different activities and users’ requirements. Moreover, big infrastructures like stadia, have great impact on surroundings, as they are usually built in a big plaza, with cities developing around it. Indeed, they can be either a cooling resource or a source of risk, increasing urban heat island effect.

In the expected future warmer scenario global warming 1.5 °C (with respect to pre-industrial levels), the comfort-related issues in such a building type will further increase. With raising temperatures and consequent heat stress and risks, sport infrastructures will face an even bigger challenge in providing the right conditions for all users, especially in the semi-outdoor area, represented by the tiers and the field, which is the most vulnerable to changing outdoor conditions.

The designer, therefore, should be able to integrate the design of such infrastructures with elements that create a comfortable micro-climate, in particular dealing with rising temperature. Reduction in the amount of solar radiation, control of humidity and ventilation are necessary and must be achieved by adopting sustainable solutions able to bring benefits both to the indoor climate and the surrounding urban context.

2.2 RESEARCH QUESTIONS

2.2.1 Main question

Within the defined context, it is assumed that in a future warmer scenario, stadia will be strongly affected by the raising temperature. It is, therefore, necessary to properly design them to adapt to climate change. In this framework, the main research question is determined.

How can the envelope of a large-scale stadium be designed to integrate passive strategies to provide cooling in a future warmer scenario and guarantee a comfortable micro-climate to users, while reducing the UHI in the surroundings?

2.2.2 Sub-questions

Linked to the main research question, sub-questions are defined. Some refer to the impact of climate change on users, stadium and surroundings:

How are the stadium and its surroundings affected by climate change, in particular by rising temperatures?

How do users' comfort requirements vary according to the carried-out activity?

Other sub-questions are linked to the possible design strategies:

Which are the parameters affecting the indoor comfort the most?

How can the design allow for shading in such a way that daylight is still provided?

How can natural ventilation be implemented in the design? What would be the effectiveness of the measure?

How can cooling be provided to the space?

Which materials can be used in the design of the envelope so that the indoor comfort is improved? How they help mitigate UHI in the surroundings?

2.3 AIMS AND OBJECTIVES

The general goal of this research is to explore possible design strategies to make stadia adaptable to climate change and define the most effective one.
Nowadays, stadia around the world are designed to be sustainable but not to face the challenges of climate change, in particular the raising temperatures. This shows a general lack of knowledge among citizens on the real effect of global warming. In fact, in many cases, cities develop around stadia or big infrastructures without taking into consideration the climate.
Taking actions to face the climate change is urgent, therefore stadia should not only be integrated with sustainable solutions, but with strategies that will allow them to work in a future warmer scenario. However, sustainability and CO_2 neutrality should always be a key element in the design.

In order to guarantee the required comfort to all the users and avoid health issues due to heat, the aim is to design the stadium in such a way that it will allow for temperature control, therefore for a comfortable indoor micro-climate. The main focus will be on the semi-outdoor space of the stadium, namely tiers and field. In addition, the newly designed components aim at impacting the

surrounding urban context to reduce the effect of climate change, therefore reduce the urban heat island effect.
By introducing adaptation measures, the stadium will guarantee proper livability of users in a future warmer scenario.
The ultimate goal is, therefore, to guarantee temperature and comfort control by integrating passive solutions whenever it is feasible, thus increasing sustainability and reducing energy consumption.
The whole approach to design should represent a model to be replicated in other case studies, therefore guidelines will be provided.

2.4 RESEARCH OVERVIEW

The project methodology will be based on research by design and design by research, through five steps: knowledge, design exploration, analysis and digital design, comparison and evaluation, and final design.

First, knowledge is acquired in order to acquaint with the research topic and background information. Literature review provides information to get a proper insight into the different aspects of the research. The focus is on climate change, its consequences and effects on built environment and human beings, and on the various Organizations who deal with it. Numbers are provided to confirm the general information. On the other hand, Feyenoord City project and its urban context are studied to define the potentials and challenges of the area, and verify the feasibility of some proposed adaptation measures. An analysis of stadia around the world is introduced: this allows to explore possibilities in terms of climate adaptation measures integration in the design of sport infrastructures.

The second phase is the design exploration. Based on the literature review, design alternatives for climate adaptability of the new Feyenoord Stadium are explored. In order to get to the selection of the most effective design solutions, hand calculations are performed to have a first overview. This will give insight into the elements and parameters affective the indoor comfort the most.

In the third phase, software will be used to simulate the actual behaviour of the stadium and its relation with the context. They will also support calculations. In particular, Ladybug plug-in for grasshopper will be used for CFD analysis and Ladybug for solar radiation study.
Simulations also allow to evaluate the performance of the design proposal in terms of adaptability to climate change, indoor comfort and benefits brought to the site. In particular, Design Builder will be used to verify indoor temperature and ventilation, ENVI-met will help check the effect of the stadium on the surroundings, and Honeybee for grasshopper to see the amount of daylight on the field.

With the support of these tools, design could be developed in a coherent way, exploiting the potentials of the site.

Various alternatives will be explored and compared based on the previously obtained calculations and simulations outcomes, but at the same time they will be tested when needed.

Last, a design proposal is developed, which should be able to deal with climate change by regulating indoor temperature and comfort, while bringing benefits to the surroundings. The performance of the final design proposal will be evaluated by means of calculations or simulations, depending on the need.

The ultimate goal of the whole process is to create guidelines to the design approach for stadia to make them climate adaptive.

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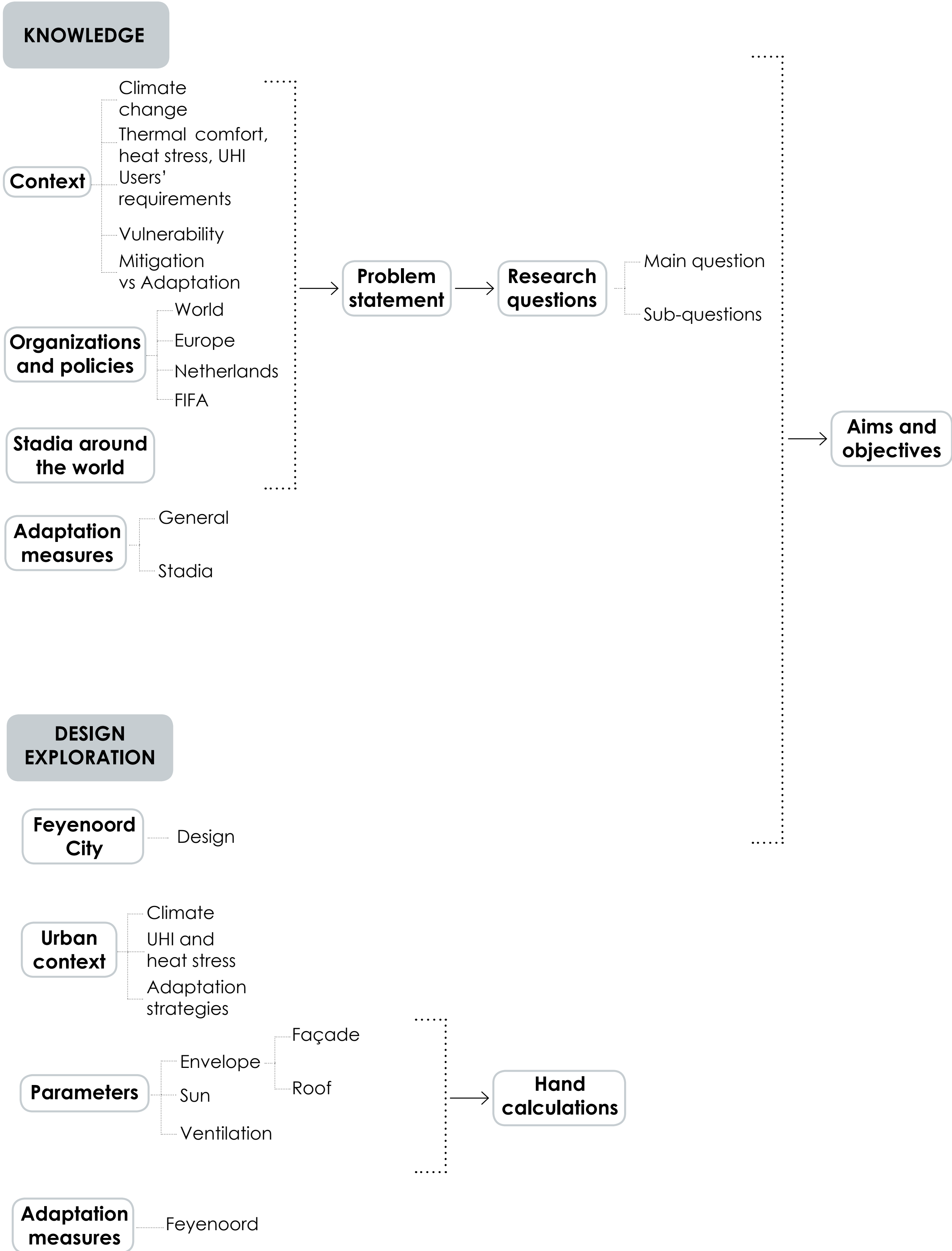
How are the stadium and its surroundings affected by climate change, in particular by rising temperatures?

How do users' comfort requirements vary according to the carried-out activity?

Which are the parameters affecting the indoor comfort the most?



How can the design allow for shading in such a way that daylight is still provided?

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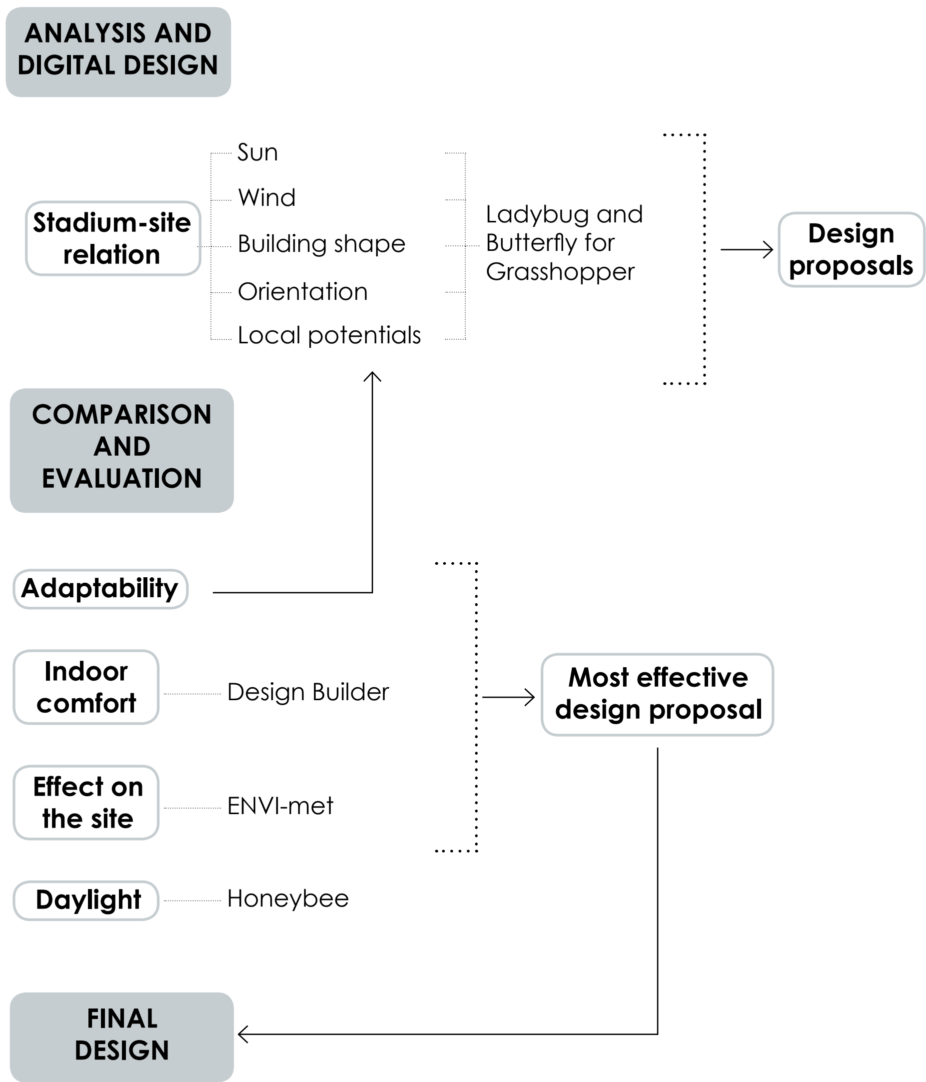


How can the envelope of a large-scale stadium be designed to integrate passive strategies to provide cooling in a future warmer scenario and guarantee a comfortable micro-climate to users, while reducing the UHI in the surroundings?

3 BACKGROUND KNOWLEDGE

In this chapter, World, European and Dutch organizations are introduced with the focus on the developed policies to adapt to climate change and mitigate the effects. Next to it, FIFA's regulations for sport infrastructures are listed to understand which are the requirements to be met in the design of a stadium.

General climate adaptation measures are explained, with their effect on the users' comfort and on heat or water-related risks.
Also, a selection of stadia around the world is presented. All the selected cases study are either built or renovated after 2000, or newly built in the same site of an existing stadium. The analysis has been limited by these characteristics to show examples similar to the case of the new Feyenoord stadium, which is designed to be built next to the old stadium, built in 1937.
Possible climate adaptation strategies are observed in the listed stadia to understand the effectiveness of design measures.

3.1 ORGANIZATIONS AND POLICIES

3.1.1 World

The main world organization dedicated to climate change and its consequences is the Intergovernmental Panel on Climate Change (IPCC), established in 1988 by th World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP).
As stated in the IPCC website (n.d.), IPCC is the United Nations body for assessing the science related to climate change, with the ultimate goal to provide the world with an objective, scientific view of climate change and its political and economic impacts, as well as develop adaptation and mitigation options .
From 1990 to 2014, the IPCC has published five assessment reports reviewing the latest climate science, as well as a number of special reports on particular topics. The 6th report is expected to be completed by 2022.

IPCC, in particular, produces reports that support the United Nations Framework Convention on Climate Change (UNFCCC), the main international agreement on climate action, established in 1992 at the Rio Earth Summit and recognized by 195 countries. The objective of the UNFCCC is to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system", by making countries working together to limit global warming and climate change, in order to mitigate and adapt to the expected consequences (IPCC, n.d.).
The main international agreements defined in the past decades are:

1) Kyoto Protocol
With the agreement in 1997, it introduced legally binding emission reduction targets for developed countries. The second commitment period (2013-2020), instead, is covered by the Doha amendment: the participating countries have committed to reducing emissions by at least 18% below 1990 levels.

2) Paris Agreement
Defined in 2015, the goal is to keep the global temperature rise below 2 °C above pre-industrial levels and adopt measures to limit the temperature increase even further to 1.5 °C
("International agreement on climate action", European Council, 2018).

3.1.2 Europe

The main organization providing information on the environment in Europe, is the European Environment Agency (EEA), established in 1994, with the goal to support sustainable development to improve Europe's environment, by providing relevant and reliable information to policymakers and public. The

EEA aims to help in the transition towards a low-carbon, resource efficient and ecosystem-resilient society by 2050.

In 2007, Europe's goals for 2020 have been defined: the 20-20-20 target refers to a 20 % reduction of GHG emissions compared with 1990, a 20 % share of renewables in EU energy consumption, and energy improvement by 20 %. A further step in the strategy, setting the goals for 2030, has been defined in 2014, with the 40-27-27 target.

In addition to the aforementioned goals, sixteen EEA member countries have prepared National Climate Change Adaptation Strategies. To support National policies, the European Climate Adaptation Platform (Climate-ADAPT) has been created (EEA, n.d.).

3.1.3 The Netherlands

The Dutch Government, in particular the Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Quality Ministry of the Interior and Kingdom Relations, is working hard on climate adaptation. Several plans have been defined from 2007, with the first one being the Delta Program, started in 2010 then revised and published in the final version in 2019. The goal of the Delta Program 2019 is to mitigate the impact of flooding, heat and drought, with the focus on flood risk management, fresh water supply and spatial adaptation, in order to guarantee secure climate-proof and water-resilient spatial design in the Netherlands by 2050 with the first effects to be observed from 2020 (Dutch Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Quality, Ministry of the Interior and Kingdom Relations, 2019).

In addition, in 2013, the Government has published the Climate Agenda, a document that contains ambitions, goals and actions guidelines to prevent and to adapt to climate change. It also provides guidance for companies, civil society organizations, and members of the public for going forward together towards a sustainable society (Dutch Government, 2013).

Last, the National Climate Adaptation Strategy (NAS) has been published in 2016, which relies on collectivity to develop smart planning of the Netherlands. In 2017, also the Climate Adaptation Implementation Programme has been presented. The approach is to launch new adaptation initiatives and to support and accelerate existing adaptation practices, cooperating with local governments, industry and citizens (Kennisportaal Ruimtelijke Adaptatie, 2018).

An overview of the world, Europe and Dutch climate change strategies to limit the global warming is shown in figure 3.1.1.

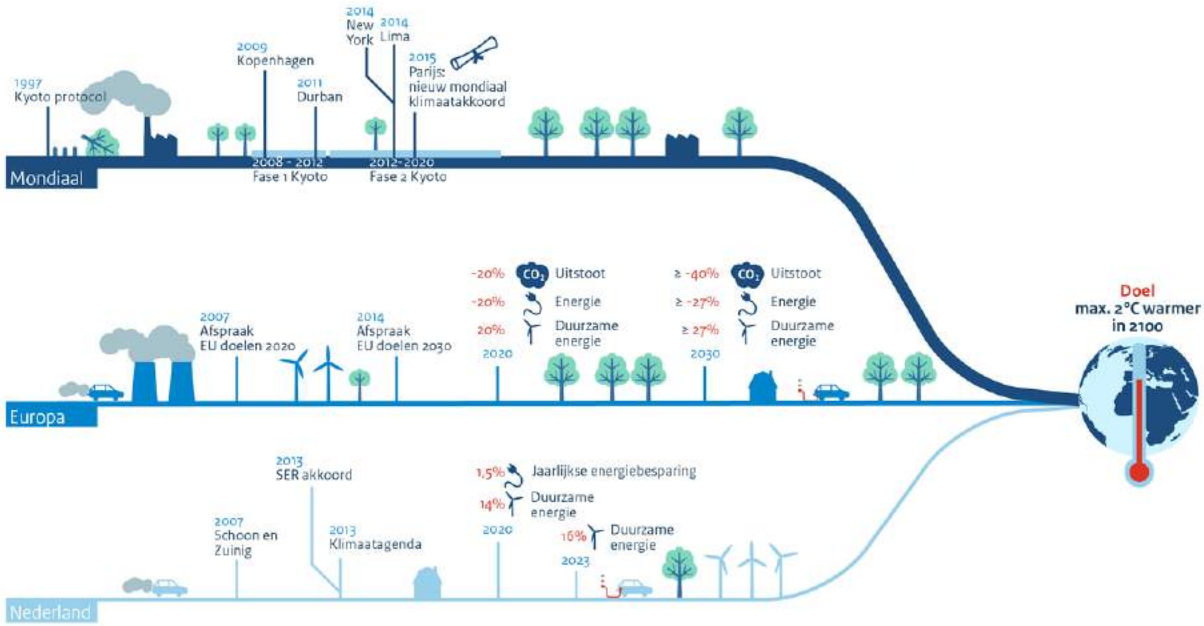


Figure 3.1.1: Climate Adaptation strategies to limit global warming
Ministry of Infrastructure and Water Management, 2018

3.1.4 FIFA's sport infrastructures rules and regulations

FIFA (Fédération Internationale de Football Association in French, 'International Federation of Association Football'), founded in 1904, is the international organization of football and beach soccer, responsible for the organization of football's major international tournaments, among which the World Cup (Wikipedia, n.d.).
In 2007 FIFA published the 4th Edition of "Technical recommendations and requirements for Football Stadia", which states the requirements a stadium must meet in order to be eligible for hosting important competitions, such as World Cup's matches.
Requirements are divided into ten main categories: Pre-construction decisions, Safety, Orientation and Parking, Playing area, Players and match officials, Spectators, Hospitality, Media, Lighting and power supply, Communications and additional areas.
In a future climate change scenario, the sections influencing the most the stadium's design are Pre-construction decisions and Spectators, which are related to sustainability, environmental impact and comfort of users.
In section 1 (Pre-construction decisions), FIFA sets rules to address environmental sustainability through the Green Goal™ programme. The principal goals of the programme are: the reduction in the consumption of potable water, the avoidance and/or reduction of waste, the creation of a more efficient energy system and an increase in the use of public transport to FIFA events. These goals should contribute to the establishment of a neutral climate as far as greenhouse gas emissions are concerned.
In section 6 (Spectators), the organization addresses the required comfort level standards for spectators. In particular, a cover should be provided to protect spectators from rain and glare due to sunlight.

Other sections are mainly dedicated to space requirements and safety issues.

3.2 ADAPTATION MEASURES

A variety of potential climate adaptation measures exists, which includes both active and passive strategies that can be implemented in the design of a building or in the urban context. Whereas some measures are generally applicable, therefore valid and effective, some others have to be locally adjusted, depending either on the building typology or the context, as well as on the specific climate of the site.
The measures contribute to easing problems with flooding, heat and drought at the same time, and an integral approach to these three problems is preferred.
Referring to the Final report Climate Proof Cities 2010-2014 classification method (Climate Proof Cities Consortium, 2014), the most common adaptation measures have been collected and analyzed to understand their effect on heat or water-related issues, their effectiveness and validity.
In the following tables, measures for cooling are explained. These are divided into three main categories: passive measures, elements to integrate passive measures, and extra measures for sustainable cooling production.

Table content - legend:
H = prevent or reduce heat stress.
W = prevent or reduce damage caused by flooding due to extreme rainfall.

- = negative effect
± = little/no effect
+ = positive effect
++ = very positive effect

G = measure is generally applicable, therefore the effects are generally valid, independent of a specific context, urban or building typology.
T = measure is typology-linked. It is valid for a certain urban or building typology. but independent of a specific context.
C = measure is context-dependent. Must be determined for each individual situation.
(Climate Proof Cities Consortium, 2014).

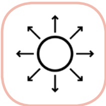
The following icons refer to the passive measures that can be integrated in the design:

Natural ventilation

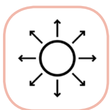
Evaporative cooling

Shading

Solar reflectance



Radiative cooling



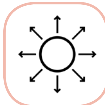
Measure	What	Benefits
Passive measures		
Natural ventilation	Cross ventilation or stack effect.	Improved air quality. Health environment. Lower cooling demand. Thermal comfort.
Evaporative cooling	Reduction in temperature resulting from the evaporation of a liquid, which removes latent heat from the surface from which evaporation takes place. The principle underlying evaporative cooling is the fact that water must have heat applied to it to change from a liquid to a vapor. When evaporation occurs, this heat is taken from the water that remains in the liquid state, resulting in a cooler liquid.	Lower cooling demand, less energy consumption.
Shading	Screening of solar radiation.	Reduce solar heat gains. Lower cooling demand.
Solar reflectance	Reflection of solar radiation.	Reduce solar heat gains. Reduce heat absorption. Lower UHI. Lower cooling demand.
Radiative cooling	Radiative cooling is the process by which a body loses heat by thermal radiation.	Lower cooling and heating demand.

Table 3.2.1: General adaptation measures - passive measures

Drawbacks	Goal	Effectiveness	Type
Hard to control cause outdoor temperature might lead to an increase in indoor temperature in some areas.	H	++	G
Not very effective at high dampness. Purification needed to avoid legionella.	H	++	G
Might increase electricity demand.	H	++	C
Increase heating demand.	H	+	C
Increase heating demand.	H	+	C

Measure	What	Benefits	Dra
Design to integrate passive measures			
Materials			
High albedo	Increase surfaces reflectivity and absorb less solar radiation. Mainly used in roof (cool roof) or pavement (cool pavement).	UHI effect mitigation. Cooling load reduction in summer, but savings decrease as the climate gets colder.	UHI effect Heating load increa
Thermal mass	Property of the mass of a building which enables it to store heat, providing "inertia" against temperature fluctuations.	Reduce heating and cooling demand.	In summer, thermal r night-time ventilatio of cooling) can be u heat absorbed by th the day.
Roof			
Cool roof	High albedo. Reflect more sunlight (high reflectance) and absorb less heat (high emittance). Can be made of highly reflective type of paint, a sheet covering, or highly reflective tiles or shingles. SRI (Solar reflectance index) as measure of its performance).	Lower cooling demand. Smaller HVAC. Improved comfort in not air conditioned spaces. Decrease roof temperature and UV absorption: roof life span is increased. Reduce UHI. Reduce power plants emissions, including GHG. Lowered peak electricity demand, which helps prevent power outages.	Increased energy de reduced heat gains. Moisture accumulat cold climate.
Green roof	Roof that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane.	Rainwater buffer. Lower temperature, less need for cooling. Air purification: filter pollutants and CO2. Acoustic insulation. Biodiversity. Extend lifespan of the roof by protecting materials.	Extra costs, weight a
Blue roof	Roof to store water, typically rainfall.	Reduce cooling demand. Water storage and reuse.	Weight. Roof could be used
Retractable roof	Roof system designed to roll back the roof on tracks so that the interior of the facility is open to the outdoors. In stadia, it is generally used in areas where changing weather, with extreme heat or extreme cold are prevalent during the respective sports seasons.	It helps control thermal, rain, wind and light comfort by closing/opening. Insulation against hot and cold.	Maintenance. Weight of the system

Table 3.2.2: General adaptation measures - Elements to integrate passive measures

wbacks	Goal	Effectiveness	Type	Passive measure	
se in winter.	H	++	G	Solar reflectance	
mass is only beneficial if n (or some other means used to remove the ne building fabric during				Radiative cooling	
emand in winter due to . ion by condensation in	H	++	G	Solar reflectance	
nd maintenace.	H/W	±	C	Evaporative cooling	
in a more efficient way.	W	+	T	Evaporative cooling	
n.	H	++	G	Shading Natural ventilation	 

Measure	What	Benefits	Dra
Facade			
Green facade	Wall partially or completely covered with greenery that includes a growing medium, such as soil or a substrate.	Lower temperature, less need for cooling. Air purification: filter pollutants and CO2. Acoustic insulation. Biodiversity. Extend lifespan of the roof by protecting materials.	Extra costs, weight a
Operable facade	System to open/close the facade when needed.	Regulate sunlight, temperature and natural ventilation (especially if combined with retractable roof to balance the pressure).	Maintenance. Weight of the system
Solar shading		Natural light provision lead to reduction in lighting demand. Reduction of cooling demand. Regulate thermal and visual comfort, avoiding overheating and glare.	View blocked. Materials degradatio sunlight. Maintenance.

Table 3.2.2: General adaptation measures - Elements to integrate passive measures

Measure	What	Benefits
Extra measures		
Solar cooling	It allows to produce cooling from a heating source, namely sun. Solar collectors absorb solar radiation and transfer the produced heat to fluids, such as water. In the chiller, the warm water exchanges the heat with the cold water coming from the air conditioners. In this way the cold water is further cooled down and sent back to the machine to produce cooling for the building.	Renewable source for cooling production.

Table 3.2.3: General adaptation measures - Extra measures for sustainable cooling production

wbacks	Goal	Effectiveness	Type	Passive measure
nd maintenace.	H/W	±	C	Evaporative cooling
n.	H	++	G	Shading Natural ventilation
on due to exposure to	H	++	G	Shading

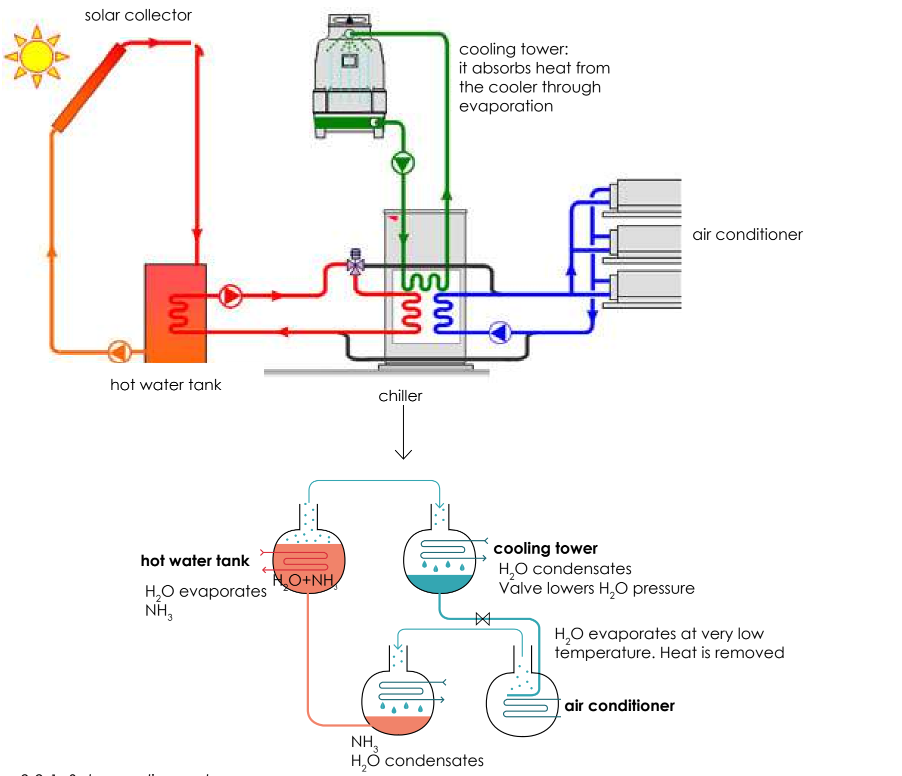


Figure 3.2.1: Solar cooling system
From "ENEA - Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile", 2018.
http://www.enea.it/it/seguici/le-parole-dellenergia/solare-termico/solar-cooling

Measure	What	Benefits
Extra measures		
Tubes through the skin	Collect rain water or use the nearby river as source of cold water.	Re-use collected water for cooling.
Aquifer thermal energy storage	Cooling and heating production by storing heat and cold in two wells located in the ground.	Renewable source for cooling production.

Table 3.2.3: General adaptation measures - Extra measures for sustainable cooling production

Figures 3.2.2 and 3.2.3: Sony City Osaki Building, BioSkin cooling concept
From "Material District", 2016. https://materialdistrict.com/article/worlds-first-cooling-bioskin-facade/

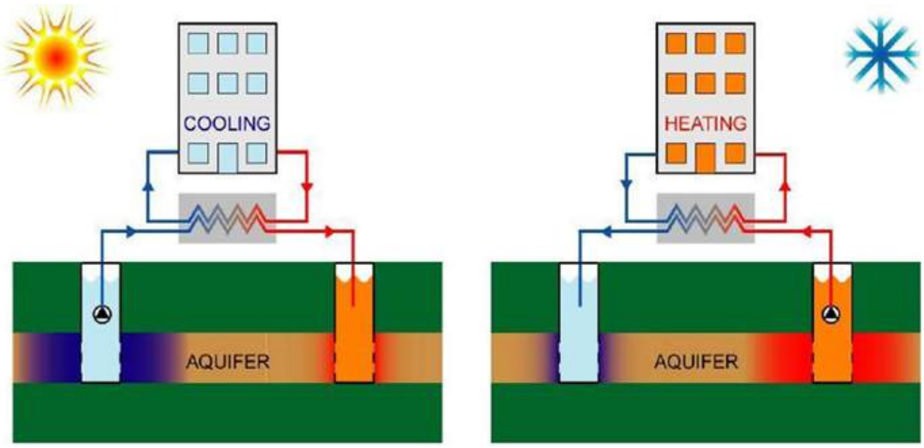


Figure 4.5.5: ATES system
From "International Geothermal Association", 2006

3.3 STADIA IN THE WORLD: EXAMPLES

Innovative elements of the chosen examples are here explained. This to give an overview on the current stadia design in the world and existing possible adaptation measures, if integrated.

1) **Estádio Nacional**, Brasilia, Brazil
Old stadium built in 1974
New stadium built in 2013, design by Lucio Costa and Oscar Niemeyer

Figures 3.3.1 and 3.3.2: Estádio Nacional - outside and inside
From "Portal da copa", 2013. www.copa2014.gov.br

The roof incorporates a photocatalytic membrane which breaks down nitrogen oxides, helping to combat pollution from vehicle exhaust. The special roof, which has a retractable centre, is semi-transparent, allowing natural light to filter through and so reduce lighting costs inside.

2) **Marlins Park**, Miami, Florida
2012, design by Populous

Figures 3.3.3 and 3.3.4: Marlins Park retractable cool roof and operable façade
From "Local 10 news", 2017. https://www.local10.com/sports/mlb/marlins. Copyright 2017 by WPLG Local10.com.

The retractable roof is made of a white reflecting material (white rubber membrane), which makes it a cool roof. This element helps reducing UHI and heat gains. In addition, the outfield wall is operable. It allows for natural light and view. It also makes possible to have ventilation, together with the roof by balancing the pressure when the roof is open.

3) **Mercedes-Benz Stadium**, Atlanta, Georgia
2017, design by HOK


Figures 3.3.5 and 3.3.6: Mercedes-Benz Stadium steel retractable roof - open and closed
From "CreedLA", 2017. http://www.creedla.com/atlantas-newly-completed-mercedes-benz-stadium-promises-impress/. Copyright 2016 CreedLA.com.

The innovative element is the steel retractable roof, which can be open or closed based on the type of event or climatic conditions.

4) **Weserstadion**, Bremen, Germany
Built in 1947
Renovated in 1963–1965
Renovated in 1989
Renovated in 2005
Renovated in 2008–2012

Figures 3.3.7 and 3.3.8: Weserstadion roof
From "Alwitra", 2018. https://alwitra.de/en/referenz/weser-stadium/

10470 m2 solar waterproofing membranes are used as roofing: they generate 1000 MWH/yr, which leads to a CO2 emissions reduction of 450 tons.

5) **Johan Cruijff Arena,** Amsterdam, Netherlands
Built in 1996, design by Rob Schuurman and Sjoerd Soeters
Renovated in 2005 (escalators)
Renovated in 2013-2015
Future renovation in 2020 (expansion with convex façade)

Figure 3.3.9: Johan Cruijff ArenA - outside
From "Nissan Netherlands", 2016. https://netherlands.nissannews.com/nl-NL/channel/

Figure 3.3.10: Johan Cruijff ArenA - inside
From "Axios", by Ed van de Pol, 2016. https://www.axios.com/storage-system-in-amsterdam-stadium-shows-potential-for-used-batteries-dc434fda-fb5a-4d01-82f3-2225c7b00fec.html

The principal element who could work as climate adaptation measure is the retractable roof, which can be open or closed according to the event. The ArenA also shows many sustainable measures, such as PV panels on the roof.

6) **Khalifa International Stadium**, Doha, Qatar
Built in 1976
Renovated in 2005 (roof)
Renovated in 2014-2017

Figures 3.3.11: Khalifa International Stadium
From "Yandex", 2018. https://yandex.com/collections/card/5873a71f7d9950443bcc74e4/

Figures 3.3.12: A computer-generated image of the interior of Khalifa International Stadium.
From "Arabian Industry", 2016. https://www.arabianindustry.com/construction/news/2016/dec/8/khalifa-international-stadium-roof-nearly-finished-5565352/

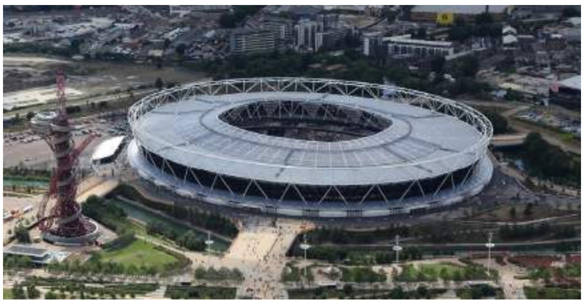
In the 2005 renovation, the ETFE new roof was introduced: it provides shade to both the stands and the pitch, while letting sufficient sunlight through to ensure healthy grass growth of the natural turf pitch. The shape of the roof has been optimized with shadow analysis.

7) **Kaohsiung National Stadium,** Kaohsiung, Taiwan
Built in 2009, design by Toyo Ito


Figures 3.3.13 and 3.3.14: Kaohsiung National Stadium PVs covered envelope
From "Solaripedia", 2011. http://www.solaripedia.com/13/346/taiwan_stadium_100_percent_. Copyright 2012 Grzebik Design Group solar-powered.html

The envelope is fully covered with PV panels, with 1.14 kWh/yr energy production. In addition, the shape of the envelope has been optimized to have natural ventilation.

8) **London Olympic Stadium**, London, United Kingdom
Built in 2012, design by Populous




Figures 3.3.15 and 3.3.16: London Olympic Stadium general views
From "Stadiumdb", 2015. http://stadiumdb.com/stadiums/eng/london_olympic_stadium. Copyrigh 2015 Queen Elizabeth Park.

It is the lightest weight stadium ever: less materials use means less GHG emissions due to transportation. However, in terms of design, it does not show any potential for climate adaptation.

9) **Tottenham Hotspur Stadium,** Tottenham (London), Unitd Kingdom
Expected to be built by 2019, design by Populous


Figures 3.3.17 and 3.3.18: Tottenham Hotspur Stadium general views under construction
From "NBC sports", 2018. https://soccer.nbcsports.com/2018/09/26/tottenham-hopeful-on-opening-date-for-new-stadium/

The retractable roof is meant to adapt to different event types and climatic conditions.

10) **Wembley Stadium**, London, United Kingdom
Built in 1934
Renovated in 2005-2006

Figure 3.3.19: Wembley Stadium - outside
From "Hollandiainfra", 2018. https://www.hollandiainfra.nl/en/infra/projects/102/new-wembley-stadium-london/. Copyright 2019 Hollandia.

Figure 3.3.20: Wembley Stadium - inside
From "Civitatis", 2018. https://www.civitatis.com/en/london/wembley-stadium-tour/

It is provided with a retractable, sliding roof to avoid shading the pitch and allow sunlight on the grass. Roof is pulled back on the east, west and south based on solar radiation analysis.

11) **Wanda Metropolitano**, Madrid, Spain
Built in 1993, design by Cruz y Ortiz Arquitectos
Renovated and re-opened in 2017

Figure 3.3.21: Wanda Metropolitano - outside
From "Archdaily", 2017. https://www.archdaily.com/877598/time-lapse-shows-the-roof-installation-at-madrids-wanda-metropolitano-stadium

Figure 3.3.22: Wanda Metropolitano - inside
From "Sky sports", 2017. https://www.skysports.com/football/news/11945/11045097/atletico-madrids-wanda-metropolitano-stadium-to-host-the-2019-champions-league-final

The design of the stadium takes into consideration the improvement of energy efficiency and the reduction of CO2 emissions through the use of LED lighting, optimization of the air conditioning system and the use of solar energy to heat up water by means of solar thermal panels. Next to it, the stadium reuse rainwater to irrigate the pitch. Rainwater is collected in dedicated tanks.

The stadia innovative elements, potentials and climate adaptation possible measures are summed up in Table 3.3.1.

Stadium	Innovative Component	What	Thermal comfort	Wind comfort
Estádio Nacional Brasilia, Brazil 1974 Lucio Costa and Oscar Niemeyer, 2013 new stadium	Roof	The roof incorporates a photocatalytic membrane which breaks down nitrogen oxides, helping to combat pollution from vehicle exhaust. The special roof, which has a retractable centre, is semi-transparent, allowing natural light to filter through and so reduce lighting costs inside.	±	-
Marlins Park Miami, Florida Populous, 2012	Roof Façade	Retractable roof made of white reflecting material (white rubber membrane), which make it a cool roof. It reduce UHI and heat gains. The outfield wall is operable. It allows for natural light and view. It also make possible to have ventilation, together with the roof. It balances the pressure when the roof is open.	++	++
Mercedes-Benz Stadium Atlanta, Georgia HOK, 2017	Roof	Steel retractable roof	++	-
Weserstadion Bremen, Germany 1947 1963–1965 renovation 1989 renovation 2005 renovation 2008–2012 renovation	Roof	Solar waterproofing membranes as roofing.	-	-
Johan Cruijff Arena Amsterdam, NL Rob Schuurman and Sjoerd Soeters, 1996 2005 escalators 2013-2015 renovation 2020 future renovation	Roof	Retractrable roof	++	?
Khalifa International Stadium Doha, Qatar 1976 2005 renovation (roof) 2014-2017 renovation	Roof	ETFE new roof: provide shade to both the stands and the pitch, while letting sufficient sunlight through to ensure healthy grass growth of the natural turf pitch. Optimized with shadow analysis.	±	-

**Compared to similar projects*

Table 3.3.1: Stadia - Innovative components and climate adaptation potentials.

Rain comfort	Light comfort	Sustainability	Climate change adaptation
±	++	LEED platinum (80 points). Materials reuse from old stadium. 2,5 MWH production; extrais sent to the grid. It harvests rainwater and use low-flow plumbing fixtures to minimise water use.	Roof.
++	++	LEED gold. Most sustainable stadium in the Major League Baseball. Site: Little Havana neighborhood on the former Orange Bowl site - community connectivity and multiple alternative transportation options. Water use reduction 52% due to plumbing design and operational strategies. Potable water use for irrigation reduction 60% due to landscape design.* 22,4% (by cost) energy use reduction.* Recycling plan. 75% construction waste recycled. Low-emitting interior finish materials. Smart lighting and thermal design. No CFC-refrigerants.	Combination of operable roof and façade to allow for ventilation, regulate temperature and humidity.
+ (leaks issues)	+	LEED platinum (88 points) - most sustainable stadium. 2000000 gallons of storm water stored in site. 47% less water use.* 29% less energy use.* The stadium can power 10 Atlanta Falcons games or 13 Atlanta United matches with the renewable energy generated through its 4,000 solar PV panels. LED lighting.	---
-	-	10470 m2 solar waterproofing membranes as roofing: they generate 1000 MWH/yr, which leads to a CO_2 emissions reduction of 450 tons.	--
-	+	Over 4200 PV panels on the roof, with energy stored in a battery in car park P1. Energy-generating escalators. LED lighting. Rain water collection in the roof and used to water the field. 116683 CO_2 saving. Windmill+Oudekerkeplas.	Retractable roof.
±	++	4 stars Global Sustainability Assessment System (GSAS) - first stadium. Cooling technology uses an energy recovery system in order to reduce energy consumption. Energy-efficient lighting systems and plumbing fixtures.	---

Stadium	Innovative Component	What	Thermal comfort	Wind comfort
Kaohsiung National Stadium Kaohsiung, Taiwan Toyo Ito, 2009	Envelope Structure	Covered with PV panels: 1,14 kWh/yr energy production. Optimization for cooling by wind.	++	++
London Olympic Stadium London, UK Populous, 2012	Structure	Lightest weight stadium ever. Less materials use means less GHG emissions due to transportation.	-	-
Tottenham Hotspur Stadium Tottenham, London, UK Populous, 2019	Pitch	Retractable roof to host different functions and events.	-	-
Wembley Stadium London, UK 1934 2005-2006 renovation	Roof	Retractable, sliding roof to avoid shading the pitch and allow sunlight on the grass. Roof is pulled back on the east, west and south.	-	-
Wanda Metropolitano Madrid, Spain Cruz y Ortiz Arquitectos, 1993 2017 renovation	Rain water collection	It is be reused for irrigating the pitch.	±	-

**Compared to similar projects*

Table 3.3.1: Stadia - Innovative components and climate adaptation potentials.

Rain comfort	Light comfort	Sustainability	Climate change adaptation
-	-	First and largest solar powered stadium in the world: PVs production covers 100% game/event days demand + 80% neighborhoods demand (in non-game days electricity is sent to the grid). 7 hectares of green space+plants. Raw materials sourced from Taiwan, 100% reusable. In site energy production, preventing the release of 660 tons of CO2 into atmosphere annually. The roof also collects rainwater for use inside the stadium. Structure optimized to maximize the effect of natural cooling by wind: sides and roof of the stadium create a tunnel through which air passes that refreshes the viewer during the hot summer.	Structure optimization to allow for natural ventilation.
-	-	Almost no construction waste sent to landfills: materials either recycles, rused or sent to the Waste-to-Energy center to produce heat and energy for the stadium and surrounding homes. Construction can be reused and adaptated for new functions.	---
-	-	Focus on energy and resource conservation by utilising approximately 75% of demolition material for building work. LED lighting.	---
-	-	Improved management rather than new technologies for energy savings. Zero waste: partnership with Veolia to send food waste for anaerobic digestion, recycling to a materials recovery facility and general waste to an energy recovery facility. Sustainable events policy. Collaboration with Eco-Age: the introduction of the Environmental Management System, has helped Wembley to reduce electricity consumption by 30%, achieve event-day recycling rates of 86%, become a zero waste to landfill venue, and report on progress in four sustainability reports. Achievements include becoming the first sports organisation to achieve Carbon Trust Standard treble certification (carbon, water and waste) and receiving the highest Industry Green award, Green Apple, Green Tourism and the International Stadium Business Sustainability Award.	---
±	±	LED lamps will reduce power and electric consumption by 30 % and maintenance costs*. The resistance and the composition of these lamp (they do not have mercury) contributes to improve the quality of environment. Solar thermal panels are used to produce domestic hot water, so energy consumption is reduced by 75 MWhEF, the consumption of natural gas by 10,000 m3, and the CO2 emissions by 18.9 tons.	Rainwater collection.

4 CASE STUDY: THE NEW FEYENOORD STADIUM

This chapter focuses on the analysis of the case study.

In the first part, the project for Feyenoord City by OMA is introduced, then the focus moves to the city of Rotterdam, and its climate and plans for adaptation to climate change. Based on these, adaptation measures are proposed, which refer to those studied in chapter 3, based on the context analysis.

The second part of the chapter, instead, is about parameters study: calculations are performed to check the effect of different elements on the indoor comfort in the stadium. In addition, effect of measures on the cooling demand is estimated.

These analyses will help to set the focus of the design in chapter 5.

4.1 OVERVIEW

The new Feyenoord stadium is here taken as case study to develop a design proposal which can be replicated and adapted to other stadia around the world. Feyenoord is chosen due to its strategic position nearby the Nieuwe Maas river, which can be seen either as a hazard source with the increasing risk of floods, or as a potential for cooling and water collection. Also, the plan for Feyenoord City does not only include the stadium but many facilities and new activities which will attract lots of visitors, thus making the area highly vulnerable in a future warmer scenario.

The Feyenoord City project is located in the Feijenoord district (Rotterdam South), near the Nieuwe Maas.
Feijenoord has nearly 74'000 inhabitants divided over eight districts. These are Afrikaanderwijk, Bloemhof, Feijenoord, Hillesluis, Katendrecht-Wilhelminapier, Kop van Zuid-Entrepot, Noordereiland and Vreewijk (Gemeente Rotterdam, n.d.).

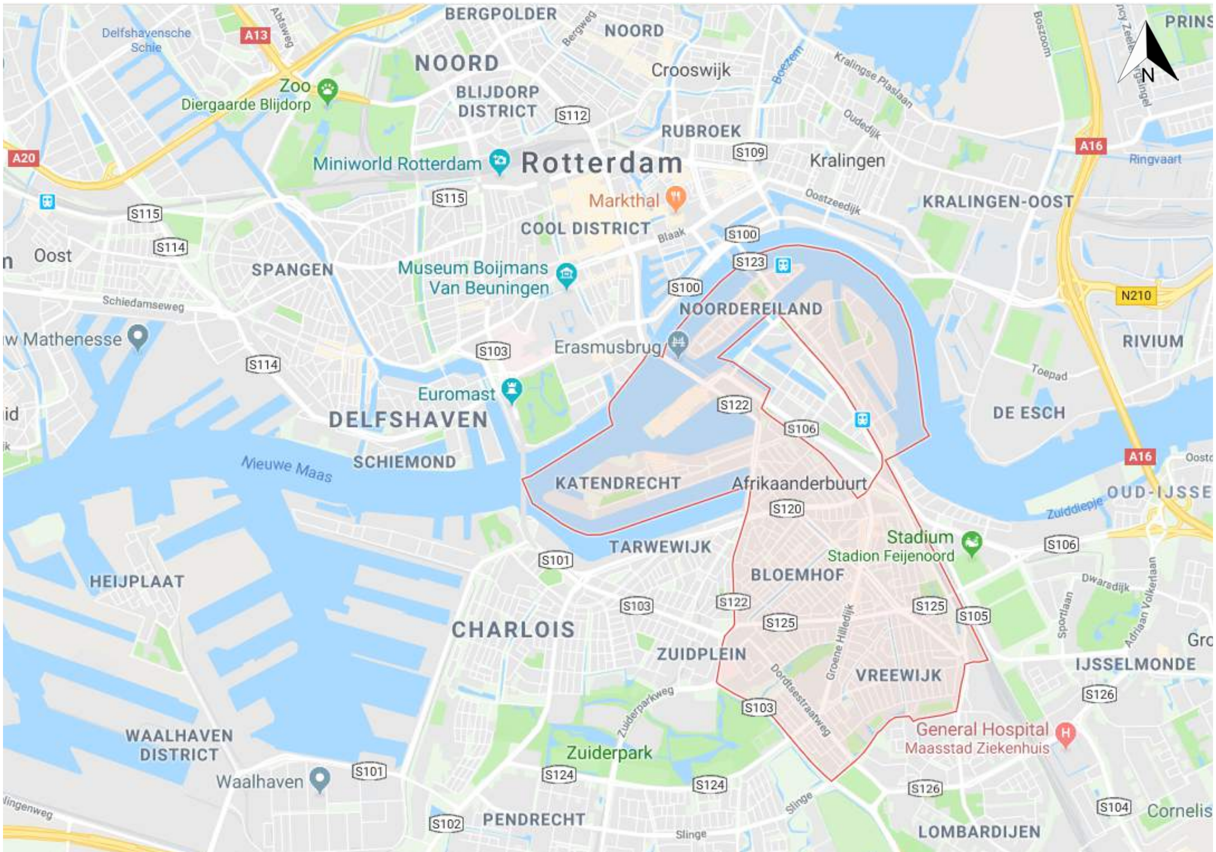


Figure 4.1.1: Feijenoord District, Rotterdam South
Google maps

De Kuip - Old Stadium

Surroundings


KFC

ingang


Nieuwe Maas bank

All pictures are taken by the author.

In 2014, Feyenoord decided to renovate the old stadium (De Kuip), expanding it to 70'000 seats and providing it with a retractable roof. In March 2016, Feyenoord announced they preferred building a completely new stadium. In May 2017, the city of Rotterdam agreed with a plan to build a new stadium with a capacity of 63,000 seats. The plan is called Feyenoord City, a project by OMA, which combines living, working, sports and recreation. The ambitious plan covers 325,000 m², of which 180,000 m² for homes. Sports facilities, shops, hotels, restaurants and public functions are also provided. An important element is the redevelopment of De Kuip with attractive new functions.
Construction of the stadium is planned to begin in 2019 and be completed in time for the 2022/23 Eredivisie season.

As mentioned in the Feyenoord City website (n.d.), the project consists of four sub-areas:

1) **The New Stadium**
The Rotterdam architectural firm OMA is designing the Nieuwe Stadion (New Stadium). In the design it takes into account the preservation of characteristic atmospheric elements of De Kuip. For example, spectators on the first and second ring are also close to the field in the new stadium, the view from every podium is good, the stands run in the corners, the long side has an oval shape and there is a player tunnel.
The ultimate goal of the construction of the New Stadium is to meet the current requirements of promoters, event organizers, KNVB and UEFA. In this way Rotterdam becomes eligible for major music events and international competitions and finals.
The New Stadium is easily accessible by rail, bus, tram, car, bicycle, on foot and over water. It is, indeed, located next to the Nieuwe Maas.
In addition, revenue is substantially increased by additional ticket sales, higher revenue from hospitality (catering and special arrangements), a higher sponsorship value and more non-football events.

2) **The City Boulevard (Urban Bridge)**
The Stadsboulevard (City Boulevard) is, for slow traffic, the entrance to Feyenoord City from the city center. This so called Urban Bridge runs diagonally and crosses the New Stadium.
The west side has an urban character. On the east side, instead, the proposed design allow visitors to walk on the river. Next to the City Boulevard, two residential towers, a 4-star hotel, a spa/wellness center will be built.

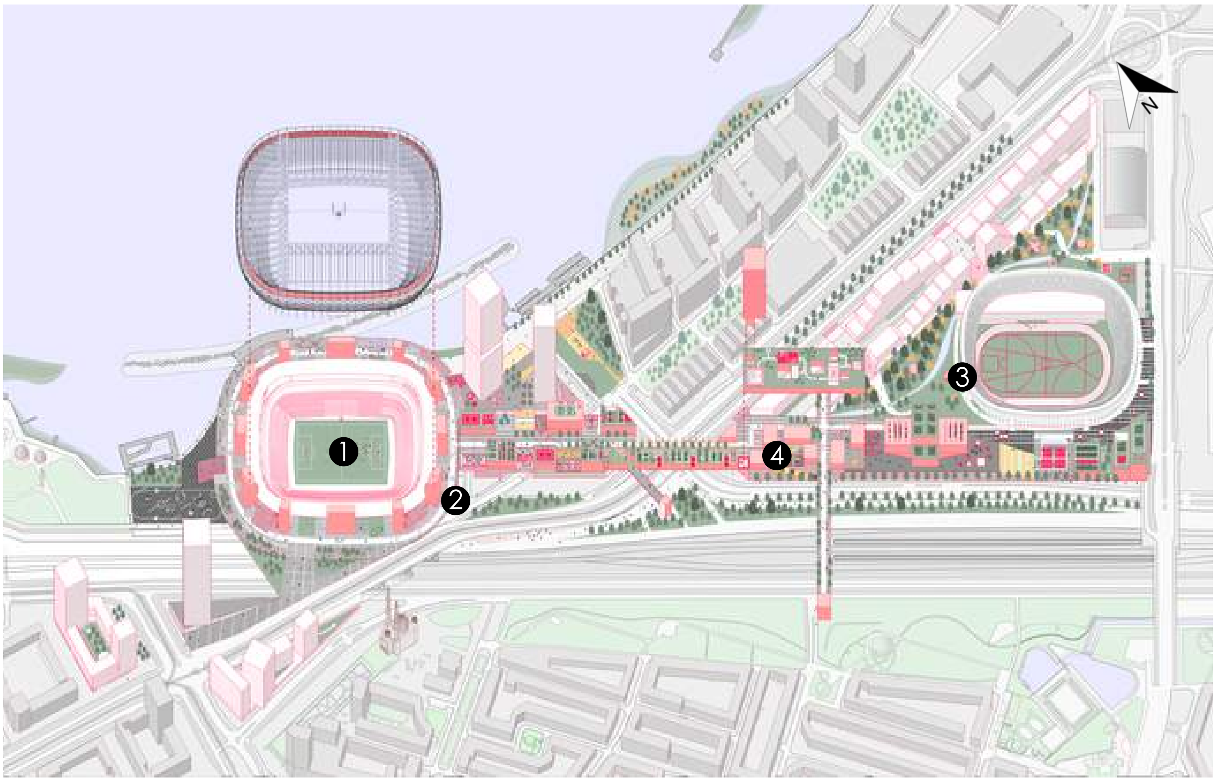
3) **De Kuip and the Kuip Park**
Within the Feyenoord City project, the old stadium will receive a profitable second life after redevelopment.
By keeping the main qualities of the stadium intact and adding new functions, De Kuip remains a lively place with a large social role for all Rotterdammers.
Both an indoor and outdoor athletics track will be realized. Also, the Feyenoord Museum will be established. Furthermore, a health center, a sports hotel and a

traditional beer brewery are planned.
The Kuip Park will be located between De Kuip and Stadionweg: a green public space combined with houses. In the Kuip Park there is room for recreation and free sports. The construction of Kuip Park is one of the last phases of Feyenoord City and only starts after the redevelopment of De Kuip has been completed.

4) **The Strip**

The Strip is the central axis of Feyenoord City and connects De Kuip with the New Stadium. It is a 600-meter-long, elevated promenade with shops, cafes, restaurants, attractions and entertainment venues, including a cinema complex. The Strip is only accessible to pedestrians and cyclists. A parking garage will be realized under the promenade.
There will also be space for companies that develop various innovations in the field of sport. The Sport experience is a special attraction. Here people can actively get acquainted with all kinds of sports, using the most modern techniques including Virtual Reality

Masterplan is shown in figure 4.1.2.



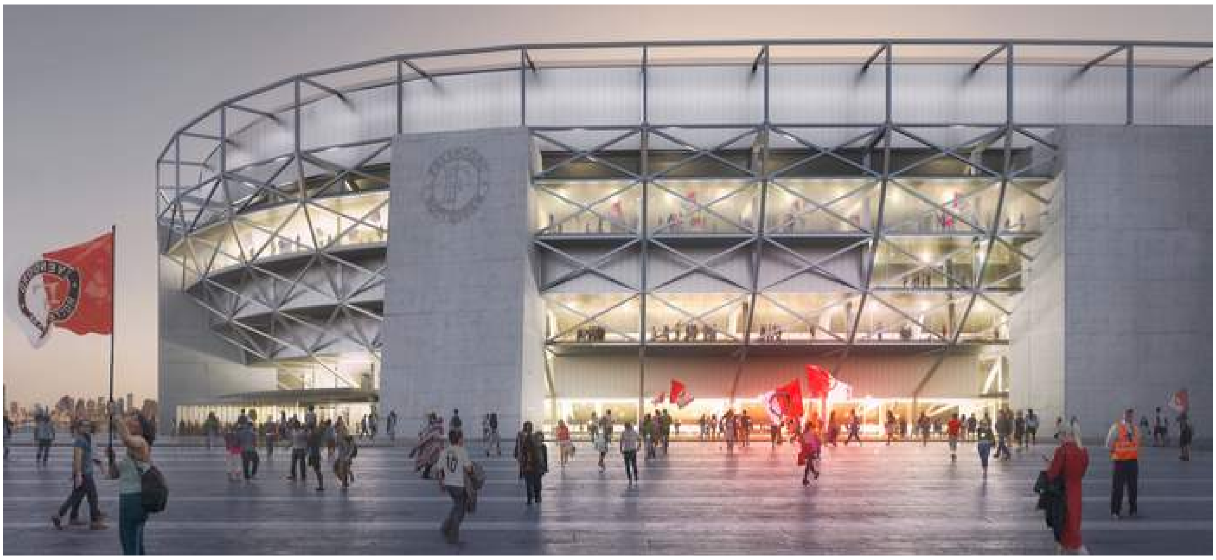
❶ New Stadium ❸ De Kuip and the Kuip Park

❷ City Boulevard ❹ The Strip

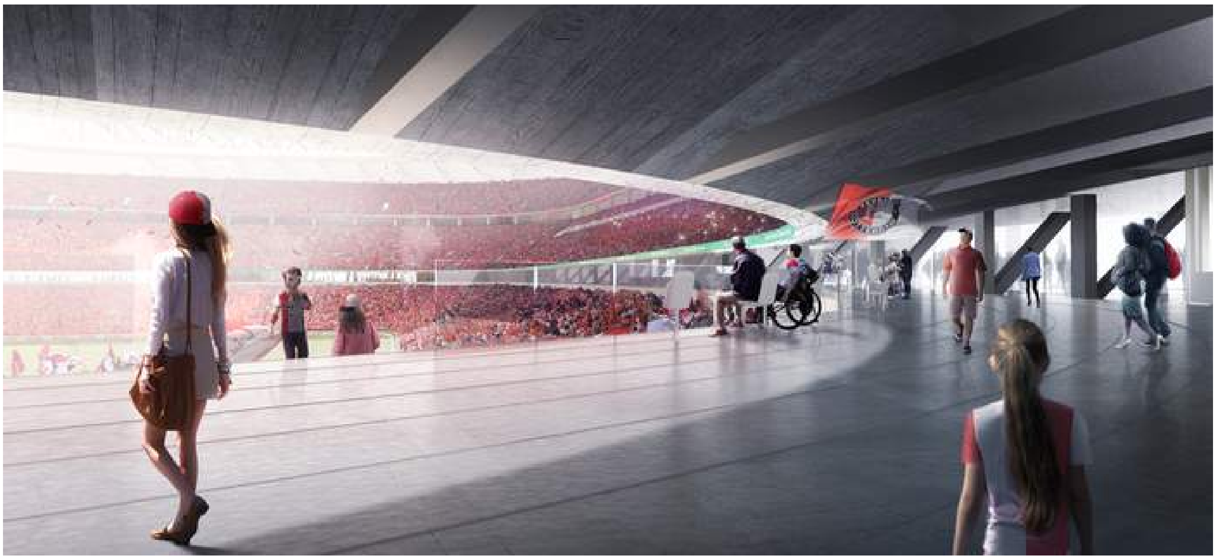
Figure 4.1.2: Masterplan of Feyenoord City
OMA, 2018.

Overview at night

New Stadium



New Stadium - interior



De Kuip - Old Stadium

Renders by OMA, 2018

4.2 CLIMATE

In general, the Netherlands are classified as a country characterized by Cfb climate (oceanic climate), according to the Köppen climate classification. Cfb climates usually occur in the higher middle latitudes, between 40° and 60°, on the western sides of continents. This type of climate is characterized by mild and very cloudy and rainy winters, and cool short summers due to the ocean currents, with no dry season experienced. Moreover, a constant high relative humidity is registered throughout the year, with a mean value of 77.9% (Wikipedia, n.d.)

The average wind speed in Rotterdam is 3.8 m/s, with a prevailing wind direction to the west and south face of the building. The most windy period runs from December to March, with the achievement of wind speed up to 61 km/h in the West - South - West direction, as shown in figure 4.2.1. However, higher wind speeds can be expected for higher elevations. The yearly average wind speed distribution is shown in the wind rose (figure 4.2.2). The prevailing wind direction is southwest. Of the winds from the SW direction, wind speeds are most often in the 19 - 28 km/h range.

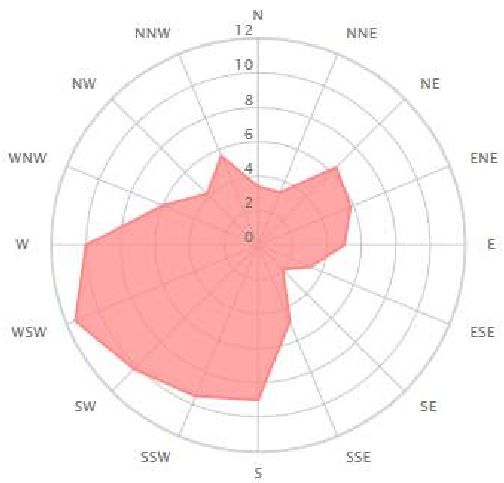


Figure 4.2.1: Wind direction distribution in (%) in a year
From "Meteoblue", 2018. https://www.meteoblue.com/en/weather/netherlands_2747891

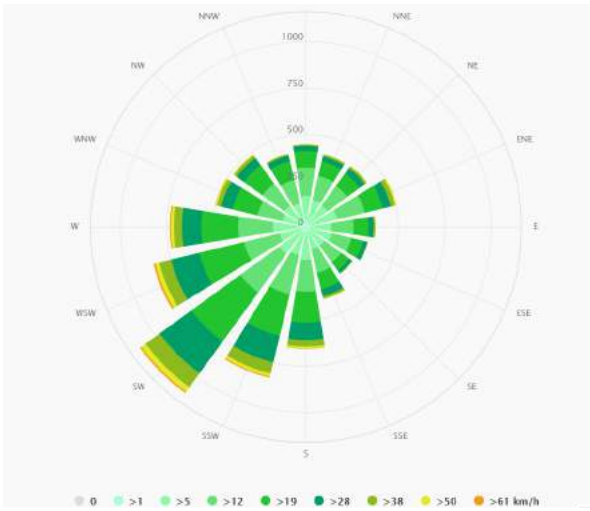


Figure 4.2.2: Wind rose
From "Meteoblue", 2018. https://www.meteoblue.com/en/weather/netherlands_2747891

The average air temperature in the Netherlands is approximately 10°C, which can be considered as the same of the ground at a depth of 2 m.
Based on 30-year hourly model simulations, the minimum daily average temperature is 1°C and the maximum daily average temperature is 23°C, as shown in figure 4.2.3. However, either lower or higher temperatures are registered. In fact, the minimum annual temperature is -6.1°C in December, while the maximum is 26.6°C in May, but outdoor air temperature could be even warmer as the highest temperature ever reached in the Country is actually 38°C.
A diurnal temperature swing (difference between nighttime and daytime

temperature) of 5-10°C is registered for 8 months, while for the rest of the year the swing is usually lower than 5°C.
Solar radiation is a factor that has a big influence on the design choices. The annual hourly mean global radiation for the area of Rotterdam is 105.8 W/m2, while the mean daily global radiation is 2531.3 Wh/m2.
As shown in figure 4.2.4, throughout the year, the amount of sunny days is much lower compared to cloudy, or partially cloudy, days. Moreover, precipitations are quite constant, reaching a peak in December and January. (“Meteoblue”, n.d.)

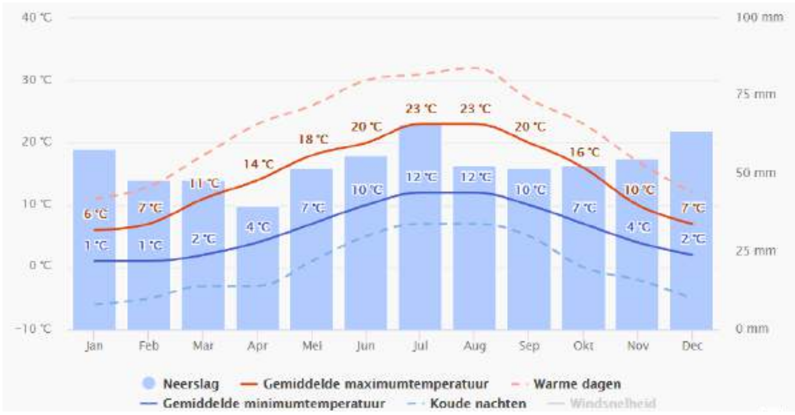


Figure 4.2.3: Average temperature and precipitation
From “Meteoblue”, 2018. https://www.meteoblue.com/en/weather/netherlands_2747891

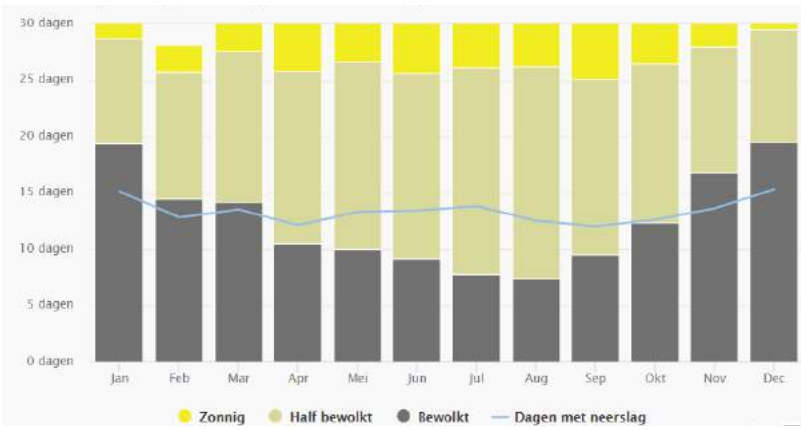


Figure 4.2.4: Cloudy, sunny and rainy days
From “Meteoblue”, 2018. https://www.meteoblue.com/en/weather/netherlands_2747891

Because of the daily average temperature, the amount of solar radiation and precipitation, the heating demand results to be much more important than the cooling demand. The Heating Degree Days – HDD (18.3) is 3029.4, almost four times the Cooling Degree Days – CDD (10.0), which are 782.4 (IES Limited, 2012). The heating and cooling degree days for a specific location are a good indication of the amount of time during which the temperature is outside the range of the comfort zone, and thus of the energy demand to heat or cool a building (IES Limited, 2012).

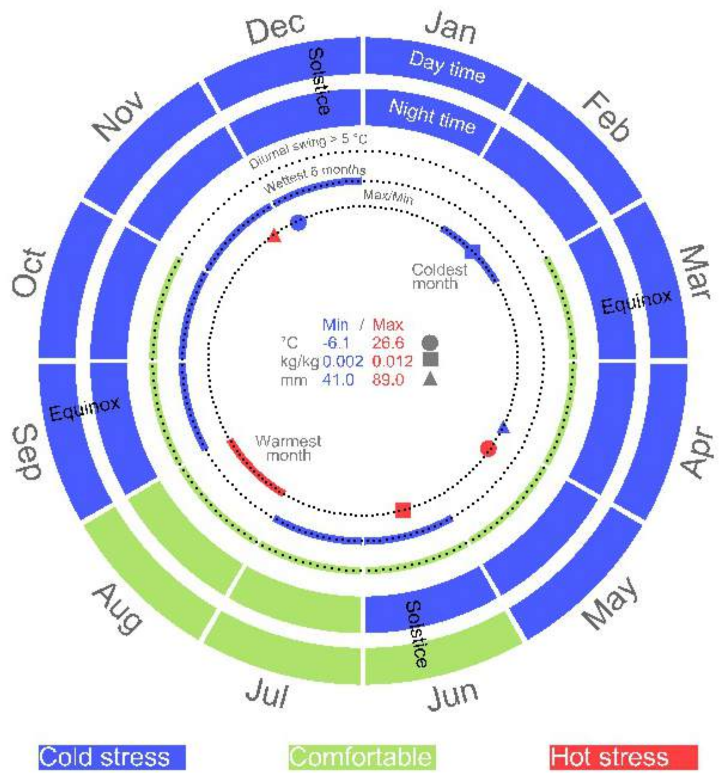


Figure 4.2.5: Summary metrics
IES Limited, 2012

4.3 URBAN HEAT ISLAND EFFECT AND HEAT STRESS IN ROTTERDAM

Heat waves are expected to become more frequent in the next decades (van den Hurk et al., 2006) due to climate change and global warming. The elderly are especially vulnerable and current housing design and construction is not sufficient to prevent them to suffer from heat stress. It is, therefore, necessary to measure and understand the urban micro-climate in order to forecast the UHI and human thermal stress. Collected data must be used to provide a tool for urban planners in reducing the UHI and adverse effects on human comfort.

Current UHI studies rely on fixed weather stations that only cover limited spatial variability and that can be affected by local conditions. Hence, new techniques must be developed.

In 2009, temperature data were collected during a study that measured temperatures in various neighborhoods in the city of Rotterdam (Figure 2.4.7), with a new non-fixed method.
Two cargo bicycles were used as a mobile platform, equipped with innovative instruments to quantify micro-meteorological conditions inside urban canyons. These bicycles facilitated easy access within complex urban canyons, rather

than just traversing wide asphalt roads, and included a range of sky view factors, greenery, and building densities. The measurement platform was equipped with a complex set of sensors to quantify human thermal exposure (Heusinkveld et al., 2014).
The registered UHI is shown in Figure 4.3.1.

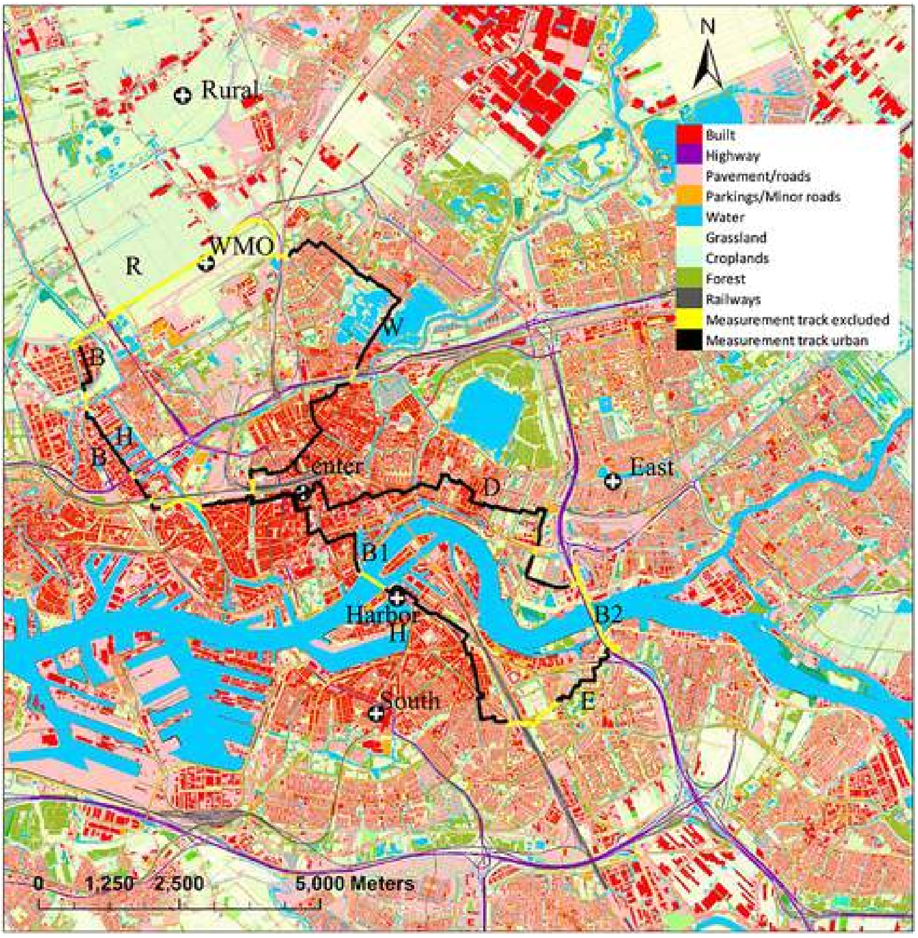


Figure 4.3.1: Topographic map of Rotterdam and surroundings. White crosses are the four urban, one rural and one official WMO meteorological stations. Black circular loops show the two mobile measurement routes; the yellow loop sections include tunnels, bridges, dikes, or rural areas.
Heusinkveld et al., 2014.

To understand the possible effect of climate change on heat stress in Rotterdam, current temperature values (referring to years 2011/2012) from the Zuid weather station in Rotterdam and the reference location were transformed into temperature values for 2050 and 2100.
Looking at Figure 2.4.9, an increase in the number of days with lower thermal comfort in both cities and the countryside is expected (Climate Proof Cities Consortium, 2014).

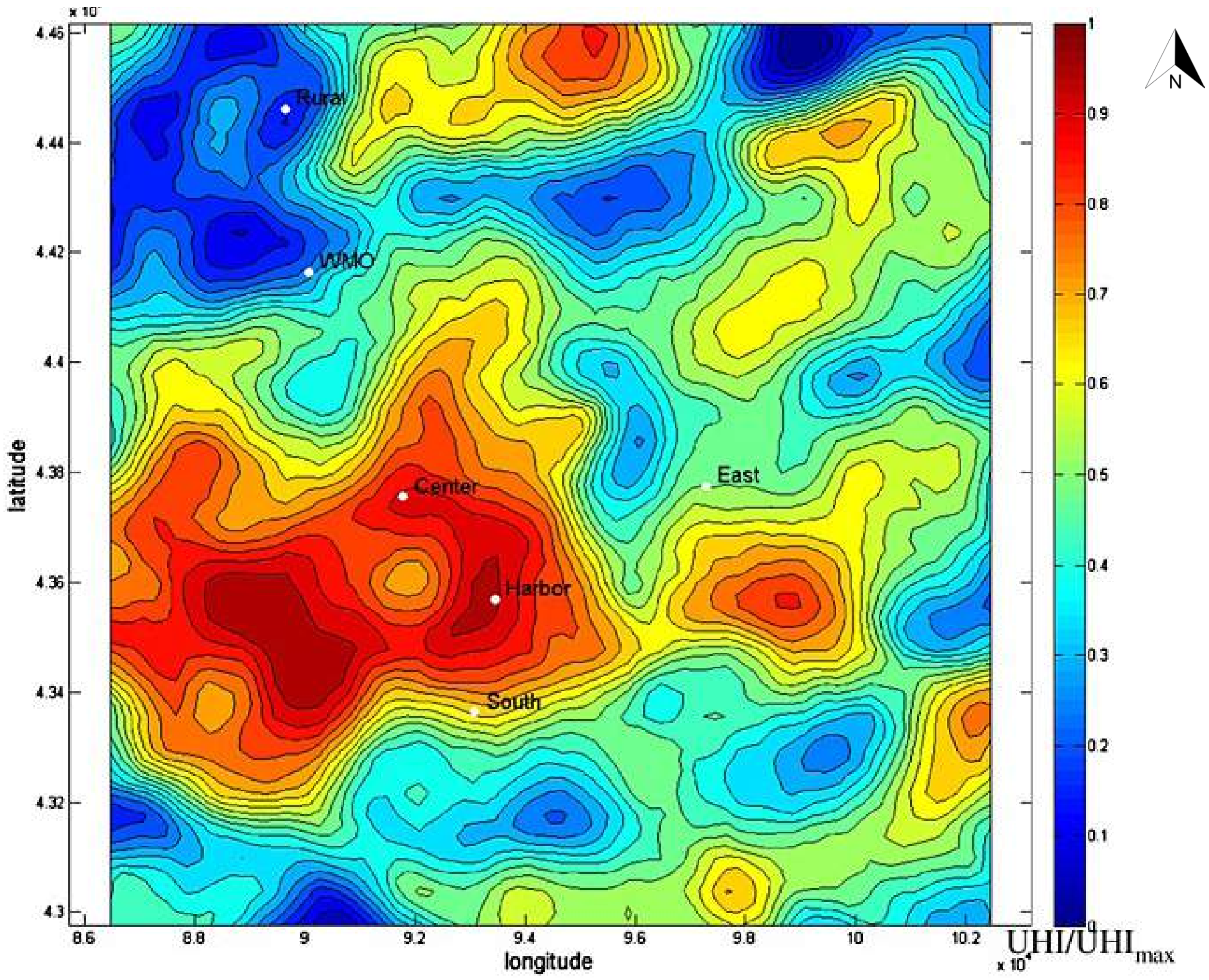


Figure 4.3.2: Spatial variation in UHI in Rotterdam and surroundings. Normalized UHI values are presented (UHI Centre = 1)
Heusinkveld et al., 2014

4.4 ROTTERDAM ADAPTATION STRATEGIES

Rotterdam Municipality has already launched its own adaptation program "Rotterdam Climate Proof" with the ultimate goal to make the city fully climate resilient by 2025. With Rotterdam Climate Proof (RCP, 2008) and Rotterdam Climate Initiative (RCI, 2007), the city of Rotterdam is tackling the full range of climate-related challenges. RCI takes care of mitigation initiatives, whereas RCP is responsible for adaptation strategies, with the emphasis on the subject of water and particularly water safety. However, non-water related themes, such as rising temperatures, UHI and heat waves, also feature in the RCP programme but in a much smaller scale (Gemeente Rotterdam, 2010).

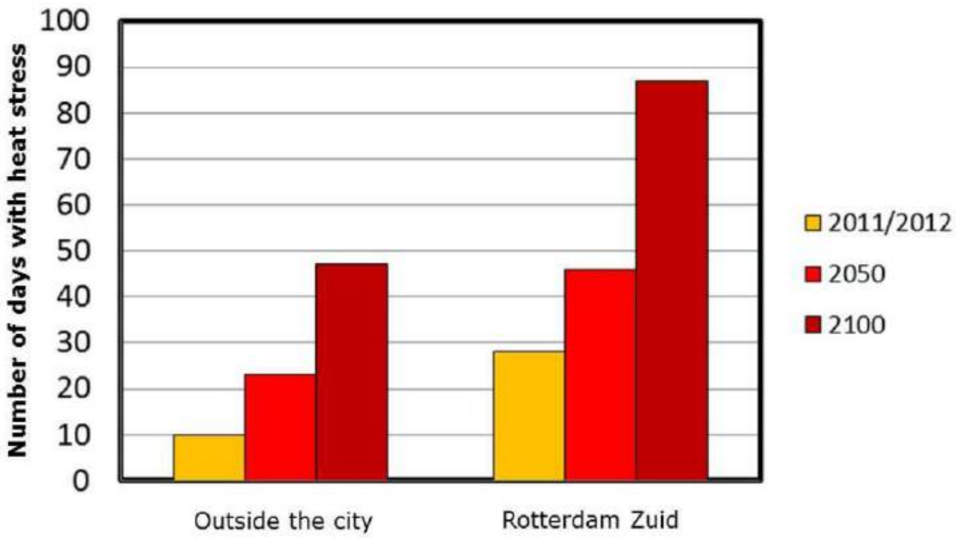


Figure 4.4.1: Number of days with moderate to strong heat stress for the countryside and 'Rotterdam Zuid' locations, calculated for 2011/2012, 2050 and 2100.
Climate-proof Cities final report, 2014.

4.5 NEW FEYENOORD STADIUM - ADAPTATION MEASURES

By exploring possible climate adaptation strategies in section 3.2, and by collecting information on the design of Feyenoord City, as well as on the surroundings, feasible adaptation measures for the new stadium are defined.
They are divided into two main categories, referring to those mentioned in section 3.2: Design to integrate passive measures and extra measures. In this case, the aforementioned measures were elaborated based on possible potentials in the area. Their effect at building and urban scale is explained.

4.5.1 Design to integrate passive measures

1) **Solar shading**

SHADING

Sun is one of the main causes of high indoor temperature. In particular, transparent parts in the envelope are the components allowing for most solar radiation to enter. In order to prevent overheating, solar shading devices can be used. These represent a measure that is generally applicable, therefore valid, and that has immediate effectiveness.
If properly designed, based on solar radiation analysis, they can reduce cooling demand, regulate thermal as well as visual comfort, avoiding overheating and glare. Solar shading devices can be either fixed or movable. Hence, their effect on thermal comfort also depends on how they are built.

However, materials are likely to degrade due to exposure to sunlight, which leads to quite a high need of maintenance, and the effect at urban scale is, in general, not so relevant.
Example of solar shading application in stadia is shown in the figures below.


Figures 4.5.1 and 4.5.2: Cotton Bowl Stadium, Dallas, Texas. Fixed solar shading integrated in the design of the façade. From "Archiexpo", 2018. http://www.archiexpo.com/prod/cambridge-architectural-mesh/product-62232-1440557.html

2) **Cool roof**

SOLAR REFLECTANCE

Cool roofs are characterized by high albedo, therefore they absorb more sunlight (high reflectance) and absorb less heat (high emittance). Its performance is measured by Solar Reflectance Index (SRI)
They can be made of highly reflective type of paint, a sheet covering, or highly reflective tiles or shingles.
Cool roofing materials are generally stainless steel or white thermoplastic membranes (PVC or TPO). Stainless steel is the material having the highest SRI, around 110-115, which is close to the one of a perfect mirror (SRI=120). In the case of thermoplastic membrane, usually the solar reflectance is 80% and the emissivity 70% (The constructor website, n.d.).
A cool roof can have lots of benefits on the building: it lowers the cooling demand, therefore smaller HVAC systems can be installed, it improves comfort in not air conditioned spaces, it decreases roof temperature and UV absorption, so that roof life span is increased. It also brings benefits at urban scale as it can reduce UHI in the surroundings by not absorbing much heat.
On the other hand, a cool roof might increase the energy demand in winter due to reduced heat gains, and can be damaged by moisture accumulation by condensation in cold climate. It is, therefore, necessary to properly design it according to the climate.

3) **Retractable roof**

SHADING / NATURAL VENTILATION

It is a roof system designed to roll back the roof on tracks so that the interior of the facility is open to the outdoors. In stadia, it is generally used in areas where changing weather, with extreme heat or extreme cold are prevalent during the respective sports seasons. It helps control thermal, rain, wind and light comfort by closing and opening. In this way not only people's comfort requirements are met, but also the grass field is protected. In fact, Feyenoord is known for its excellent pitch. In order to preserve it, sunlight, humidity and air velocity should be controlled.
There are several types of retractable roof based on the frequency of opening and closing, the structural design and the type of movement. The most common in stadia design are the retractable roof that is primarily closed and opens in special cases, or the one that is primarily open and closes in special cases (Mahovic, 2015).
Retractable roof helps in reducing cooling load as it can allow for keeping solar radiation outside, therefore reduce indoor temperature. In addition, it allows for natural ventilation to control heat, humidity and air quality. To optimize the natural ventilation, it is better to combine it with an operable façade for pressure balance. Moreover, it can help in acoustic control in case of a concert or similar events. Its effect on the surroundings is mainly determined by the materials used and not by the way it functions. The main drawback of this system is the weight it imposes on the structure as it requires special tracks to be operated. In addition, higher maintenance is needed.

4) **Operable façade**

SHADING / NATURAL VENTILATION

It is a system where the façade can be open or closed when needed, adapting to climatic conditions. When combined with a retractable roof, it allows for pressure control, therefore for natural ventilation, which can remove heat, thus guaranteeing thermal comfort and good air quality to users. Also in this case, the effect on the surrounding environment depends mainly on the materials.
The main drawback is that the weight imposed to the structure might be a problem, therefore it should be integrated in the design from an early stage.

From the literature study, the combination of retractable roof (preferably cool roof) and operable façade results to be the most efficient in terms of climate adaptability as it can tackle many heat-related issues at once. Cooling load are reduced, heat is further removed by natural ventilation, and UHI in the surroundings is mitigated. It also allows to meet FIFA's requirements for the amount of daylight on the pitch, and preservation of the grass. In addition, by implementing operable systems, lighting and acoustic requirements of various activities could be met.

Marlins Park (Miami, Florida) is an example of how these three measures work together.

Figures 4.5.3 and 4.5.4: Marlins Park, Miami, Florida. The stadium design combines a retractable cool roof with an operable façade.
From "Local 10 news", 2017. https://www.local10.com/sports/mlb/marlins. Copyright 2017 by WPLG Local10.com.

7) **Thermal mass**

RADIATIVE COOLING

From the project rendered views it is possible to observe that in the new stadium there will be lots of concrete (to be verified from project drawings). This could allow for using its thermal mass properties for lowering heating and cooling loads. However, According to the WBDG website (n.d.), in summer, thermal mass is only beneficial if night-time ventilation (or some other means of cooling) can be used to remove the heat absorbed by the building during the day.
When talking about concrete, this could be helpful in terms of thermal mass, but its production has great environmental impact, as it produces lots of CO_2.

6) **Evaporative cooling from the field and river**

EVAPORATIVE COOLING

A specific potential of stadia themselves is the presence of a natural grass field. It allows for evaporative cooling by absorbing water through the grass then transpiring it over time to keep surfaces cooler.
On the other hand, if the field is of synthetic turf, the turf fibers and the infill can contribute to higher temperatures if they do not have a mechanism to cool themselves.
Looking at the site of the new Feyenoord Stadium, it will be built next to the Nieuwe Maas. The river also shows big potentials in terms of evaporative cooling. In addition, UHI effect in the area can also be mitigated by adopting this measure.

4.5.2 Extra measures

7) **Aquifer thermal energy storage (ATES)**

The basic principle of an ATES system is the extraction and injection of ground water into two separate storage wells, located at sufficient distance apart from each other. During summertime water is extracted from the coldest well and used to cool the building. This heats the water from approx. 8 to 16 °C. The heated water is injected at the warm well and stored until the winter season. During winter the extraction/injection flow is inversed and the heated water (with a temperature of approx. 14 °C) is pumped back to the building. Using a heat pump the heat is extracted from the water and the cold water (6°C) will be injected in the cold well. This means that district heating is not required and CO_2 emissions for the building are virtually halved when compared to a conventional design (Zeiler,2017).
However, this system is not financially feasible if applied to the stadium only, as mentioned by the Energy expert of Royal Haskoning. It would be better to apply it both to the stadium and the surrounding buildings, especially those with residential function. This would allow for heat/cold exchange as residential buildings require more heating than cooling, whereas it is the opposite for the stadium.

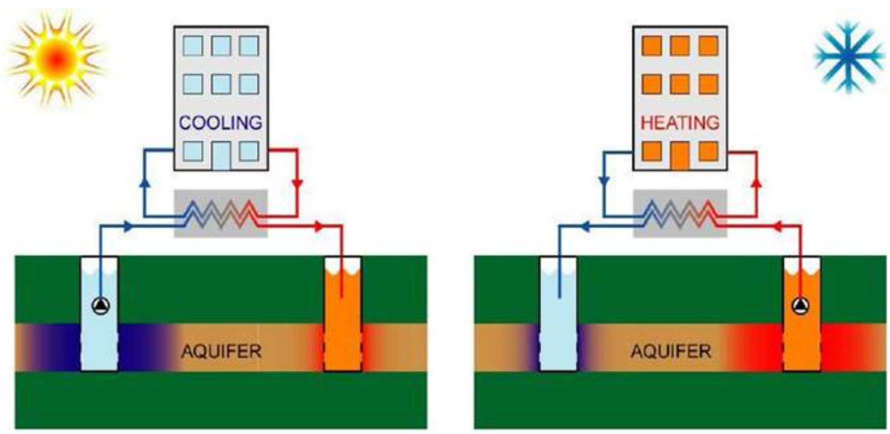


Figure 4.5.5: ATES system
From "Radboud Universiteit", 2014. https://www.ru.nl/nieuws-agenda/nieuws/vm/2014/nov/warmte-koude-opslag/

8) **Aquifer thermal energy storage (ATES) + Energy exchange with water from the river**

ATES system can be implemented by using the water from the nearby river, the Nieuwe Maas, when the temperature is favorable to provide either heating or cooling. The Maas Tower is an example of how these two systems are combined. The water of the river is led past a heat exchanger which is connected to the building's climate control system. In this way, the building can 'absorb' the warmth which is still present in the river in the autumn; due to industrial residual heat the average temperature of the river water is still above 20 °C. As the river water strongly cools down in winter a possibility is created to store the summer heat.
During winter time, when the river water is too cold to heat the office building,

the system pumps up water from the warm well and after extracting the heat it is cooled down and stored in the cold well. In the warm months, the exact opposite is done. During the first warm months of a year river water is being used, which is still cold enough at that time to cool the building. If the river temperature rises too much, water of the cold well is extracted (Zeiler,2017).

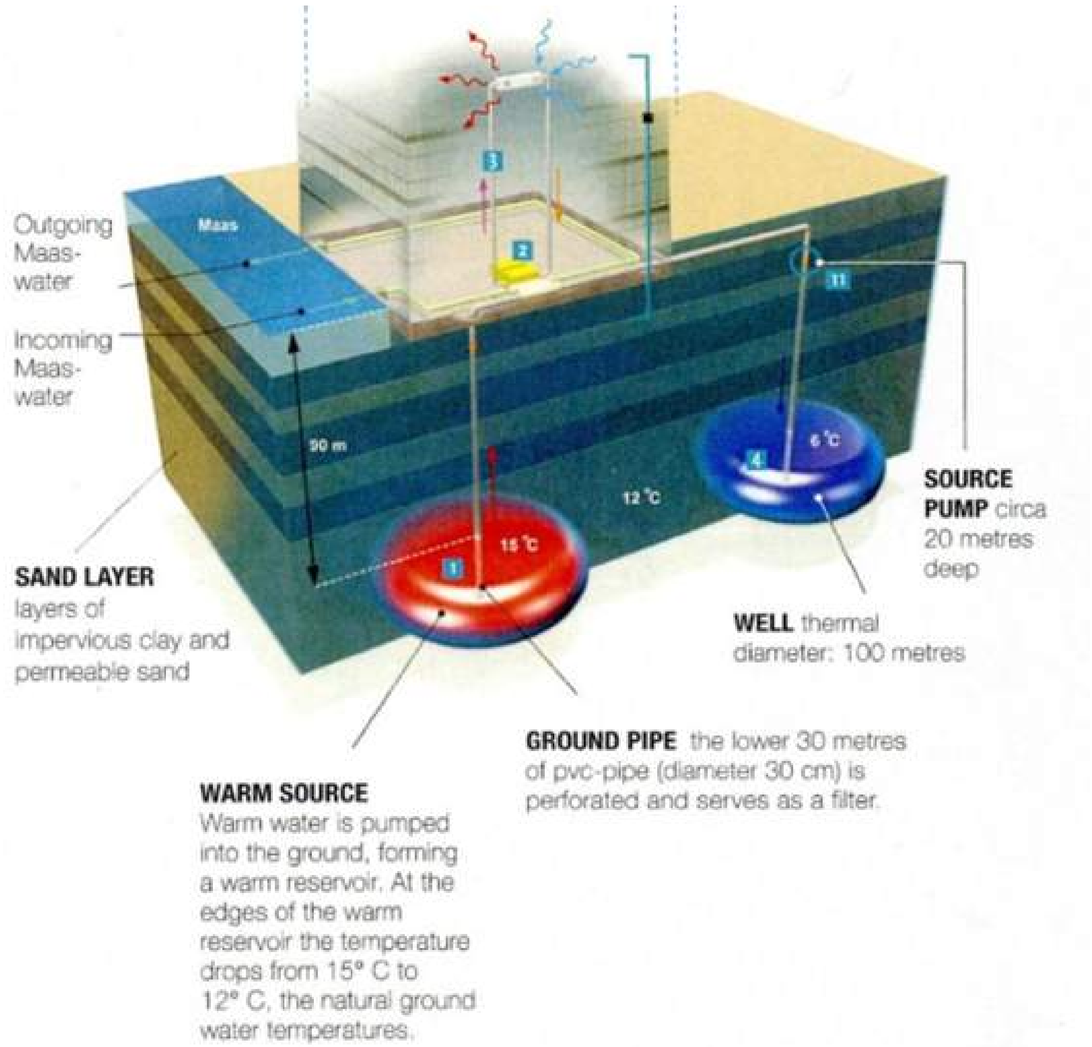


Figure 4.5.6: ATES system + Nieuwe Maas
Zeiler, 2017

9) **Solar cooling (combined with river)**

It consists of solar collectors, usually placed on the roof, combined with a refrigerating machine. It allows to produce cooling from a heating source, namely sun.

Solar collectors absorb solar radiation and transfer the produced heat to fluids, such as water. In the chiller, the warm water exchanges the heat with the cold water coming from the air conditioners. In this way the cold water is further cooled down and sent back to the machine to produce cooling for the building. The proposal is to integrate the solar cooling system with the river potential. Water coming from the Nieuwe Maas could be, indeed, used instead of the

cooling tower to condense the chiller fluid. The only requirement is to control the temperature of the water to ensure it is warm or cold enough to allow for condensation of the fluid.
Same in the previous case, the temperature of water getting back to the river might be an issue.

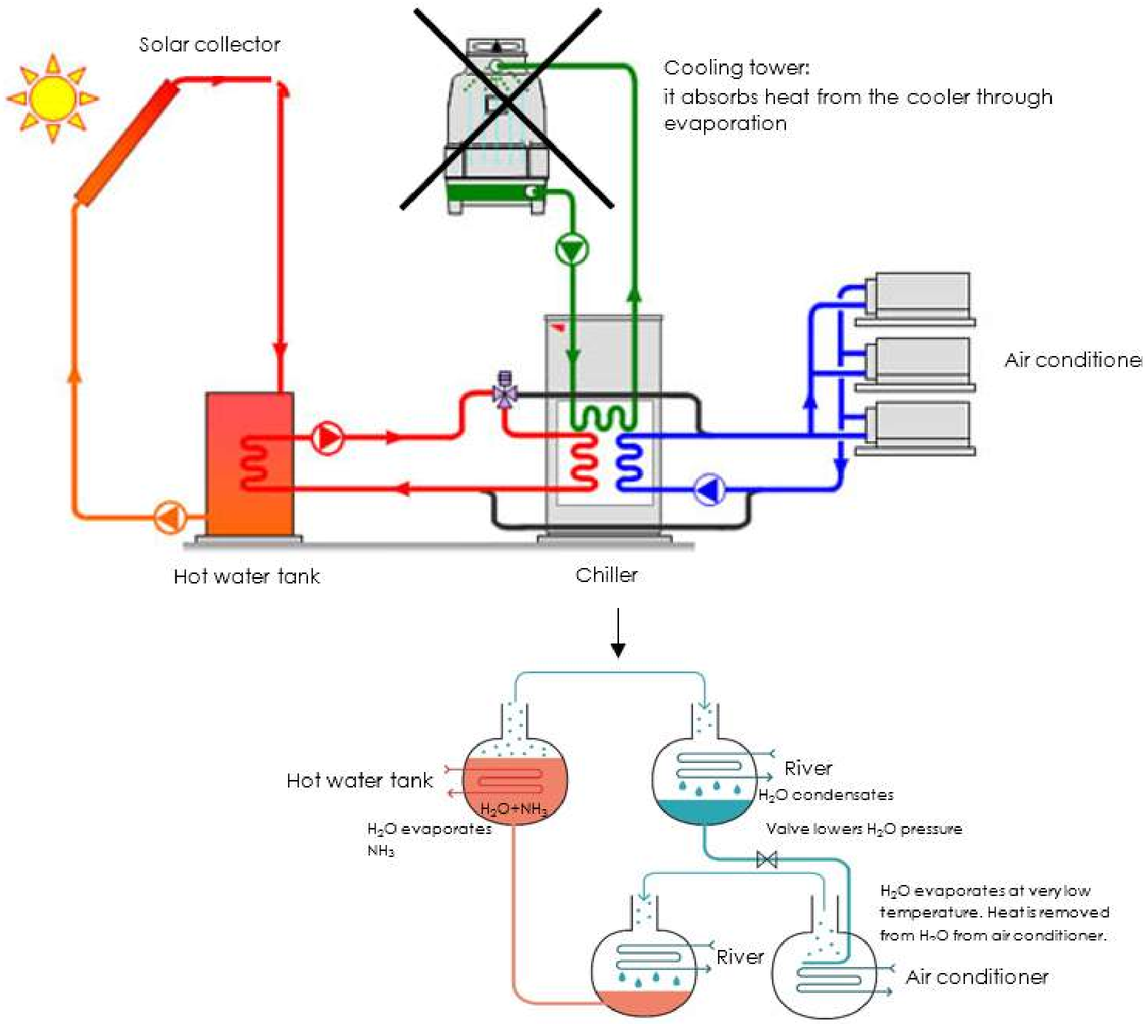


Figure 4.5.7: Solar cooling + Nieuwe Maas
From "ENEA - Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile", 2018.

10) **Radiant cooling systems**

They typically use chilled water running in pipers in thermal contact with the surface. Water only needs to be 2-4 °C below the desired indoor air temperature. The water removes heat from the surface, whereas the surfaces being cooled absorbs heat from the space.
There are different types of radiant cooling systems:
a) Chilled slabs: cooling is delivered through the building structure, namely from floors or ceilings. This system performs better in moderate climate and

combined with natural ventilation.

b) Ceiling panels: cooling is delivered through specialized panels. This system performs better in buildings with spaces with highly variable internal loads.

Systems using concrete slabs are generally cheaper than panel systems and offer the advantage of thermal mass while panel systems offer faster temperature control and flexibility (Oorja Energy Engineering, 2006).

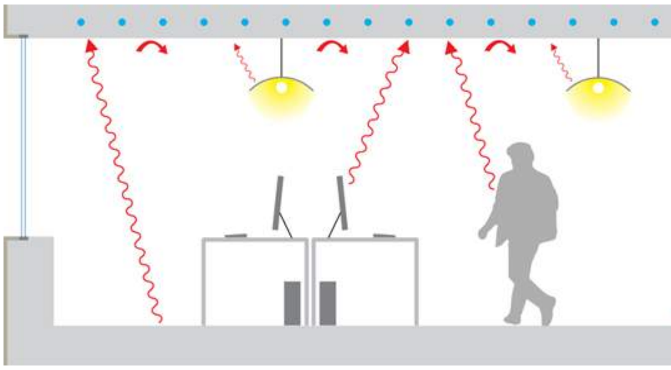


Figure 4.5.8: Radiant cooling
Wikipedia, (n.d.). https://en.wikipedia.org/wiki/Radiative_cooling

11) **Tubes under the field**

A system of tubes running under the grass field can be integrated to further cool down the ground that is in direct contact with the indoor environment. Water can be supplied to the tubes by the river.

12) **Local measures**

Analysis of the performance of local system has been done. In particular, focusing on the validation of a previous case study for Qatar. In that case, CFD analysis allowed to check the effect of various options for local cooling, when outdoor temperature is around 40 °C.

In my case, a section of the stadium is considered, which is shown in figure 4.5.9. The volume (figure 4.5.10) is 2 m high and hosts around 1/6 of the total amount of spectators. In this scenario, cold air of 18 °C is assumed to be supplied from behind the seats and people are performing light activity. In order to verify what will be the temperature at spectators' levels, heat balance equation is defined.

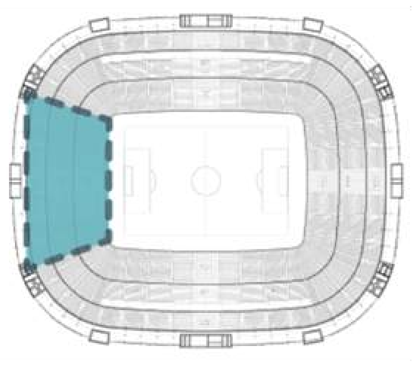


Figure 4.5.9: Area for analysis

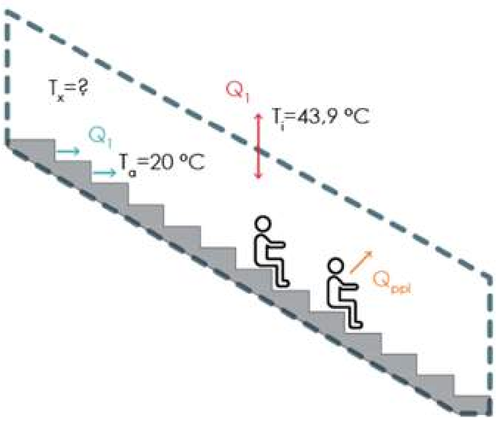


Figure 4.5.10: Volume

$$Q_1 + Q_{people} = Q_2$$

$$Q_1 = 0{,}35 \times n \times V \times (T_x - T_a)[W]$$

$$Q_2 = h \times A \times (T_i - T_x)[W]$$

$$Q_{people} = 10500 \times 93 \times 1{,}8\ [W]$$

Formula 4.5.1: Heat balance equation for the selected volume

Figure 4.5.11: Lekhwiya Sport Stadium CFD analysis – Temperature contours [°C]. Cold air supply from behind the seats at 20 °C.
From "Cibse Journal", 2017. https://www.cibsejournal.com/technical/sporting-success-a-study-of-air-conditioning-stadiums-in-qatar/

The result shows that the temperature should be around 34 °C, which quite far from the outcomes of CFD simulations for Qatar, shown in figure 4.5.11.
This difference is probably due to the large amount of people considered.
If Qatar's model is then taken as reference, it might be necessary to define different temperature for the air being supplied to the system to further cool the space down.

4.6 FEYENOORD STADIUM ANALYSIS

4.6.1 Stadium components

Feyenoord is a 63000 seats stadium planned to be built in time for the 2022/23 Eredivisie season. The project is still under development, therefore for the development of my design proposal I will refer to the "OMA schematic report" of June 2018, provided by DGMR. The stadium itself is made of two main areas: the field/spectators' area and the facilities area.

Figure 4.6.1: Elevation Feyenoord stadium
OMA, 2018

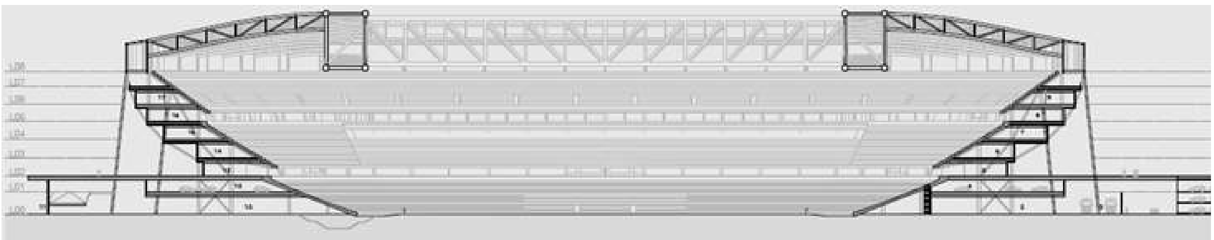


Figure 4.6.2: Section Feyenoord stadium
OMA, 2018

Looking at the main components, the external façade is made of the following materials shown in table 4.6.1.

material	U [W/m2K]	A [m2]
insulated concrete	0.043	13050
plastic	1.2	3093
polycarbonate	0.5	5040
corrugated aluminium	0.61	8438
flat alluminium	0.61	784
aluminium tubes	0.61	4433
frosted glass	1	3093
curtain wall	2.2	2833

Table 4.6.1: External façade composition

The internal façade, which corresponds to the seating areas of visitors, is fully made of concrete.

material	U [W/m2K]	A [m2]
insulated concrete	0.043	13050

Table 4.6.2: Internal façade composition

Last, the operable roof is made of polycarbonate.

material	U [W/m2K]	A [m2]
polycarbonate	0.5	39074

Table 4.6.3: Roof composition

4.6.2 Thermal comfort requirements

FIFA (Fédération Internationale de Football Association) requires an indoor temperature in the range of 20-25,5 °C in all hospitality areas of the stadium. This includes interior enclosed spaces, spectator tiers, as well as the playing field (FIFA. 2011. Football Stadiums: Technical recommendations and requirements - 5th Edition).

Adaptive thermal comfort models exist, among which the ANSI/ASHRAE one, which is shown in figure 4.6.3.

The adaptive thermal comfort model has developed based on researches by Humphreys (1976, 1978), Auliciems and deDear (1986) and deDear and Brager (1998), and relies on the adaptive principle: If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort.
By taking into consideration people's activities, the the adaptive principle links the comfort temperature to the context in which subjects find themselves. The comfort temperature is a result of the interaction between the subjects and the building or other environment they are occupying.
Many variables play a key role in the model, among which the climate, although basic mechanisms of the human relationship with the thermal environment. Then, the building configuration and its services affect the comfort. Last, time as human activities take place in a time frame, thus making responses change.

Two adaptive thermal comfort models exist, one for free-running and one for heated/cooled buildings. However, they are mainly representative for indoor spaces. Such a model for semi-outdoor spaces does not exist, therefore the ANSI/ASHRAE Standard 55-2004 "Thermal Environmental standard Conditions for Human Occupancy" is here considered.

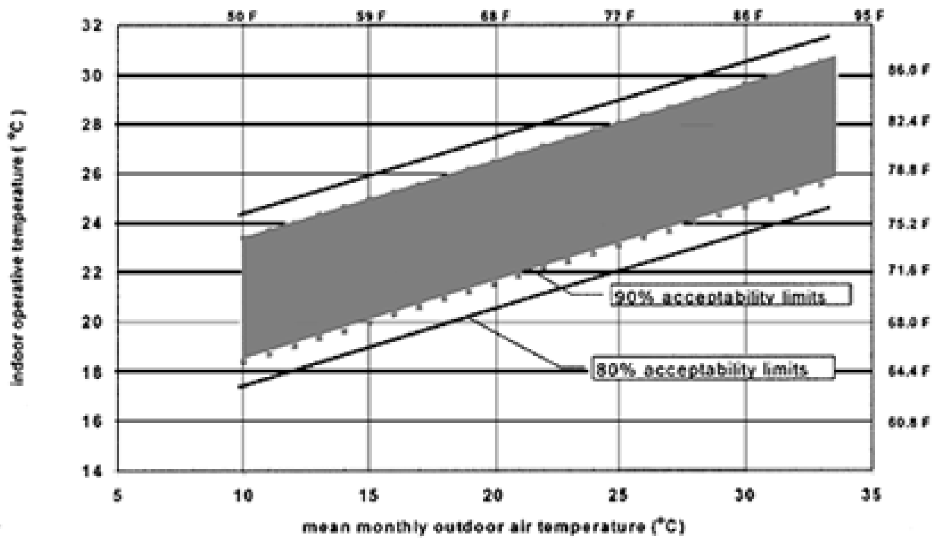


Figure 4.6.3: Adaptive thermal comfort model - ANSI/ASHRAE Standard 55-2004, Thermal Environmental standard Conditions for Human Occupancy
Nicol J.F., Humphrey M. A.,2002.

4.6.3 Worst-case scenarios

In order to define the worst-case scenarios, first the maximum and minimum temperature in the Netherlands expect for 2100 is defined. In general, an increase of 3 °C is expected with respect to 1990s temperatures.
The highest temperature registered in summer in 1990 is °C, therefore 38 °C are expected. In winter, instead the lower temperature registered in 1990 is -5 °C, as can be seen from “Weatheronline” website. However, in this case, the 3 °C increase is not considered as it is preferred to design for lower temperature. Next to outdoor temperature, it is also necessary to define the number of people who will be in the stadium for the events. Varying number of people leads to different heat gains, therefore to a different indoor temperature. The maximum amount of people that the Feyenoord Stadium can host is 63000, whereas for the opposite worst-case scenario 5000 people are considered.

Even if 38 °C are not likely to be reached in case of a concert, as it is usually performed at night, this scenario is assumed to actually check what would be the behaviour of the stadium under such conditions when it is closed.

Temperature MAX	38 °C
Number of people MAX	63000

Temperature MIN	-5 °C
Number of people MIN	5000

Table 4.6.4: Worst-case scenarios

4.7 PARAMETERS STUDY

4.7.1 urban physics and building physics

"Urban physics is the study of the physical aspects of the outdoor urban environment, including the transfer of heat and mass, acoustics, lighting and energy, and their interaction with the indoor environment and the building envelope. It is aimed at improving outdoor and indoor health, comfort, productivity and sustainability taking into account energetic, ecological and economic constraints." (Blocken, 2012)

In the field of urban physics, the main aspects to consider to design are urban wind comfort, urban thermal comfort, urban energy demand, urban pollutant dispersion and urban wind-driven rain.

The study of urban wind comfort mainly deals with pedestrian level wind conditions and pedestrian level wind comfort and danger. In order to guarantee wind comfort, it is necessary to control wind speed, nuisance and natural ventilation. In this frame, high-rise buildings are those rising more issues in the built environment.

Urban thermal comfort strongly relates to wind thermal comfort. The main parameters to control are both direct and indirect solar irradiance, air temperature and humidity, exchange of long-wave radiation between a person and the environment.

Urban energy demand depends on the amount of direct and indirect solar irradiance, the interaction between buildings, materials and their properties, as well as the urban heat island effect.

Urban pollutant dispersion is affected by the characteristics of the flow field, which is dominated by the interplay between meteorological conditions and urban morphology.

Last, wind-driven rain is the rain given horizontal velocity by wind and driven against the windward façade of the buildings. This might lead to moisture related issues, thus affecting the hygrothermal performance and durability of the façade. (Blocken, 2012)

"Urban physics is the study of the physical aspects of the outdoor urban environment, including the transfer of heat and mass, acoustics, lighting and energy, and their interaction with the indoor environment and the building envelope. It is aimed at improving outdoor and indoor health, comfort, productivity and sustainability taking into account energetic, ecological and economic constraints." (Blocken, 2012)

The parameters to consider at building scale are direct and diffuse solar irradiance, outside air temperature, humidity, wind speed and direction, number of people, number and type of appliances, amount of glazed and opaque component, materials, rainfall amount.

By means of calculations in Excel, building parameters are studied to understand their effect on the building and the indoor comfort of users. The main focus is on temperature as the goal is to guarantee proper livability of users in a future warmer scenario. The main area analyzed in the semi-outdoor one, therefore the field and the tiers. The smaller closed spaces hosting facilities are assumed to be conditioned.

After defining the heat balance equation, parameters to play with have been chosen: air change rate, solar irradiance, U-value of the façade/roof. Then, based on the outcomes, they have been combined to see their mutual effect in order to check which is the one affecting the indoor temperature the most.

Two activities have been considered:

1) Football match;
2) Concert.

These are the mainly activities carried out in the stadium, which host the higher amount of people.

For both activities, calculations have been performed for four cases:

1) Winter, maximum number of people and appliances;
2) Winter, minimum number of people and appliances;
3) Summer, maximum number of people and appliances;
4) Summer, minimum number of people and appliances.

4.7.2 Football match

Football matches are usually performed at daytime, they host a high number of spectators and the number of appliances within the considered volume is not very high. However, the four aforementioned cases are considered in calculations.

Educated assumptions are made:

- The roof is open to allow for daylight;
- Spectators are performing light activity

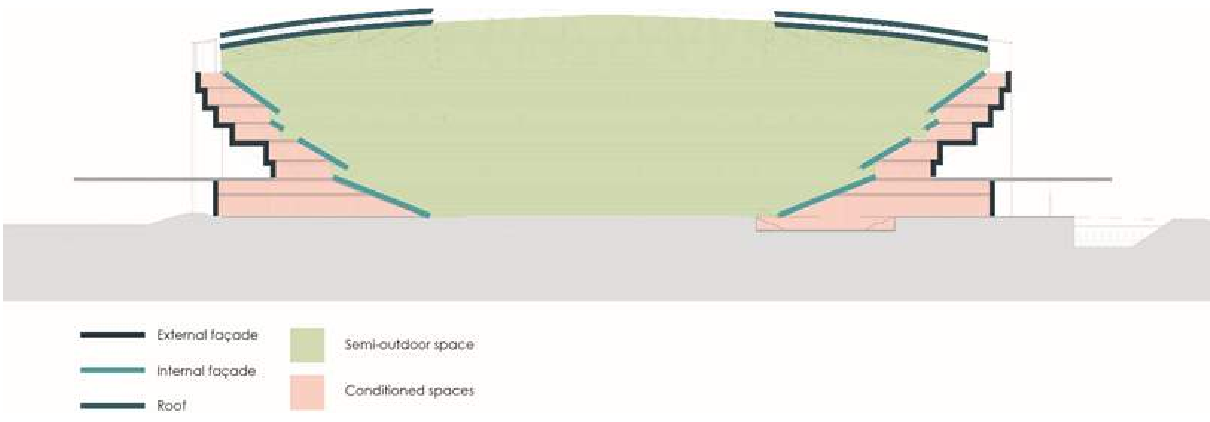


Figure 4.7.1: Football match case – spaces and envelope
OMA, 2018

T [°C]	max	38
	min	-5
Solar irradiance [W/m2]	summer	1000
	winter	150
ACH	0.627	
Volume	2347967.7	
Metabolic rate [W/m2]	93	
Number of people	Max	63000
	Min	5000

Table 4.7.1: Data – football match case

Heat balance equation for the stadium in case of a football match is defined, and heat gains and losses are shown in figure 4.7.2. Indoor temperature is calculated with varying parameter and outdoor temperature.
In this scenario, there are solar gains both through the closed and open parts of the roof, ventilation losses occur through the façade and the roof and transmission losses mainly through the external and internal façades.

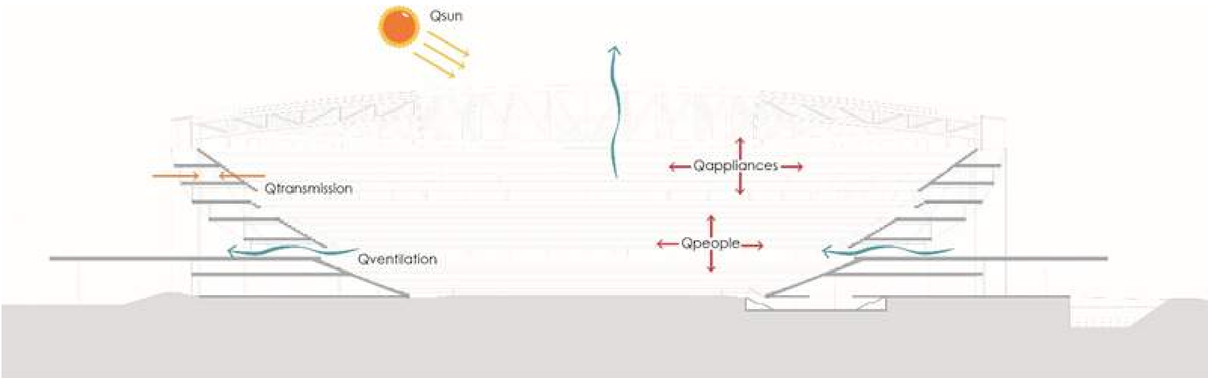


Figure 4.7.2: Football match case - heat gains and losses
OMA, 2018

$$Q_{sun} + Q_{people} + Q_{appliances} = Q_{transmission} + Q_{ventilation}$$

$$Q_{sun} = q \times g \times A_{roof,polycarbonate} + q \times g \times A_{roof,open} \ [W]$$

$$Q_{people} = n. of\ people \times metabolic\ rate\ [W]$$

$$Q_{appliances} = power\ of\ appliances\ [W]$$

$$Q_{transmission} = \sum UA_{facade\ 1} \times (T_e - T_{cs}) + \sum UA_{facade\ 2} \times (T_i - T_{cs}) \quad [W]$$

$$Q_{ventilation} = 0{,}35 \times n \times V \times (T_i - T_e)\ [W]$$

$$T_i = \frac{Q_{sun}+Q_{people}+Q_{appliances}+T_e\times\left(\sum UA_{facade\ 1}+0{,}35\times n\times V\right)+T_{cs}\times(\sum UA_{facade\ 1}+\sum UA_{facade\ 2})}{\sum UA_{facade\ 2}+0{,}35\times n\times V}\ [°C]$$

Formula 4.7.1: Heat balance for open stadium

Q_{tr} (FACADE 1) [W]	24.083.044	*(T_e-T_{cs})
Q_{tr} (FACADE 2) [W]	918.652	*(T_i-T_{cs})
Q_v [W]	515.261.512	*(T_i-T_e)
Q_{sun} summer [W]	28679360	
Q_{sun} winter [W]	4301904	
Q_{ppl} max [w]	5859000	
Q_{ppl} min [w]	46500	
Q_{app} max [w]	9000	
Q_{app} min [w]	0	

Table 4.7.2: Heat gains and losses

Although the external façade is not in direct contact with the semi-outdoor area of the stadium, which the main focus of the research, thus not being directly important for the heat balance equation, it was considered to verify if changes in the façade should be either proposed or not in the design phase.
On the other hand, exchange for radiation between the semi-outdoor space and the sky were neglected because this would have effect in time, whereas here static calculations are performed.

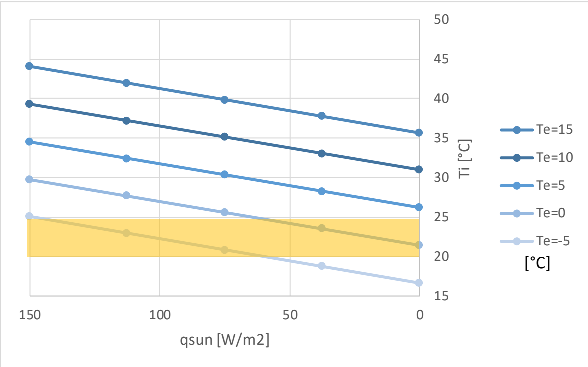
In the winter scenario, the outcomes considered for the study of indoor temperature are those for outdoor temperature between 15 and -5, while for summer those for outdoor temperature between 20 and 38. The temperature of conditioned spaces is assumed to be 20 °C.
From the outcomes, graphs are drawn. On the x-coordinate, the chosen parameter values are inserted, while on the y-coordinates indoor temperatures resulting from calculations are selected. The lines show the variation of indoor temperature with varying parameter for different outdoor temperatures.

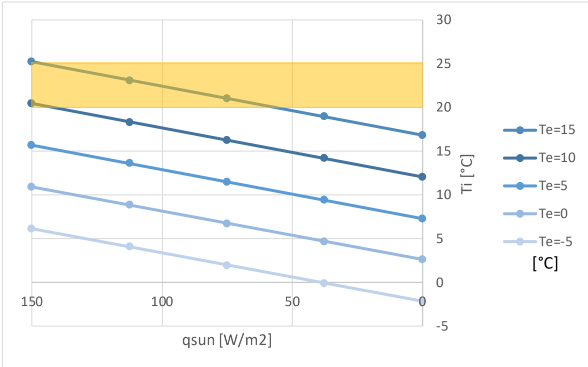
4.7.1.1 Solar irradiance

The first studied parameter is solar irradiance, defined as the quantity of radiant energy that comes from the Sun (total intensity of radiation) received by a 1 m^2 surface area, as explained in the Futura science website (n.d).
Based on research, the maximum values of solar irradiance both for winter and summer are defined. For winter, the value is 150 W/m2, whereas for summer it is 1000 W/m2. Then, the effect of solar irradiance on indoor temperature has been observed by lowering the amount from the maximum value to zero. At the same time, also outdoor temperature varies in calculations from 38 to -5.
Tables 4.7.3 and 4.7.4 and graphs 4.7.1 and 4.7.2 show the trend for indoor temperature at solar irradiance varying from 150 W/m2 to 0 W/m2 in winter.

Te [°C]		qsun	150	112.5	75	37.5	0
	38	**Ti**	65.9	63.8	61.7	59.6	57.6
	35	*max ppl*	63.0	61.0	58.9	56.8	54.7
	30	*max app*	58.3	56.2	54.1	52.0	50.0
	25		53.5	51.5	49.4	47.3	45.2
	20		48.8	46.7	44.6	42.5	40.4
	15		44.0	41.9	39.9	37.8	35.7
	10		39.3	37.2	35.1	33.0	30.9
	5		34.5	32.4	30.4	28.3	26.2
	0		29.8	27.7	25.6	23.5	21.4
	-5		25.0	22.9	20.8	18.8	16.7

qsun	150	112.5	75	37.5	0
Ti	47.1	45.0	42.9	40.8	38.7
min ppl	44.2	42.1	40.0	38.0	35.9
min app	39.5	37.4	35.3	33.2	31.1
	34.7	32.6	30.5	28.5	26.4
	30.0	27.9	25.8	23.7	21.6
	25.2	23.1	21.0	19.0	16.9
	20.4	18.4	16.3	14.2	12.1
	15.7	13.6	11.5	9.4	7.4
	10.9	8.9	6.8	4.7	2.6
	6.2	4.1	2.0	-0.1	-2.1



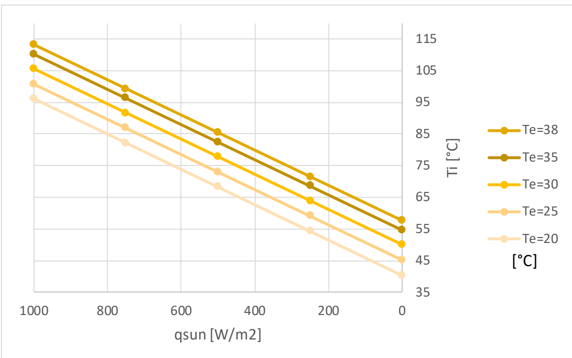


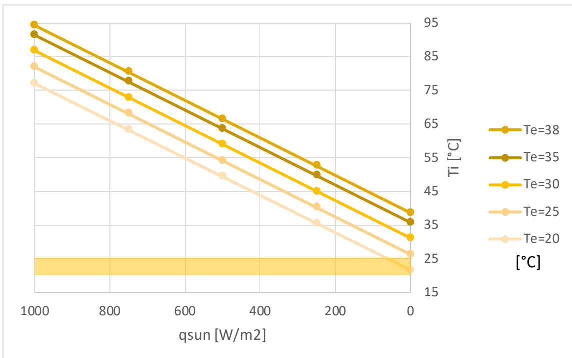
Tables 4.7.3 and 4.7.4: Winter case with solar irradiance as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.1 and 4.7.2: Variation in indoor temperature at varying solar irradiance value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

It is possible to observe that the effect of sun is not very high on the indoor temperature. For a given outdoor temperature, indeed, the resulting ΔT is in the range of 7-10 °C. However, with sun entering through the roof, the indoor temperature of the stadium exceeds the required 20-25,5 °C if the outdoor temperature is above 5 °C.
Tables 4.7.5 and 4.7.6 and graphs 4.7.3 and 4.7.4 show the trend for indoor temperature at solar irradiance varying from 1000 W/m2 to 0 W/m2 in summer.

Te [°C]		qsun	1000	750	500	250	0
	38	**Ti**	113.1	99.2	85.3	71.5	57.6
	35	*max ppl*	110.3	96.4	82.5	68.6	54.7
	30	*max app*	105.5	91.6	77.7	63.8	50.0
	25		100.8	86.9	73.0	59.1	45.2
	20		96.0	82.1	68.2	54.3	40.4
	15		91.3	77.4	63.5	49.6	35.7
	10		86.5	72.6	58.7	44.8	30.9
	5		81.7	67.9	54.0	40.1	26.2
	0		77.0	63.1	49.2	35.3	21.4
	-5		72.2	58.4	44.5	30.6	16.7

qsun	1000	750	500	250	0
Ti	94.3	80.4	66.5	52.6	38.7
min ppl	91.4	77.6	63.7	49.8	35.9
min app	86.7	72.8	58.9	45.0	31.1
	81.9	68.0	54.2	40.3	26.4
	77.2	63.3	49.4	35.5	21.6
	72.4	58.5	44.6	30.8	16.9
	67.7	53.8	39.9	26.0	12.1
	62.9	49.0	35.1	21.3	7.4
	58.2	44.3	30.4	16.5	2.6
	53.4	39.5	25.6	11.7	-2.1





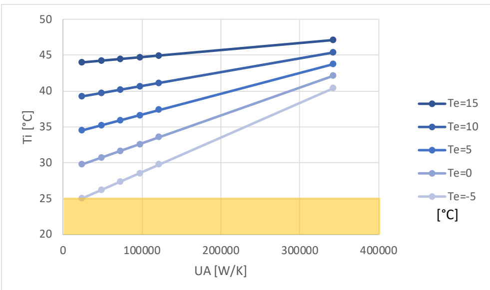
Tables 4.7.5 and 4.7.6: Summer case with solar irradiance as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.3 and 4.7.4: Variation in indoor temperature at varying solar irradiance value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

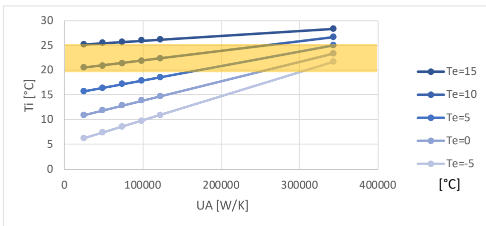
It can be observed that in summer scenario, ΔT is much higher than in winter, with a value of around 60 °C. In particular, it is important to notice that the difference in temperature between the maximum people-maximum appliances and minimum people-minimum appliances cases is very small, thus being the sun playing a major role. Therefore, solar shading is needed, or, at least, the polycarbonate roofing material should be substituted with a less transparent material.

4.7.1.2 ∑UA external façade

The second parameter is the thermal transmittance multiplied by the area of the external façade, namely the actual façade of the stadium. In fact, the considered inner façade is made of the spectator tiers, thus not being possible to make effective changes.
The study of this parameter aims to understand its effect, namely how indoor temperature changes when the U values increases.
Tables 4.7.7 and 4.7.8 and graphs 4.7.5 and 4.7.6 show the trend for indoor temperature in winter.

Te [°C]	∑Uf1Af1	24508.3	49016.6	73524.9	98033.2	122542	343116	∑Uf1Af1	24508.3	49016.6	73524.9	98033.2	122542	343116
38	Ti	65.9	65.0	64.2	63.3	62.5	54.8	Ti	47.1	46.2	45.4	44.5	43.7	36.0
35	*max ppl*	63.0	62.3	61.6	60.9	60.2	53.8	*min ppl*	44.2	43.5	42.8	42.1	41.4	35.0
30	*max app*	58.3	57.8	57.3	56.9	56.4	52.1	*min app*	39.5	39.0	38.5	38.0	37.6	33.3
25		53.5	53.3	53.1	52.8	52.6	50.5		34.7	34.5	34.2	34.0	33.8	31.6
20		48.8	48.8	48.8	48.8	48.8	48.8		30.0	30.0	30.0	30.0	30.0	30.0
15		44.0	44.3	44.5	44.7	45.0	47.1		25.2	25.4	25.7	25.9	26.2	28.3
10		39.3	39.8	40.2	40.7	41.2	45.4		20.4	20.9	21.4	21.9	22.3	26.6
5		34.5	35.2	35.9	36.7	37.4	43.8		15.7	16.4	17.1	17.8	18.5	25.0
0		29.8	30.7	31.7	32.6	33.6	42.1		10.9	11.9	12.8	13.8	14.7	23.3
-5		25.0	26.2	27.4	28.6	29.8	40.4		6.2	7.4	8.6	9.7	10.9	21.6



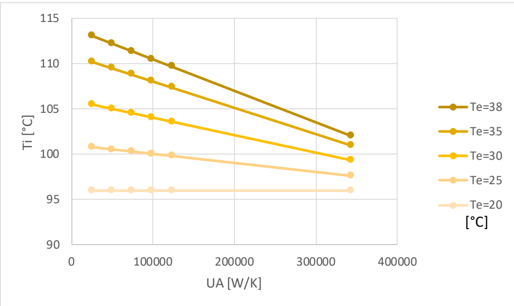


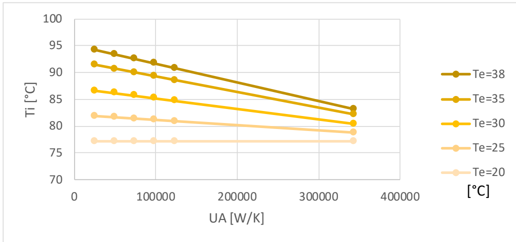
Tables 4.7.7 and 4.7.8: Winter case with thermal transmittance x surface as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.5 and 4.7.6: Variation in indoor temperature at varying thermal transmittance x surface value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

It is possible to observe that increasing U-value leads to an increase indoor temperature as expected. However, the change in temperature is very small, therefore it is possible to say that the effect of the thermal transmittance of the façade on the indoor temperature is limited in winter. The indoor temperature in winter exceeds the required 20-25,5 °C for most of the cases.
Tables 4.7.9 and 4.7.10 and graphs 4.7.7 and 4.7.8 show the trend for indoor temperature at varying U-value in summer.

Te [°C]		∑Uf1Af1	24508.3	49016.6	73524.9	98033.2	122542	343116
38		Ti	113.1	112.3	111.4	110.6	109.7	102.0
35		*max ppl*	110.3	109.6	108.8	108.1	107.4	101.0
30		*max app*	105.5	105.0	104.6	104.1	103.6	99.3
25			100.8	100.5	100.3	100.1	99.8	97.7
20			96.0	96.0	96.0	96.0	96.0	96.0
15			91.3	91.5	91.7	92.0	92.2	94.3
10			86.5	87.0	87.5	87.9	88.4	92.7
5			81.7	82.5	83.2	83.9	84.6	91.0
0			77.0	77.9	78.9	79.8	80.8	89.3
-5			72.2	73.4	74.6	75.8	77.0	87.7

Te [°C]	∑Uf1Af1	24508.3	49016.6	73524.9	98033.2	122542	343116
38	Ti	94.3	93.4	92.6	91.7	90.9	83.2
35	*min ppl*	91.4	90.7	90.0	89.3	88.6	82.2
30	*min app*	86.7	86.2	85.7	85.3	84.8	80.5
25		81.9	81.7	81.5	81.2	81.0	78.8
20		77.2	77.2	77.2	77.2	77.2	77.2
15		72.4	72.7	72.9	73.1	73.4	75.5
10		67.7	68.1	68.6	69.1	69.6	73.8
5		62.9	63.6	64.3	65.1	65.8	72.2
0		58.2	59.1	60.1	61.0	62.0	70.5
-5		53.4	54.6	55.8	57.0	58.2	68.8





Tables 4.7.9 and 4.7.10: Summer case with thermal transmittance x surface as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.7 and 4.7.8: Variation in indoor temperature at varying thermal transmittance x surface value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

In summer, like in winter, the effect of the variation in parameter on the indoor temperature is not high. For a given outdoor temperature, indeed, the resulting ΔT is in the range of 1-15 °C. However, the indoor temperature of the stadium extremely exceeds the required 20-25,5 °C.
Looking at the small effect of the considered parameter it would be possible to conclude that rather than changing materials to have a different thermal transmittance, it would be interesting to choose materials which can bring benefits to the outdoor environment, thus helping in the reduction of UHI.

4.7.1.3 Air change rate

The last important parameter considered in the football match case is the air change rate, which is a measure of the air volume added to or removed from a space divided by the volume of the space. It is indicated as ACH or n and measured in 1/h.
First of all, the required ACH for the volume of the stadium has been calculated based on the following formula:

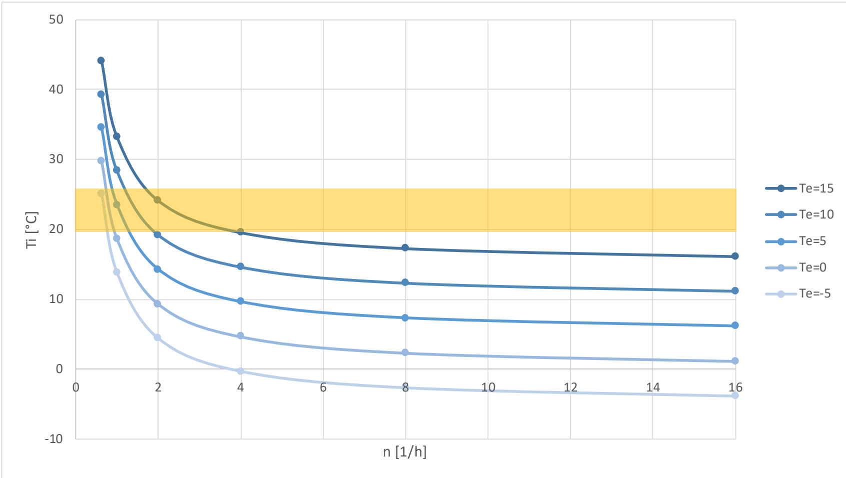
$$Q_v = \frac{60 \times n}{V} \left[\frac{m^3}{s}\right]$$

Formula 4.7.2: Flow rate

With the ventilation amount taken as the one for a gym.
The obtained air change rate is 0,627/h, which will be the basic value for calculations, where it increases up to 16/h.
Tables 4.7.11 and 4.7.12 and graphs 4.7.9 and 4.7.10 show the trend for indoor temperature at varying ACH in winter.

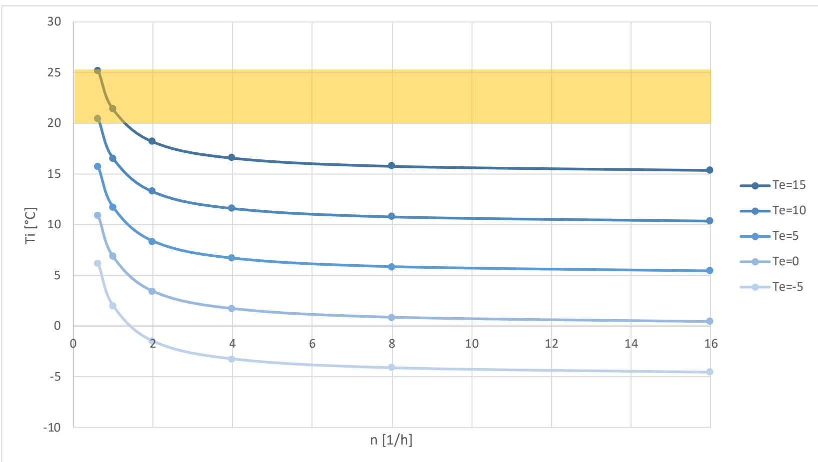
Te [°C]
38
35
30
25
20
15
10
5
0
-5

n	0.627	1	2	4	8	16
Ti	65.9	55.5	46.8	42.4	40.2	39.1
max ppl	63.0	52.6	43.8	39.4	37.2	36.1
max app	58.3	47.7	38.9	34.4	32.2	31.1
	53.5	42.9	34.0	29.5	27.2	26.1
	48.8	38.1	29.0	24.5	22.3	21.1
	44.0	33.2	24.1	19.6	17.3	16.1
	39.3	28.4	19.2	14.6	12.3	11.1
	34.5	23.5	14.3	9.6	7.3	6.2
	29.8	18.7	9.3	4.7	2.3	1.2



Te [°C]
38
35
30
25
20
15
10
5
0
-5

n	0.627	1	2	4	8	16
Ti	47.1	43.7	40.8	39.4	38.7	38.4
min ppl	44.2	40.8	37.9	36.4	35.7	35.4
min app	39.5	35.9	33.0	31.5	30.7	30.4
	34.7	31.1	28.0	26.5	25.8	25.4
	30.0	26.2	23.1	21.6	20.8	20.4
	25.2	21.4	18.2	16.6	15.8	15.4
	20.4	16.6	13.3	11.6	10.8	10.4
	15.7	11.7	8.4	6.7	5.8	5.4
	10.9	6.9	3.4	1.7	0.9	0.4
	6.2	2.0	-1.5	-3.2	-4.1	-4.6

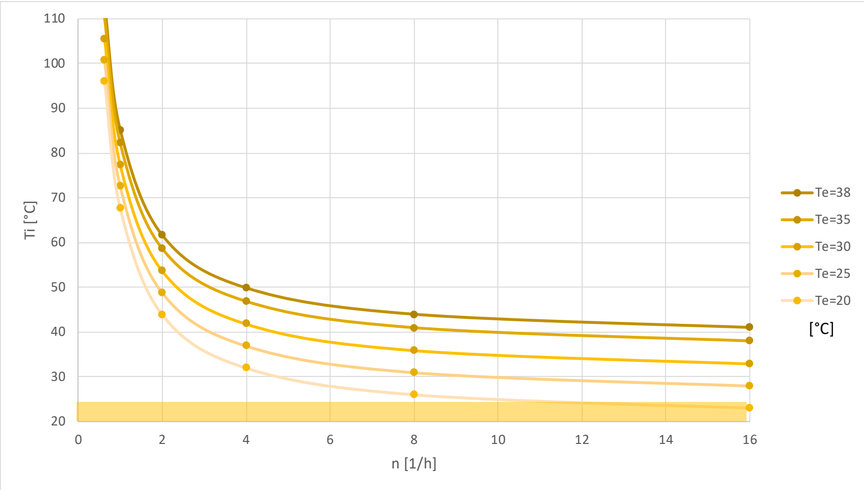


Tables 4.7.11 and 4.7.12: Winter case with air change rate as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.9 and 4.7.10: Variation in indoor temperature at varying air change rate value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

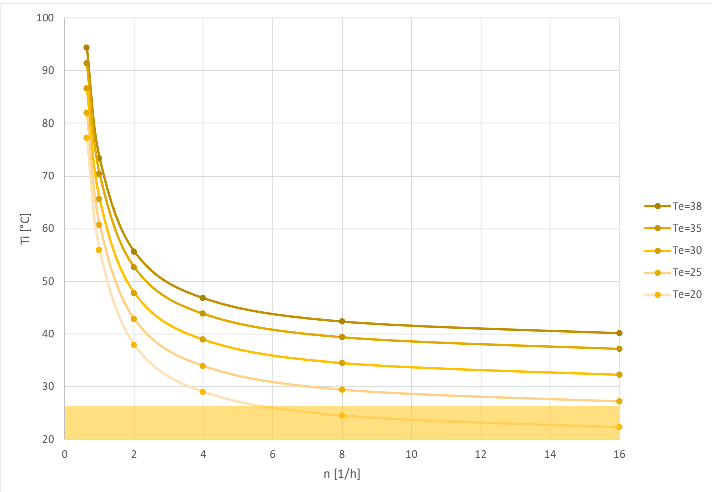
In winter, the effect of the air change rate on the indoor temperature is not so high, as it can be seen from the tables and the graphs.

Tables 4.7.13 and 4.7.14 and graphs 4.7.11 and 4.7.12 show the trend for indoor temperature at varying ACH in summer.

Te [°C]	Ti *max ppl max app* / n	0.627	1	2	4	8	16
38		113.1	85.1	61.6	49.8	43.9	40.9
35		110.3	82.2	58.6	46.8	40.9	38.0
30		105.5	77.4	53.7	41.9	35.9	33.0
25		100.8	72.5	48.8	36.9	30.9	28.0
20		96.0	67.7	43.9	31.9	26.0	23.0
15		91.3	62.8	38.9	27.0	21.0	18.0
10		86.5	58.0	34.0	22.0	16.0	13.0
5		81.7	53.2	29.1	17.0	11.0	8.0
0		77.0	48.3	24.2	12.1	6.0	3.0
-5		72.2	43.5	19.2	7.1	1.1	-2.0



Te [°C]	Ti *min ppl min app* / n	0.627	1	2	4	8	16
38		94.3	73.3	55.7	46.8	42.4	40.2
35		91.4	70.4	52.7	43.9	39.4	37.2
30		86.7	65.6	47.8	38.9	34.5	32.2
25		81.9	60.7	42.9	33.9	29.5	27.2
20		77.2	55.9	37.9	29.0	24.5	22.2
15		72.4	51.0	33.0	24.0	19.5	17.3
10		67.7	46.2	28.1	19.1	14.5	12.3
5		62.9	41.3	23.2	14.1	9.5	7.3
0		58.2	36.5	18.3	9.1	4.6	2.3
-5		53.4	31.6	13.3	4.2	-0.4	-2.7



Tables 4.7.13 and 4.7.14: Summer case with air change rate as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.11 and 4.7.12: Variation in indoor temperature at varying air change rate value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

In summer, instead, the effect of air change rate on indoor temperature is very high. Moving from a value of 0,627/h to a value of 16/h leads to a ΔT of almost 50 °C. However, the temperature inside the stadium exceeds the required 20-25,5 °C for most of the cases, especially if maximum number of people and appliances are considered.
Ventilation plays an important role in determining optimal thermal comfort conditions for users.

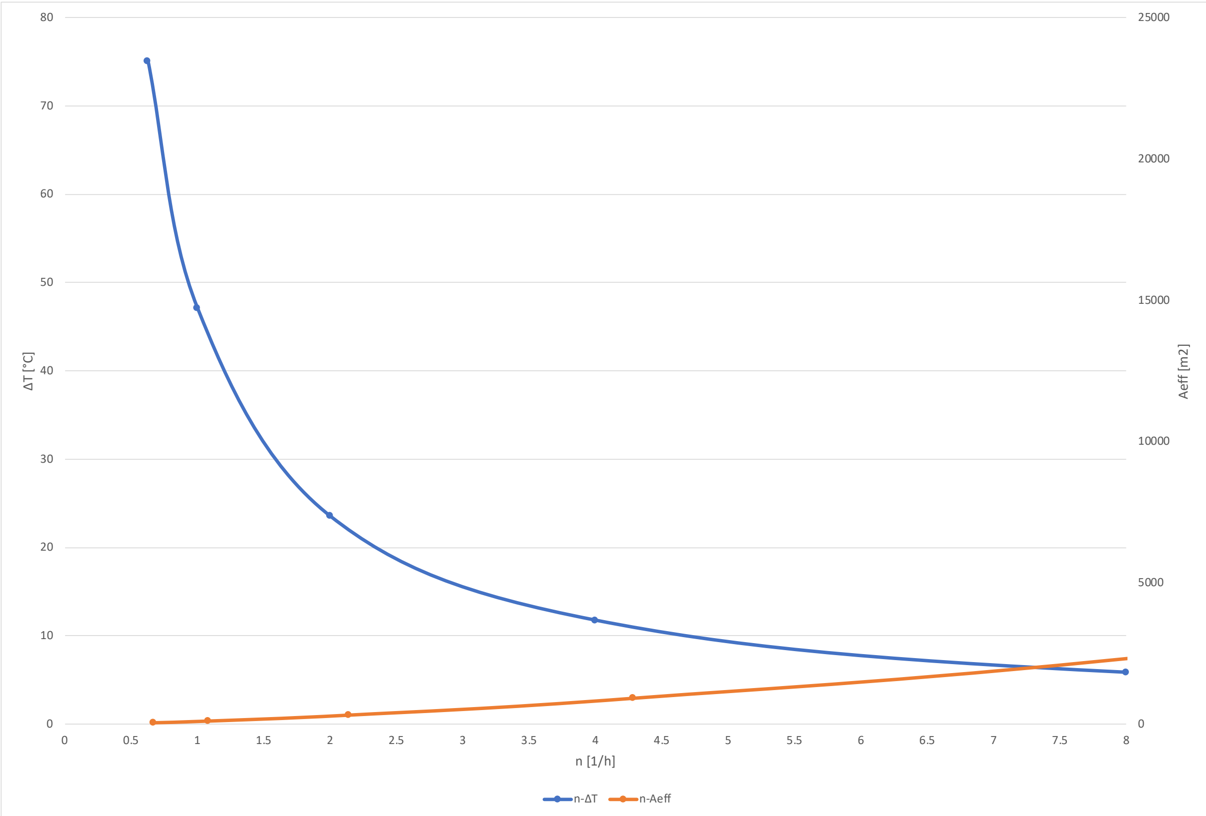
4.7.1.4 Calculated vs Optimal ACH

In the case of air change rate, further calculations have been performed. Once the effect of ACH on indoor temperature is defined, it necessary to understand if it is actually possible to provide that amount of ACH. As in case of football matches the roof will be open and air will enter from the open levels, namely the main entrance level. Therefore, in this scenario stack effect occurs.
Formula used for calculations follow:
The two formula have been combined and formula 4.7.4 has been substituted in formula 4.7.3. In order to verify the actual ACH that it is possible to provide to the volume of the stadium, all values have been set except for the effective area. Cd is assumed to be 0,6, g is known as it is gravity, H is considered as the distance between the main entrance level and the roof and Ti, Te and T come from the calculations.

$$Q_v = C_d \times A_{eff} \times \sqrt{2 \times g \times h \times \frac{T_i - T_e}{T}} \left[\frac{m^3}{s}\right] \qquad Q_v = \frac{63600 \times n}{V} \left[\frac{m^3}{s}\right]$$

Formula 4.7.3: Amount of ventilation - stack effect
Formula 4.7.4:Flow rate

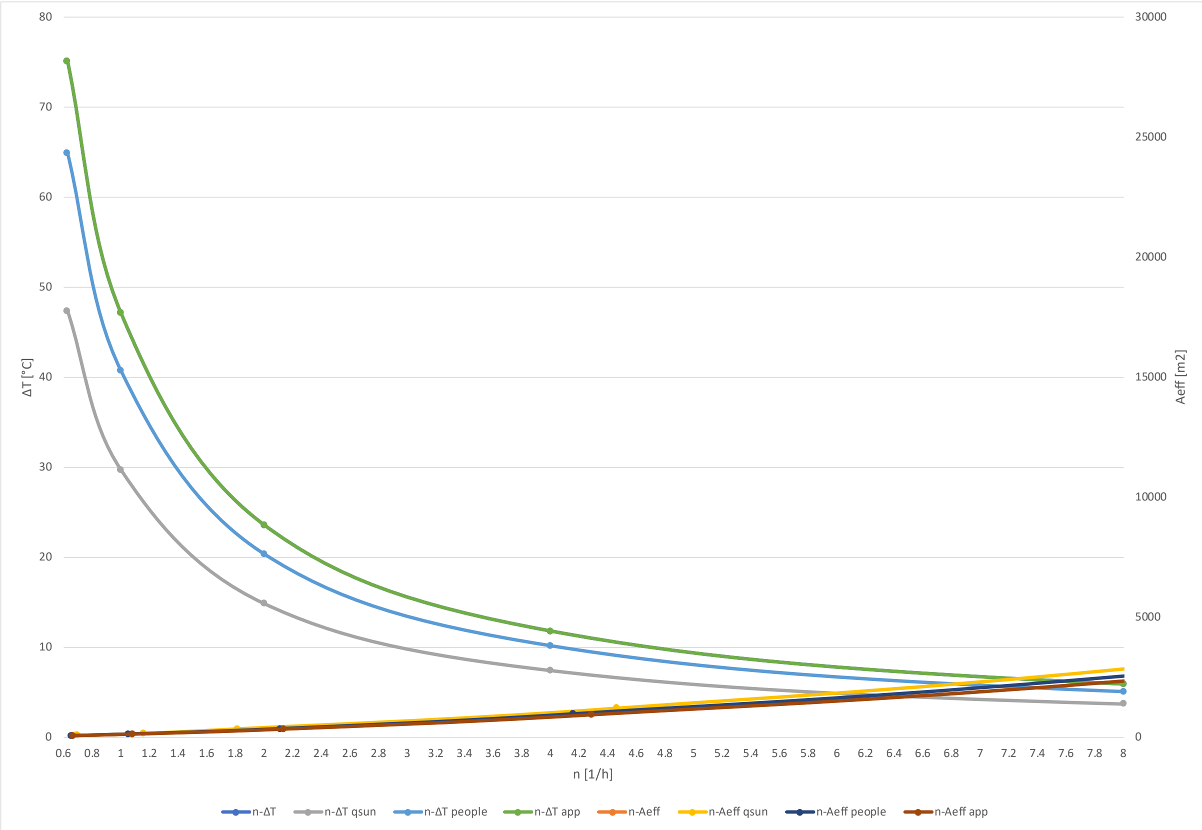
Calculations have been performed for all values of ACH, from 0,627/h to 128/h. Outcomes show that with the available area it only possible to have ACH up to 32/h.
The following graph shows the optimal air change rate obtained by the intersection of the line showing the ΔT variation at varying ACH, with the line showing the variation of ACH at varying effective area. By zooming in it can be observed that the optimal ACH value is around 7,4.



Graphs 4.7.13: Optimal ACH

This ACH optimal value has then been substituted into all the previous calculations having solar irradiance or U-value of the façade as parameters to see the influence of ventilations on indoor temperature in those cases. Results show that by increasing ACH from 0,627/h to 7,4/h, indoor temperatures drop. It is therefore possible to affirm that ventilation plays a key role on the indoor temperature of the stadium.

Further steps in calculations involved to play with those parameters influencing ACH. Therefore, solar gains, people and appliances heat gains values have been halved one by one to see the effect on possible optimal values of ACH.
The graph below show all the possible matching point between the lines showing the ΔT variation at varying ACH, with the lines showing the variation of ACH at varying effective area. It can be observed that the effect of other parameters on th optimal ACH is limited in most of the cases.
In fact, by halving the solar gains, optimal ACH is 6;
By halving people heat gains, optimal ACH is 7,2;
By halving appliances heat gains, optimal ACH is 7,8.



Graphs 4.7.14: Optimal values of ACH at varying parameters

In the case of a football match, therefore, the parameter affecting the most the indoor temperature, thus the comfort of users, is the air change rate, which defines the ventilation within the stadium boundaries.

4.7.2 Concert

Concerts usually occur at nighttime, they host a high number of spectators and the number of appliances within the considered volume can be very high due to lights and other tools for performance high. The four previously aforementioned cases are considered in calculations.
Educated assumptions are made:

- The roof is closed for acoustic reasons;
- People perform heavy activity, such as dancing;
- Solar gains are zero as it is night.

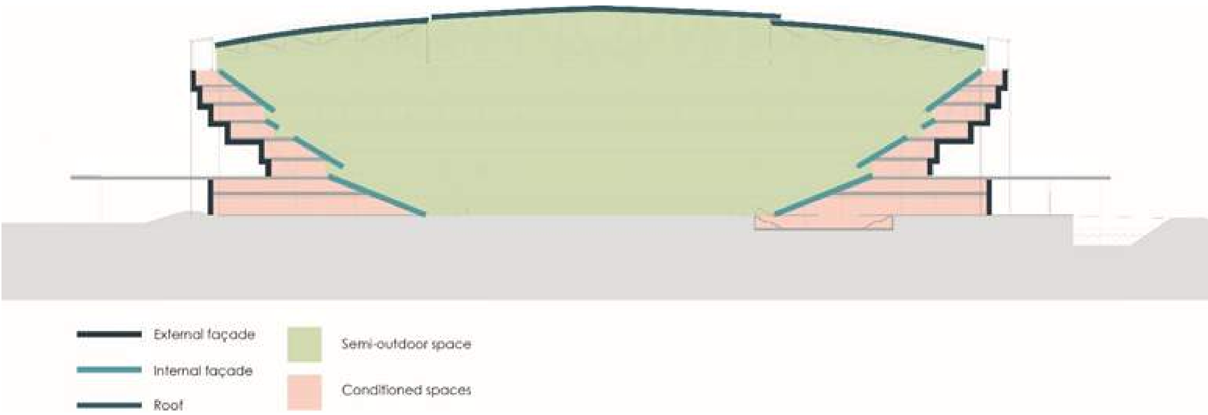


Figure 4.7.3: Concert case – spaces and envelope
OMA, 2018

T [°C]	max	38
	min	-5
Solar irradiance [W/m2]	summer	1000
	winter	150
ACH	0.627	
Volume	2347967.7	
Metabolic rate [W/m2]	290	
Number of people	Max	63000
	Min	5000

Table 4.7.15: Data – concert case

Heat balance equation for the stadium in case of a concert is defined, and heat gains and losses are shown in figure 4.8.4. Indoor temperature is calculated with varying parameter and outdoor temperature.

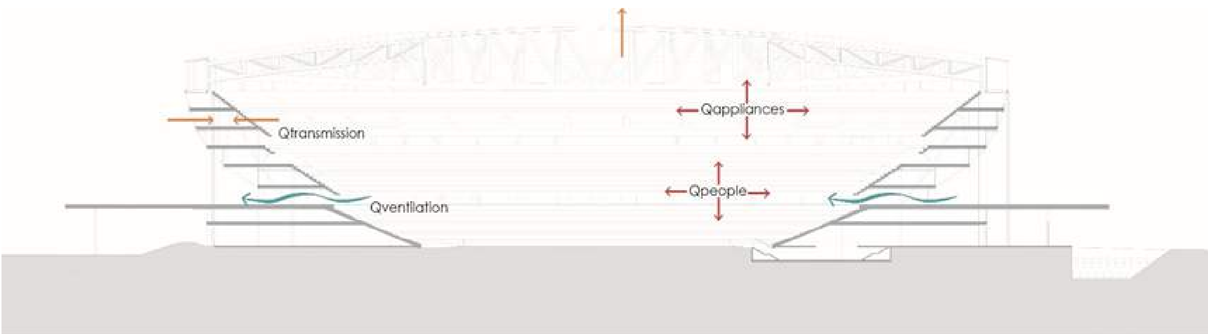


Figure 4.7.4: Concert case - heat gains and losses
OMA, 2018

$$Q_{sun} + Q_{people} + Q_{appliances} = Q_{transmission} + Q_{ventilation}$$

$$Q_{sun} = q \times g \times A_{roof,polycarbonate} + q \times g \times A_{roof,open}\ [W]$$

$$Q_{people} = n.of\ people \times metabolic\ rate\ [W]$$

$$Q_{appliances} = power\ of\ appliances\ [W]$$

$$Q_{transmission} = \sum UA_{facade\ 1} \times (T_e - T_{cs}) + \sum UA_{facade\ 2} \times (T_i - T_{cs}) + \sum UA_{roof} \times (T_i - T_e)\ [W]$$

$$Q_{ventilation} = 0{,}35 \times n \times V \times (T_i - T_e)\ [W]$$

$$T_i = \frac{Q_{sun}+Q_{people}+Q_{appliances}+T_e\times\left(\sum UA_{roof}-\sum UA_{facade\ 1}+0{,}35\times n\times V\right)+T_{cs}\times\left(\sum UA_{facade\ 1}+\sum UA_{facade\ 2}\right)}{\sum UA_{facade\ 2}+\sum UA_{roof}+0{,}35\times n\times V}\ [°C]$$

Formula 4.7.5: Heat balance for closed stadium

Q_{tr} (FACADE 1) [W]	24.083.044	*(T_e-T_{cs})
Q_{tr} (FACADE 2) [W]	918.652	*(T_i-T_{cs})
Q_{tr} (ROOF) [W]	547036	*(T_i-T_e)
Q_v [W]	4766374.431	*(T_i-T_e)
Q_{sun} summer [W]	28679360	
Q_{sun} winter [W]	4301904	
Q_{ppl} max [w]	5859000	
Q_{ppl} min [w]	46500	
Q_{app} max [w]	10000	
Q_{app} min [w]	0	

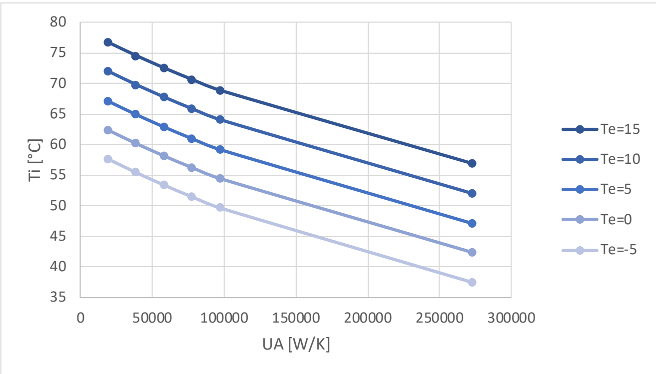
Table 4.7.16: Heat gains and losses

In the winter scenario, the outcomes considered for the study of indoor temperature are those for outdoor temperature between 15 and -5, while for summer those for outdoor temperature between 20 and 38. The temperature of conditioned spaces is assumed to be 20 °C.
From the outcomes, graphs are drawn. On x-coordinate, the chosen parameter values are inserted, while on the y-coordinates indoor temperatures resulting from calculations are selected. The lines show the variation of indoor temperature with varying parameter for different outdoor temperatures.

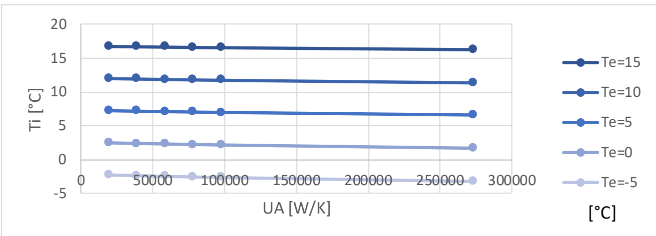
4.7.2.1 ∑UA roof

In this case, the first analyzed parameter is the thermal transmittance multiplied by the surface of the roof. Now, as the roof is closed and transmission losses occur, its effect on indoor temperature is considered.
Tables 4.7.17 and 4.7.18 and graphs 4.7.15 and 4.7.16 show the trend for indoor temperature in winter.

Te [°C]		∑Uf1Af1	19537	39074	58611	78148	97685	273518
	38	**Ti**	98.6	96.4	94.4	92.6	90.8	79.1
	35	*max ppl*	95.7	93.6	91.6	89.7	88.0	76.2
	30	*max app*	90.9	88.8	86.8	84.9	83.2	71.3
	25		86.2	84.0	82.0	80.1	78.4	66.5
	20		81.4	79.2	77.2	75.3	73.6	61.7
	15		76.6	74.5	72.5	70.6	68.8	56.8
	10		71.9	69.7	67.7	65.8	64.0	52.0
	5		67.1	64.9	62.9	61.0	59.2	47.1
	0		62.4	60.2	58.1	56.2	54.4	42.3
	-5		57.6	55.4	53.3	51.4	49.6	37.5



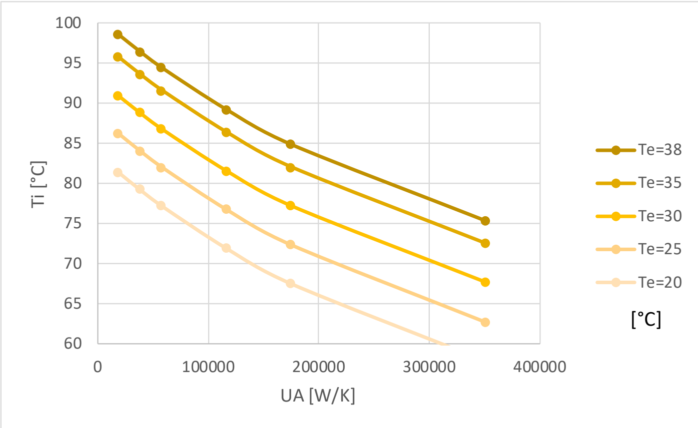
Te [°C]		∑Uf1Af1	19537	39074	58611	78148	97685	273518
	38	**Ti**	38.7	38.7	38.7	38.6	38.6	38.5
	35	*min ppl*	35.9	35.8	35.8	35.8	35.7	35.6
	30	*min app*	31.1	31.0	31.0	31.0	30.9	30.7
	25		26.3	26.3	26.2	26.2	26.2	25.9
	20		21.6	21.5	21.5	21.4	21.4	21.1
	15		16.8	16.7	16.7	16.6	16.6	16.2
	10		12.0	12.0	11.9	11.8	11.8	11.4
	5		7.3	7.2	7.1	7.1	7.0	6.5
	0		2.5	2.4	2.3	2.3	2.2	1.7
	-5		-2.3	-2.3	-2.4	-2.5	-2.6	-3.1



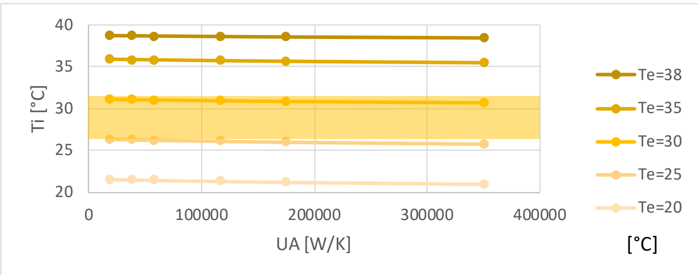
Tables 4.7.17 and 4.7.18: Winter case with thermal transmittance x surface as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.15 and 4.7.16: Variation in indoor temperature at varying thermal transmittance x surface value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

It is possible to observe that an increasing value leads to a very small decrease in indoor temperature. Therefore, it is possible to say that the effect of the thermal transmittance of the roof on the indoor temperature is limited in winter. The indoor temperature in winter exceeds the required 20-25,5 °C for most of the cases with maximum number of people and appliances, whereas in case of minimum number of people and appliances the indoor temperature is quite low.
Tables 4.7.19 and 4.7.20 and graphs 4.7.17 and 4.7.18 show the trend in summer.

Te [°C]	∑Uf1Af1	19537	39074	58611	78148	97685	273518
38	**Ti**	98.6	96.4	94.4	92.6	90.8	79.1
35	*max ppl*	98.1	93.6	91.6	89.7	88.0	76.2
30	*max app*	93.3	88.8	86.8	84.9	83.2	71.3
25		88.5	84.0	82.0	80.1	78.4	66.5
20		83.7	79.2	77.2	75.3	73.6	61.7
15		78.9	74.5	72.5	70.6	68.8	56.8
10		74.1	69.7	67.7	65.8	64.0	52.0
5		69.3	64.9	62.9	61.0	59.2	47.1
0		64.5	60.2	58.1	56.2	54.4	42.3
-5		59.7	55.4	53.3	51.4	49.6	37.5



Te [°C]	∑Uf1Af1	19537	39074	58611	78148	97685	273518
38	**Ti**	38.7	38.7	38.7	38.6	38.6	38.5
35	*min ppl*	35.9	35.8	35.8	35.8	35.7	35.6
30	*min app*	31.1	31.0	31.0	31.0	30.9	30.7
25		26.3	26.3	26.2	26.2	26.2	25.9
20		21.6	21.5	21.5	21.4	21.4	21.1
15		16.8	16.7	16.7	16.6	16.6	16.2
10		12.0	12.0	11.9	11.8	11.8	11.4
5		7.3	7.2	7.1	7.1	7.0	6.5
0		2.5	2.4	2.3	2.3	2.2	1.7
-5		-2.3	-2.3	-2.4	-2.5	-2.6	-3.1



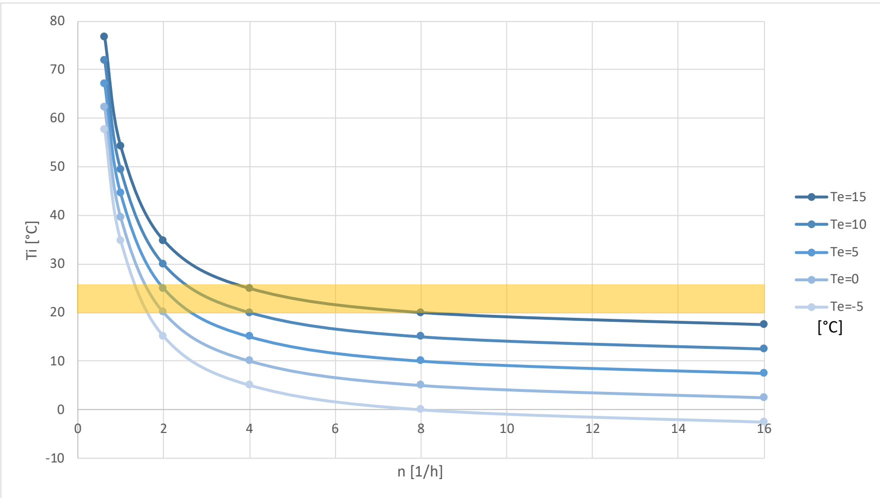
Tables 4.7.19 and 4.7.20: Winter case with thermal transmittance x surface as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.17 and 4.7.18: Variation in indoor temperature at varying thermal transmittance x surface value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

In summer, when maximum number of people and appliances is considered, indoor temperature decreases at increasing parameter. However, the variation in temperature is not very high. In the case of minimum number of people and appliances, instead, the indoor temperature remains constant. Looking at the results, it can be concluded that this parameter does not affect much the indoor temperature of the stadium, therefore, as in the case of the façade, it would be better to change the roof materials with those who can either provide spectators with shading, or that can bring benefits to the outdoor environment (eg. a cool roof).

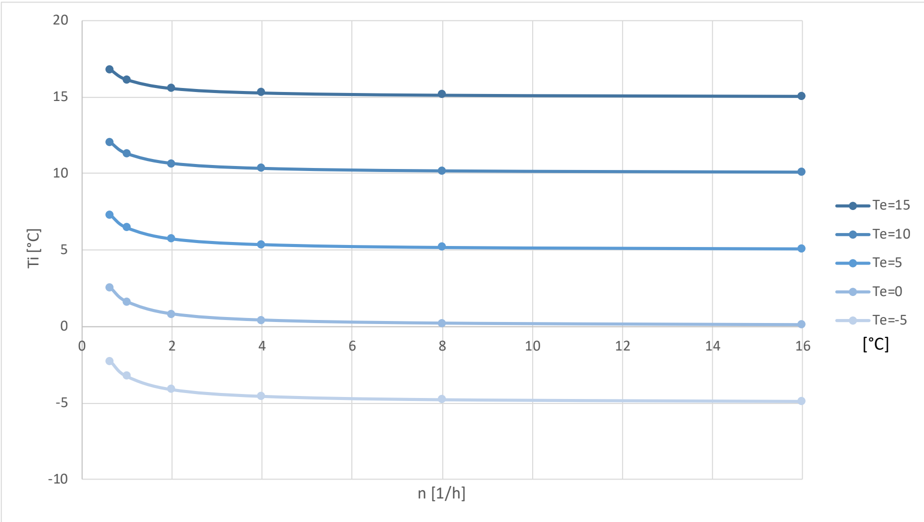
4.7.2.2 Air change rate

The other important parameter to consider is the air change rate. As in the football match case, the calculated air change rate is 0,627/h, which will be the basic value for calculations, where it increases up to 16/h.
Tables 4.7.21 and 4.7.22 and graphs 4.7.19 and 4.7.20 show the trend for indoor temperature at varying ACH in winter.

Te [°C]	n	0.627	1	2	4	8	16
38	**Ti**	98.6	76.5	57.5	47.8	42.9	40.5
35	*max ppl*	95.7	73.6	54.5	44.8	39.9	37.5
30	*max app*	90.9	68.8	49.6	39.9	34.9	32.5
25		86.2	63.9	44.7	34.9	30.0	27.5
20		81.4	59.1	39.8	29.9	25.0	22.5
15		76.6	54.2	34.8	25.0	20.0	17.5
10		71.9	49.4	29.9	20.0	15.0	12.5
5		67.1	44.5	25.0	15.1	10.0	7.5
0		62.4	39.7	20.1	10.1	5.1	2.5
-5		57.6	34.8	15.2	5.1	0.1	-2.5



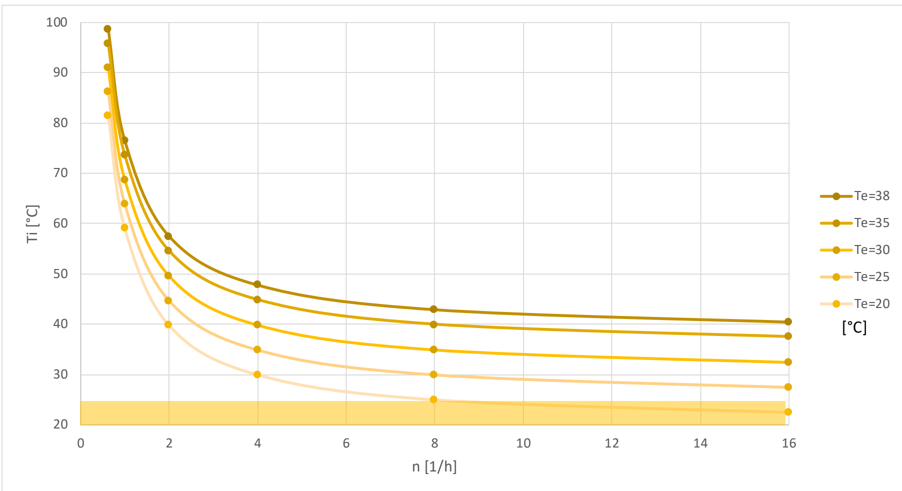
Te [°C]	n	0.627	1	2	4	8	16
38	**Ti**	38.7	38.5	38.2	38.1	38.1	38.0
35	*min ppl*	35.9	35.5	35.3	35.1	35.1	35.0
30	*min app*	31.1	30.7	30.4	30.2	30.1	30.0
25		26.3	25.8	25.4	25.2	25.1	25.1
20		21.6	21.0	20.5	20.3	20.1	20.1
15		16.8	16.1	15.6	15.3	15.1	15.1
10		12.0	11.3	10.7	10.3	10.2	10.1
5		7.3	6.4	5.7	5.4	5.2	5.1
0		2.5	1.6	0.8	0.4	0.2	0.1
-5		-2.3	-3.3	-4.1	-4.6	-4.8	-4.9



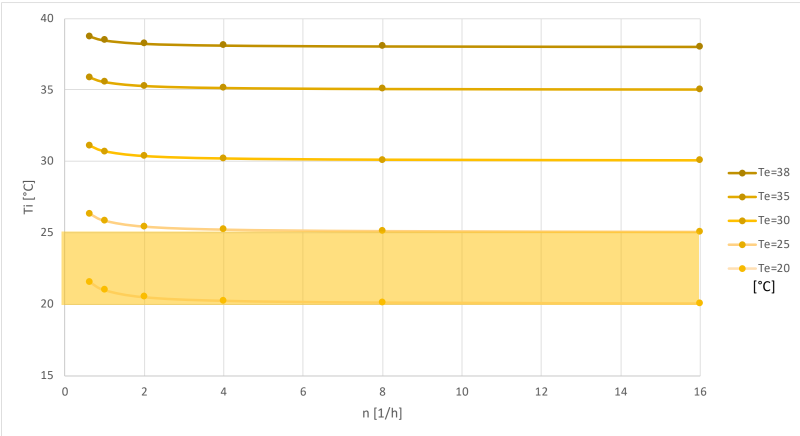
Tables 4.7.21 and 4.7.22: Winter case with air change rate as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.19 and 4.7.20: Variation in indoor temperature at varying air change rate value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

In winter, the effect of the air change rate on the indoor temperature is not so high, as it can be seen from the tables and the graphs.
Tables 4.7.23 and 4.7.24 and graphs 4.7.21 and 4.7.22 show the trend for indoor temperature at varying ACH in summer.

Te [°C]	**n**	0.627	1	2	4	8	16
38	**Ti**	98.6	76.5	57.5	47.8	42.9	40.5
35	*max ppl*	95.7	73.6	54.5	44.8	39.9	37.5
30	*max app*	90.9	68.8	49.6	39.9	34.9	32.5
25		86.2	63.9	44.7	34.9	30.0	27.5
20		81.4	59.1	39.8	29.9	25.0	22.5
15		76.6	54.2	34.8	25.0	20.0	17.5
10		71.9	49.4	29.9	20.0	15.0	12.5
5		67.1	44.5	25.0	15.1	10.0	7.5
0		62.4	39.7	20.1	10.1	5.1	2.5
-5		57.6	34.8	15.2	5.1	0.1	-2.5



Te [°C]	n	0.627	1	2	4	8	16
38	Ti	38.7	38.5	38.2	38.1	38.1	38.0
35	*min ppl*	35.9	35.5	35.3	35.1	35.1	35.0
30	*min app*	31.1	30.7	30.4	30.2	30.1	30.0
25		26.3	25.8	25.4	25.2	25.1	25.1
20		21.6	21.0	20.5	20.3	20.1	20.1
15		16.8	16.1	15.6	15.3	15.1	15.1
10		12.0	11.3	10.7	10.3	10.2	10.1
5		7.3	6.4	5.7	5.4	5.2	5.1
0		2.5	1.6	0.8	0.4	0.2	0.1
-5		-2.3	-3.3	-4.1	-4.6	-4.8	-4.9



Tables 4.7.23 and 4.7.24: Summer case with air change rate as parameter – maximum people/maximum appliances and minimum people/minimum appliances
Graphs 4.7.21 and 4.7.22: Variation in indoor temperature at varying air change rate value for different outdoor temperatures – maximum people/maximum appliances and minimum people/minimum appliances

In summer, the effect of air change rate on indoor temperature is high for maximum number of people and appliances, whereas is almost null for minimum number of people and appliances. In the first case, moving from a value of 0,627/h to a value of 128/h leads to a ΔT of almost 40 °C. However, the temperature inside the stadium exceeds the required 20-25,5 °C for most of the cases, especially if maximum number of people and appliances are considered. In the second case, the indoor temperature follows the outdoor temperature variation.
Also in the concert scenario, ventilation plays an important role in determining optimal thermal comfort conditions for users.

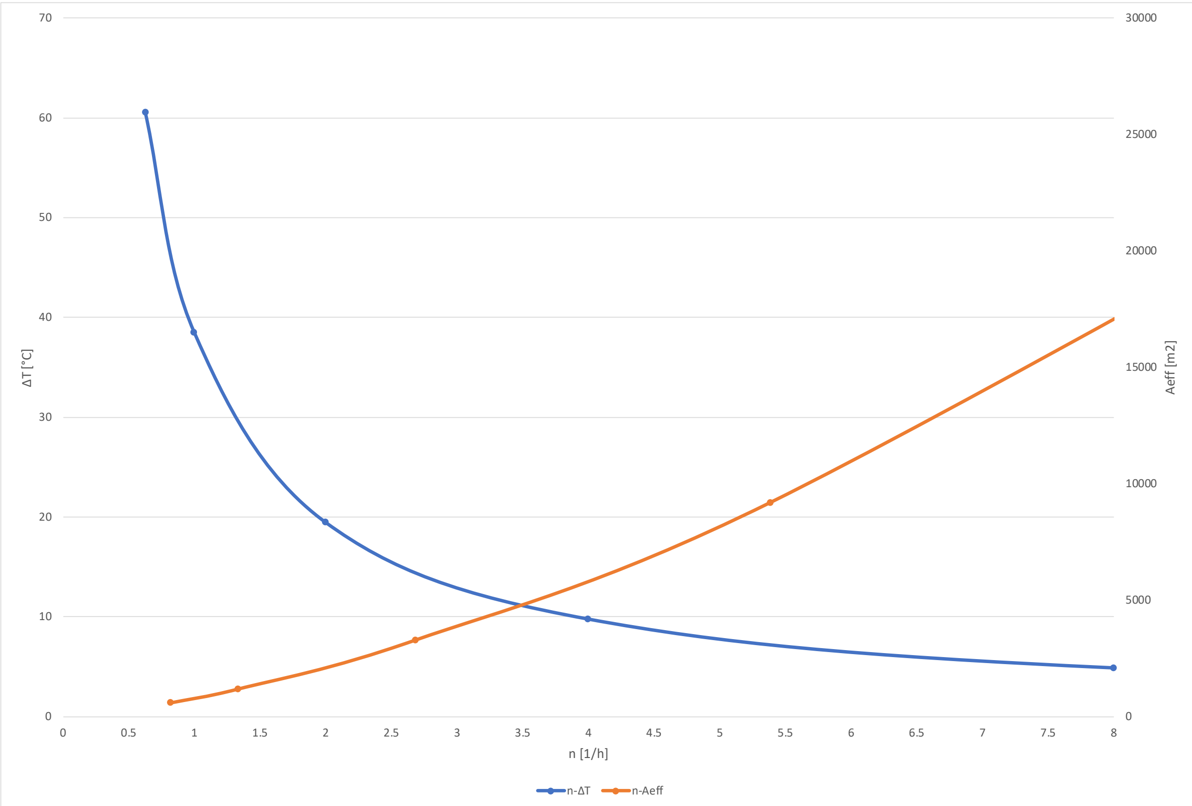
4.7.2.3 Calculated vs Optimal ACH

In the case of air change rate, further calculations have been performed also for the concert case. However, in this scenario, the roof is closed and air can enter only through the façade. Therefore, ventilation through an orifice is considered.
Formula used for calculations follow:

$$Q_v = C_d \times A_{eff} \times \sqrt{g \times h \times \frac{\Delta T}{T_i}} \left[\frac{m^3}{s}\right] \qquad Q_v = \frac{63600 \times n}{V} \left[\frac{m^3}{s}\right]$$

Formula 4.7.6: Amount of ventilation - one opening
Formula 4.7.7: Flow rate

The two formula have been combined and formula X has been substituted in formula X. In order to verify the actual ACH that it is possible to provide to the volume of the stadium, all values have been set except for the effective area. Cd is assumed to be 0,6, g is known as it is gravity, H is considered as the height of the main entrance level, and Ti and ΔT come from the calculations.
Calculations have been performed for all values of ACH, from 0,627/h to 128/h. Outcomes show that with the available area it only possible to have ACH up to 8/h.
The following graph shows the optimal air change rate obtained by the intersection of the line showing the ΔT variation at varying ACH, with the line showing the variation of ACH at varying effective area. By zooming in it can be observed that the optimal ACH value is around 3,4.

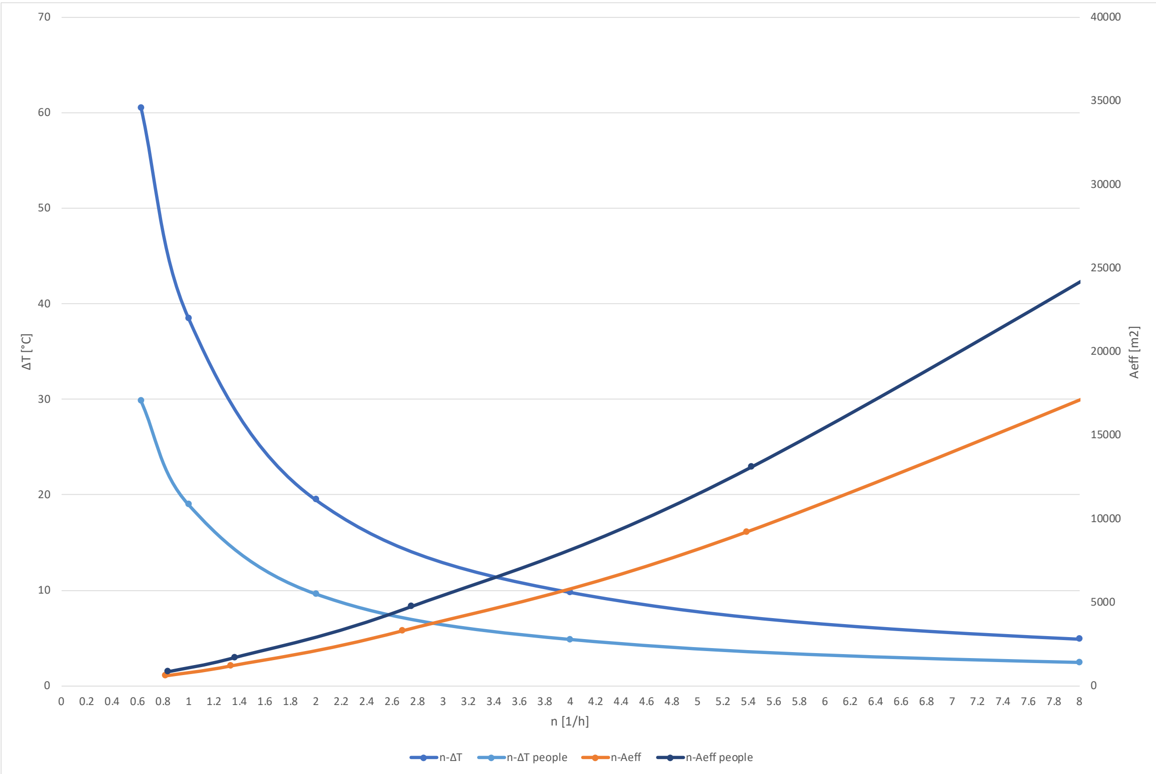


Graphs 4.7.23: Optimal ACH

This ACH optimal value has then been substituted into all the previous calculations having U-value of the roof as parameter to see the influence of ventilation on indoor temperature in that case. Results show that by increasing ACH from 0,627/h to 3,4/h, indoor temperatures drop, as in the case of a football match. It is therefore possible to affirm that ventilation plays a key role on the indoor temperature of the stadium.

Further steps in calculations involved to play with those parameters influencing ACH. Therefore people and appliances heat gains values have been halved one by one to see the effect on possible optimal values of ACH.

The graph below show all the possible matching point between the lines showing the ΔT variation at varying ACH, with the lines showing the variation of ACH at varying effective area. It can be observed that the effect of other parameters on th optimal ACH is limited.
By halving people heat gains, optimal ACH is 3,4;
By halving appliances heat gains, optimal ACH is 2,5.



Graphs 4.7.24: Optimal ACH

Also in the case of a concert, therefore, the parameter affecting the most the indoor temperature, thus the comfort of users, is the air change rate, which defines the ventilation within the stadium boundaries.

4.8 PASSIVE COOLING

Passive cooling refers to measures such as natural ventilation, solar shading, orientation of the building, thermal mass, PCMs or ground. The effects of natural ventilation and sun on the indoor temperature of the stadium have been studied in the previous section, with the former being the parameter affecting the temperature the most, whereas the latter does not have much influence. Passive measures such as orientation of the building, or of the openings, will be analyzed in the next step by means of digital modeling. The effect of thermal

mass, PCM or ground in terms of cooling is shown in this section.
First of all, the cooling demand is defined by using the heat balance equation as follows. This helps estimate the amount of cooling needed by the stadium throughout the seasons.

$$Q_{sun} + Q_{people} + Q_{appliances} - Q_{cooling} = Q_{transmission} + Q_{ventilation}$$

Graphs 4.8.1: Heat balance equation with cooling

Once the cooling demand is defined both for the open and closed configuration, the effect of passive measures on this is calculated to see which could be the most effective in the reduction of cooling loads.

4.8.1 Thermal mass

The presence of thermal mass in the Feyenoord stadium is quite evident. Most of the structure of the building is made of insulated concrete. In order to understand the effect of the thermal mass on the indoor temperature of the semi-outdoor area of the stadium, the internal façade, namely the seating area, is considered. This is, indeed, made of concrete and it is in direct contact with the indoor spaces.
Based on the assumption that the temperature of the thermal mass follows the ambient temperature, calculations are performed. The thermal mass temperature is considered as the average between the highest and lowest temperature. In this case the ambient temperature will be the calculated indoor temperature, and the thermal mass will absorb the solar radiation entering from the roof.
The thermal mass is likely to exchange heat with the indoor air by convection, therefore the cooler concrete will cool down the space.

$$Q_{thermal\ mass} = h \times A \times \left(T_{i,stadium} - T_{thermal\ mass}\right)[W]$$

Table 4.8.2: Thermal mass cooling effect by convection

Where he is the external liminar coefficient (14 W/m2K), A is the concrete surface exposed to the indoor space (26308 m2) and ΔT is the difference of temperature between the indoor calculated temperature and the temperature of the thermal mass. With this calculation it would be possible to estimate how much cooling comes from the thermal mass.
For all the previous parameters calculations the effect of thermal mass in introduced to verify its effects on the indoor temperature, by adding this element to the heat balance equation.

$$Q_{sun} + Q_{people} + Q_{appliances} + Q_{thermal\ mass} = Q_{transmission} + Q_{ventilation}$$

Table 4.8.3: Thermal mass effect on indoor temperature. Football match case – summer – max gains - ACH parameter

Example of calculations in excel is shown in the following tables.

T_e [°C]		n	0.627	1	2	4	8	16
	38	**Ti**	113.1	85.1	61.6	49.8	43.9	40.9
	35	*max ppl*	110.3	82.2	58.6	46.8	40.9	38.0
	30	*max app*	105.5	77.4	53.7	41.9	35.9	33.0
	25	summer	100.8	72.5	48.8	36.9	30.9	28.0
	20		96.0	67.7	43.9	31.9	26.0	23.0
	15		91.3	62.8	38.9	27.0	21.0	18.0
	10		86.5	58.0	34.0	22.0	16.0	13.0
	5		81.7	53.2	29.1	17.0	11.0	8.0
	0		77.0	48.3	24.2	12.1	6.0	3.0
	-5		72.2	43.5	19.2	7.1	1.1	-2.0

THERMAL MASS

max ppl *max app* summer

he	14	W/m2K
A	26308	m2

Ttm	102.19	73.99	50.26	38.38	32.44	29.47
[°C]	100.76	72.54	48.78	36.89	30.95	27.97
	98.39	70.11	46.32	34.41	28.46	25.48
	96.01	67.69	43.86	31.93	25.97	22.98
	93.63	65.27	41.40	29.45	23.48	20.49
ΔT	10.93	11.14	11.32	11.41	11.46	11.48
[°C]	9.51	9.69	9.85	9.92	9.96	9.98
	7.13	7.27	7.38	7.44	7.47	7.49
	4.75	4.85	4.92	4.96	4.98	4.99
	2.38	2.42	2.46	2.48	2.49	2.50
Qtm	4026943.75	4104681.15	4170098.01	4202833.86	4219208.64	4227397.75
[W]	3501690.21	3569287.96	3626172.19	3654638.14	3668877.08	3675998.04
	2626267.66	2676965.97	2719629.14	2740978.60	2751657.81	2756998.53
	1750845.11	1784643.98	1813086.09	1827319.07	1834438.54	1837999.02
	875422.55	892321.99	906543.05	913659.53	917219.27	918999.51
Ti	105.3	80.1	59.0	48.5	43.3	40.6
[°C]	103.5	77.9	56.4	45.7	40.4	37.7
	100.4	74.1	52.0	41.0	35.5	32.8
	97.4	70.4	47.7	36.3	30.7	27.8
	94.3	66.6	43.3	31.7	25.8	22.9
ΔT	7.8	5.0	2.5	1.3	0.6	0.3
Ti-Ti,tm	6.8	4.3	2.2	1.1	0.6	0.3
[°C]	5.1	3.3	1.7	0.8	0.4	0.2
	3.4	2.2	1.1	0.6	0.3	0.1
	1.7	1.1	0.6	0.3	0.1	0.1

Table 4.8.1: Thermal mass effect on indoor temperature. Football match case – summer – max gains - ACH parameter

First of all, the temperature of the thermal mass is defined as average between maximum and minimum temperature. Then the ΔT between the previously calculated indoor temperature and the concrete temperature is calculated. From that, it is possible to calculate also the cooling power of the thermal mass, which allows for re-defining the indoor temperature with its effect. Last, the temperature difference between the previously calculated indoor temperature and the one considering thermal mass is found. It can be observed that this difference varies with varying parameter (in this case ACH) but it can reach up to almost 8 °C.
In terms of cooling demand reduction, the effect of the thermal mass alone is quite small, however, if combined with the optimal ACH, the effect changes.

4.8.2 Phase change materials (PCMs)

PCMs could be integrated in the concourses' ceilings, as these spaces are open to the semi-outdoor area of the stadium. Indeed, this configuration would allow for ventilation through those spaces as well, therefore, to activate the PCMs. By assuming that PCMs would lower the temperature of the air entering the stadium by 3 °C, calculations are re-performed. Results show that by integrating PCMs and have them properly work, indoor temperature can be lowered by 2-3 °C. An example is shown in table 4.8.2, which shows the comparison between indoor temperature calculated with and without PCMs integration.

PREVIOUSLY CALCULATED

98.6	76.5	57.5	47.8	42.9
95.7	73.6	54.5	44.8	39.9
90.9	68.8	49.6	39.9	34.9
86.2	63.9	44.7	34.9	30.0
81.4	59.1	39.8	29.9	25.0

n	0.627	1	2	4	8
Ti	95.7	73.6	54.5	54.5	39.9
max ppl	92.8	70.7	51.6	51.6	36.9
max app	88.0	65.8	46.7	46.7	32.0
summer	83.3	61.0	41.7	41.7	27.0
	78.5	56.1	36.8	36.8	22.0

Table 4.8.2: PCMs effect on indoor temperature. On the right, the indoor temperature is calculated with PCMs integration, whereas on the left without - Concert case

4.8.3 Ground

As the field is in direct contact with the ground and this is usually around 12-15 °C throughout the year, some cooling for convection is expected to happen near the field. The effect of the ground temperature on the indoor temperature is calculated in the same way as the thermal mass. The result, however, is less satisfactory probably due to the smaller surface that is considered. In addition to that, calculations results show that the effect is higher for lower ACH, whereas for higher ACH the variation in indoor temperature gets to zero.
In terms on cooling demand reduction, ground effect is not particularly significant.

4.8.4 Evaporative cooling from the field

Although evaporative cooling could bring some benefits, the surface of the field is too small compared to the volume that needs cooling. Next to it, this would allow for some cooling of air only in the area of the field itself, thus not affecting the comfort of spectators.

4.9 EFFECTIVENESS OF MEASURES

Before getting to the exploration and design of active systems, calculations are performed to check how much the aforementioned passive measures

could help reduce the cooling demand of the stadium both in the football and concert scenario. Indoor temperature was set at 23 °C, which is the average in the range of 20/25°C required by FIFA.
First, the heat balance equation for both cases was defined, as follows.

$$Q_{sun} + Q_{people} + Q_{appliances} - Q_{cooling} = Q_{transmission} + Q_{ventilation}$$

Table 4.9.1: Thermal mass effect on indoor temperature. Football match case – summer – max gains - ACH parameter

Then, the amount of hours per year that the stadium is occupied for each activity is determined, and data are shown in the table 4.9.1.
Football matches are expected to happen during the day once every 2 weeks and last around 3 hours. The competition season runs from August to May, with the cooling period being mainly in August-October and April-May.
Concerts, instead, are likely to happen at night, once a week, all year long, and last around 3 hours. For cooling demand comparison the case with maximum gains and outdoor temperature was considered to check the extreme scenario.

	TIMES PER YEAR	HOURS	PERIOD
FOOTBALL MATCH	17	3	August-May
CONCERT	26	3	All year

Table 4.9.1:Activities schedule

First, the cooling demand for basic conditions was calculated, then step by step, the previously explained measures for cooling were introduced. In particular, thermal mass, PCMs, ground and optimal ACH. Also, each measure was combined with the optimal ACH to see the effect of ventilation on cooling demand.
The following table show results for cooling demand under different scenarios.

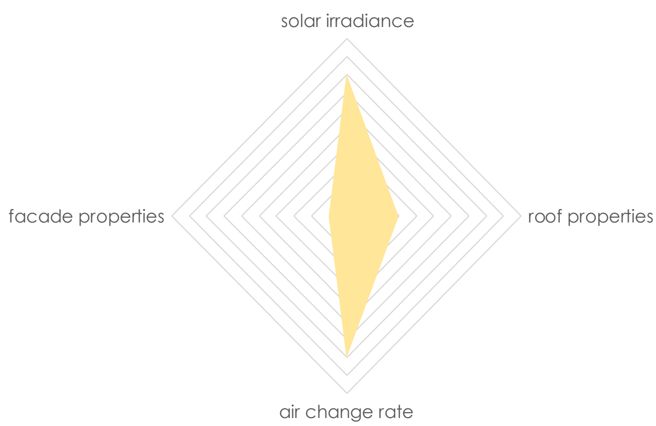
	FOOTBALL MATCH OPEN STADIUM	CONCERT CLOSED STADIUM	FOOTBALL MATCH OPEN STADIUM	CONCERT CLOSED STADIUM	
	Cooling demand		Reduction in cooling demand		
BASIC	51212.9	39961.5	-	-	kWh/an
OPTIMAL ACH	134702.6	75376.5	-83489.6	-35415.0	kWh/an
THERMAL MASS	48557.4	38583.0	2655.6	1378.4	kWh/an
THERMAL MASS + OPTIMAL ACH	132047.0	73998.0	-80834.1	-34036.5	kWh/an
PCM	49667.2	38415.7	1545.8	1545.8	kWh/an
PCM + OPTIMAL ACH	116458.9	66747.7	-65245.9	-26786.2	kWh/an
GROUND	48051.3	37548.0	3161.6	2413.5	kWh/an

Table 4.9.2: Cooling demand comparison among different measures.

It can be observed that thermal mass, PCMs, and ground cause a reduction in cooling demand. However, when ACH changes from the previously calculated 0,627 to the optimal one (7,4 for football and 3,5 for concert), cooling demand increases. This is probably due to the fact that outdoor temperature is too warm. When designing for ventilation it is, therefore important, to take into account outdoor temperature, thus letting the air in only when that is favorable to improve cooling.

4.10 OUTCOMES

Calculations outcomes help proceed with the design. Indeed, looking at the parameters that influence the comfort in the semi-outdoor area of the stadium, proposals can be developed. In particular, it turned out that the parameter having the highest effect on indoor temperature is the air change rate and therefore design for natural ventilation would be a major focus in the next step. Openings size and orientation must be defined, and the design of those should allow for pressure balance control. To do this, indeed, it could be interesting to design to integrate the existing retractable roof with an operable façade.
Another important parameter is the solar irradiance, especially in summer and in case of a football match. Therefore, measures should be implemented in the design to allow for shading, with the focus on the roof, as the external façade is not in direct contact with the semi-outdoor area of the stadium. However, whilst using a less transparent material for the roof would provide more shade, it would also reduce the daylight entering. Finding a balance is necessary.
Looking at the external façade, calculations show that it does not particularly affect the comfort in the semi-outdoor space. Materials of the façade, indeed, can be replaced with those able to mitigate UHI in the immediate surroundings. Another factor to consider when choosing the materials is their environmental impact.



Graph 4.10.1: Parameters effect

Next to the aforementioned parameters, possible cooling strategies have been defined, among which the exploitation of thermal mass and introduction of PCMs.
The Nieuwe Maas would be an important source for cooling and heating but it would b necessary to control the water temperature and storage, not to give too warm water back to the river. This could be solved by storing water in the ground, if combined with the ATES system. ATES would work more efficiently if at district scale, allowing for heat/cold exchange between the stadium and its surroundings.
Last, as calculations and existing CFD analyses show, local cooling measures would help improve the thermal comfort of the spectators.

5 FINAL DESIGN

In this chapter the design proposal for th new Feyenoord stadium is finalized.

In order to verify the conclusions drawn in chapter 4, some simulations are performed. These help support the design choices, as well as define some solutions.

The design proposal is explained, focusing on 4 elements: roof, façade, concourses, and extra measures.

The design is then verified by means of calculations, and compared to the original case study to check if the performance of the stadium has improved.

Last, the whole final design approach is explained step by step in order to give guidelines for future stadia design.

5.1 OBJECTIVE

The goal of the design phase is to propose a set of measures to improve the performance of the new Feyenoord stadium in a future warmer scenario, with the focus on the comfort of users. The analysis and exploration of the parameters affecting the comfort on the semi-outdoor space of the stadium were carried out, with results being showed in the previous chapter. From the outcomes obtained, a design able to deal with Rotterdam climate and, especially, expected future climate, will be defined based on three main steps: understanding of the relation with the surroundings and identification of nearby resources, passive measures design to improve the comfort while reducing the energy demand, systems integration to supply the required energy to the infrastructure.

With such method, the ultimate goal is to create a model in terms of approach to the design. Therefore, the process can be replicated getting to different designs for different climatic conditions.

5.2 POTENTIALS

5.2.1 Context

In order to develop a final design, able to rely as much as possible on passive measures, the context was analyzed.
Potentials were found in the nearby river as a source for heating and cooling in some periods of the year, as well as in the new buildings as they are a source for heat and cold exchange. The whole Feijenoord area will be, indeed, developed, and the Masterplan includes the construction of commercial spaces, facilities, hotels and residential buildings, with the latter being an important source for heat and cold exchange with the stadium.
Residential buildings usually have higher heating than cooling demand. On the other hand, the stadium requires more cooling due to its dimensions and to the internal heat production. This would allow to solve the heating and cooling production at district level, making the system more efficient and financially feasible.
Another element that must be considered in the design, is the urban fabric of the area. The stadium itself is, indeed, kind of isolated. Only a few buildings are planned to be built next to it, thus leaving the area quite free. In this way, the wind coming from South-West can freely flow and reach the stadium at its maximum velocity. Natural ventilation could and should, therefore, be exploited as much as possible in the design.

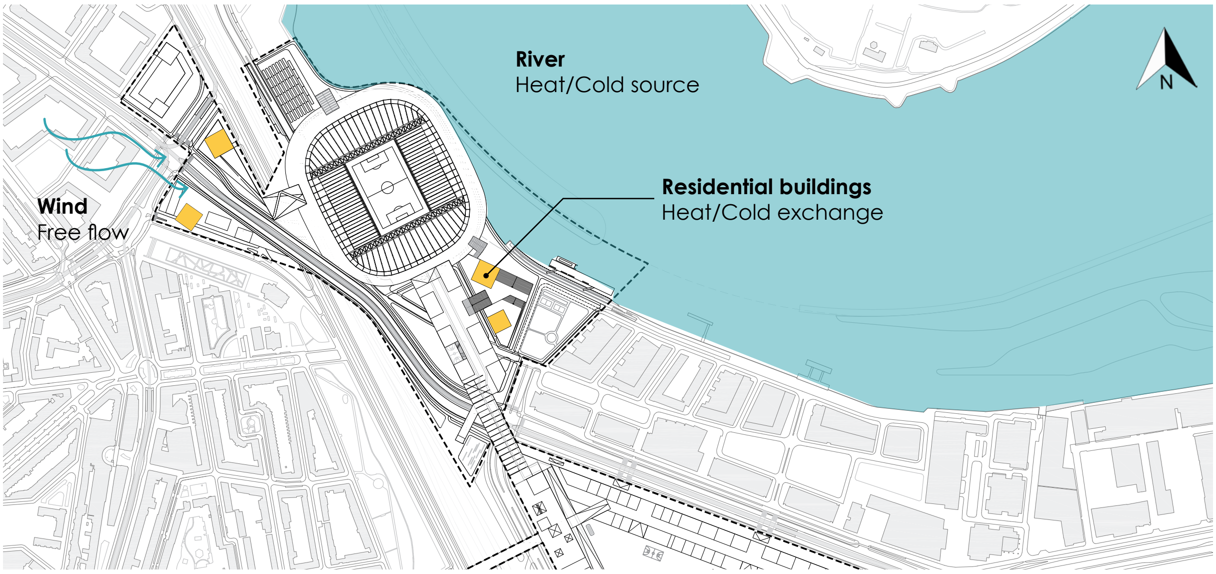


Figure 5.2.1: Feijenoord area's potentials
OMA, 2018.

5.2.2 Building

Being passive measures integration one of the main goals of this research, a more detailed analysis of the stadium itself has to be performed to actually understand how to design new components. In particular, the effect of sun and wind on Feijenoord are studied by means of simple simulations.
In order to run simulations able to give outcomes representative of the behaviour of the stadium in a future warmer scenario, the Energy Plus Weather (EPW) file for the city of Rotterdam was modified. The monthly average temperature was increased by 3 °C.
By doing that the software normalized all hourly temperatures according to the monthly average.

month	current average [°]	new average [°C]
January	4.20	7.20
February	3.70	6.70
March	5.32	8.32
April	8.45	11.45
May	12.73	15.73
June	15.20	18.20
July	16.91	19.91
August	17.14	20.14
September	14.41	17.41
October	16.91	19.91
November	6.49	9.49
December	4.44	7.44

Figure 5.2.2: New EPW file - Monthly average [°C]
Elements, Energy Plus

The modified Weather file was also used in Design Builder, to check the actual variation of weather parameters in the future warmer scenario. From the following figure, it can be observed that the maximum temperature is expected to be 35°C, whereas the minimum temperature would be -3°C.
However, in the summer months, the average temperature is around 20°C, with only a few peaks reaching 35°C.
Wind speed, direction, atmospheric pressure and solar radiation, together with air temperature are shown in figure 5.2.3.

Figure 5.2.3: Site Data with the new weather file
Design Builder

From the Site data given by Design Builder it was also possible to estimate the warmest day of the year, which would be then assumed as worst case scenario for cooling.
This day is the 3rd of August, where maximum temperature almost reaches 35°C and minimum temperature is around 20°C. The following figure shows the comparison between hourly temperature on 3rd of August simulated with the old weather file and with the new weather file where temperatures are increased.

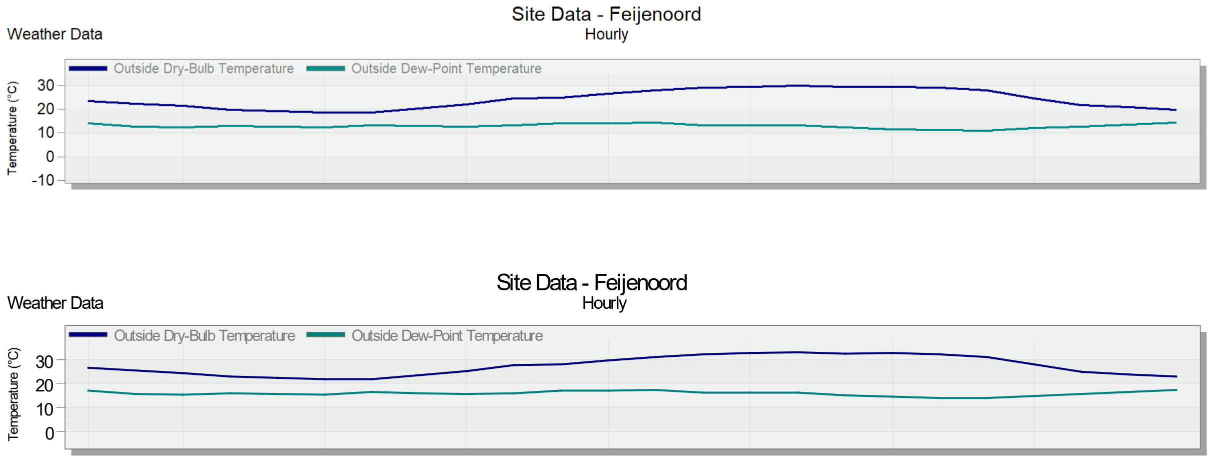
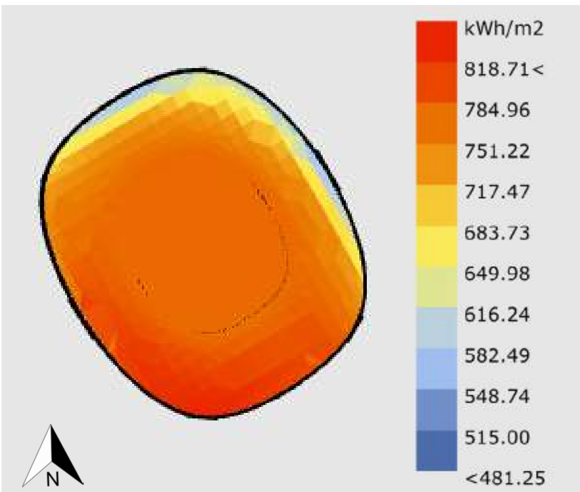


Figure 5.2.4: Comparison of hourly temperatures August 3rd - existing weather file vs new weather file

To study the effect of the solar irradiance on the stadium, the Ladybug plug-in for Grasshopper was used. The script can be found in appendix D. The focus was on the sun hitting the roof, since from the calculations outcomes it resulted that this has high effect on the stadium's indoor temperature in the semi-outdoor area. The effect of solar irradiance on the external façade was neglected as this is in contact with the conditioned spaces, which are not the focus of the research.
The stadium was, therefore, modeled in Rhinoceros with simplified geometries to allow for the simulations to better run.
The building is 30° West-oriented, with no big obstructions around it.
Two main simulations were performed to study the solar irradiance hitting the roof: one for spring/summer(April-September), one for autumn/winter (October-March). Outcomes can be observed in figures 5.2.5 and 5.2.6.



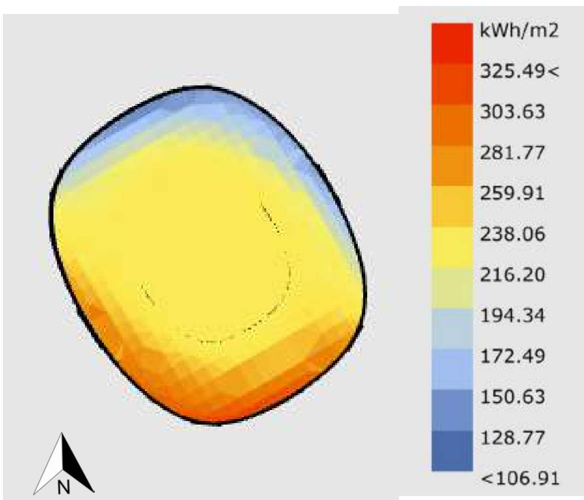


Figure 5.2.5: Solar irradiance on the roof in spring/summer
Figure 5.2.6: Solar irradiance on the roof in autumn/winter

As can been observed in these pictures, solar irradiance is very high on the South-facing side of the roof, decreasing towards the North-facing side.
Next to it, an analysis of the sun-path around the stadium was done always by using Ladybug, and it is shown in figure 5.2.7.
Solar irradiance and sun-path will support the design, especially of the roof.

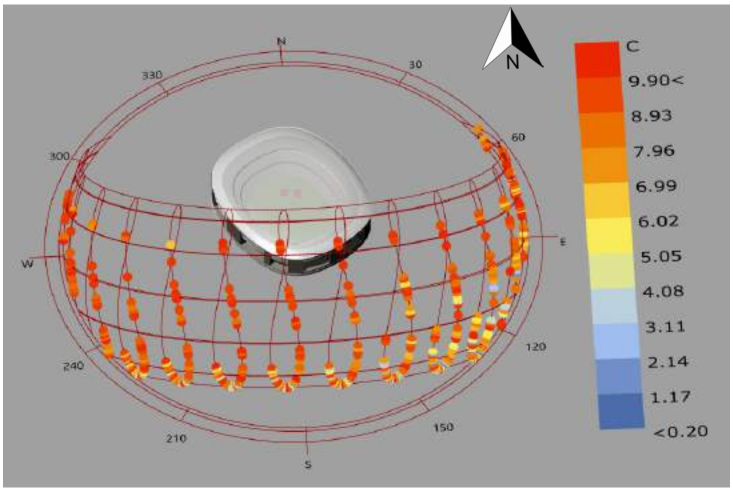


Figure 5.2.7: Yearly sun-path

Butterfly plug-in for Grasshopper was instead used to perform a simple CFD analysis of the stadium. The goal was to understand how the wind behaves when it gets closer to the stadium and when it flows through the open concourses. In the model, the open levels are L02 and L05, which corresponds, indeed, to the concourses. The wind speed was set as 3,8 m/s, which is the average wind speed in Rotterdam, and the building was oriented in such a way that wind was coming from South-West, which is the prevailing wind direction in Rotterdam.
From figure 5.2.9, it can be observed that wind tends to channel into the concourses if they are open, probably due to tunnel effect.

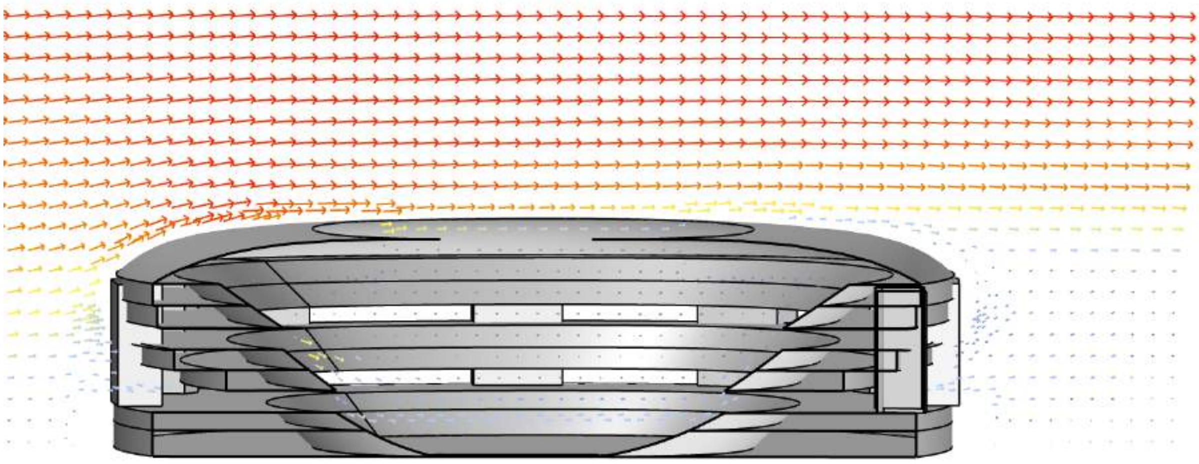


Figure 5.2.8: Cfd simulation with butterfly - overview of the wind flow around the stadium

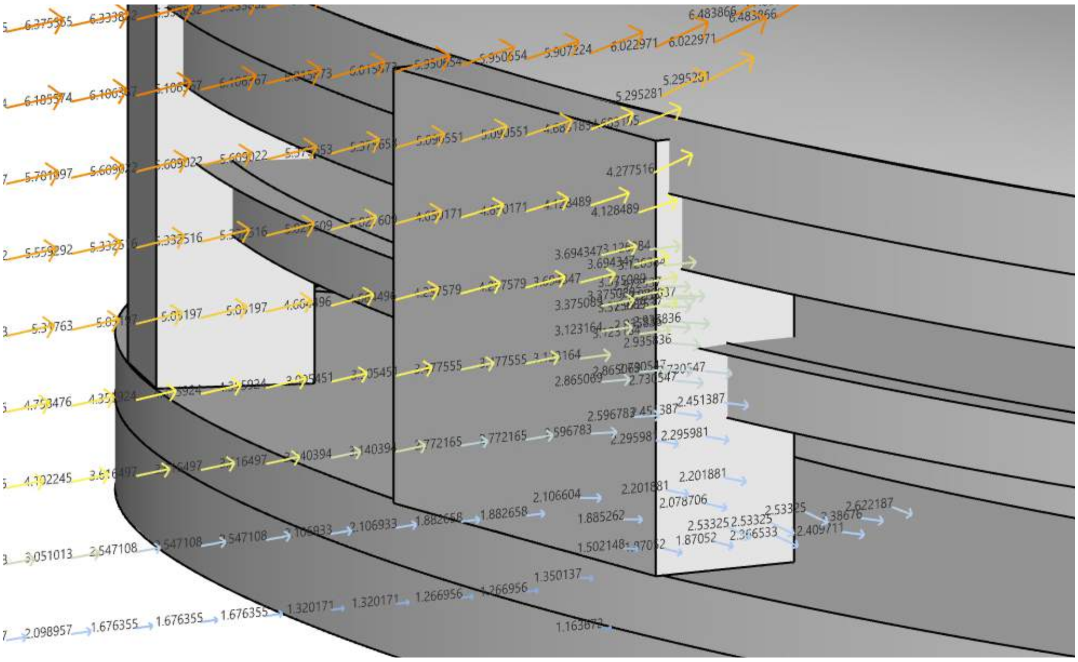


Figure 5.2.9: Cfd simulation with butterfly - outdoor wind flow

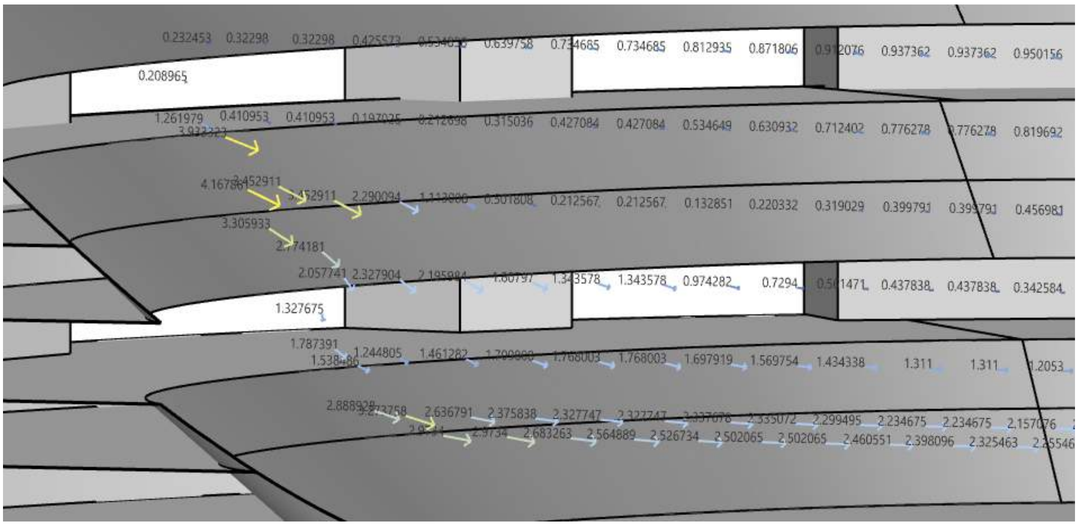


Figure 5.210: Cfd simulation with butterfly - indoor wind flow

Figure 5.2.10, instead, shows that the air velocity increases when it comes out from the concourses. Also, air tends to move downwards, following the curved shape of the tiers.

This simulation shows that ventilation could actually occurs through the concourses if they are design to be openable.

In addition, another simulation was run to check the effect of wind if another level was open, namely the bottom part of the roof structure. Here, the structure is considered to be exposed. Results are shown in the following figures.

Opening a third level helps wind flow to enter the stadium and circulate. Furthermore, it allows for air to reach the upper levels of the tiers.

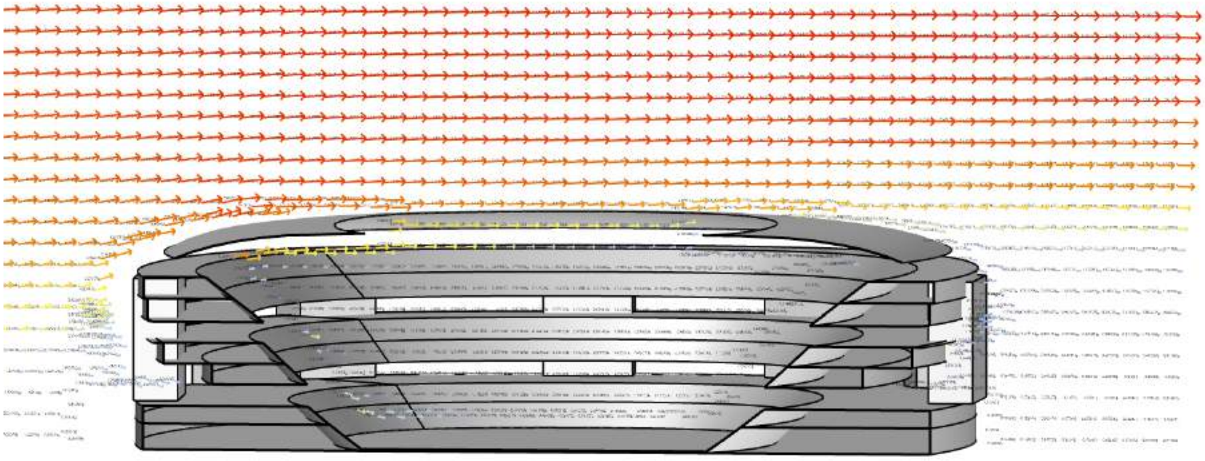


Figure 5.2.11: Cfd simulation with butterfly - overview of the wind flow around the stadium

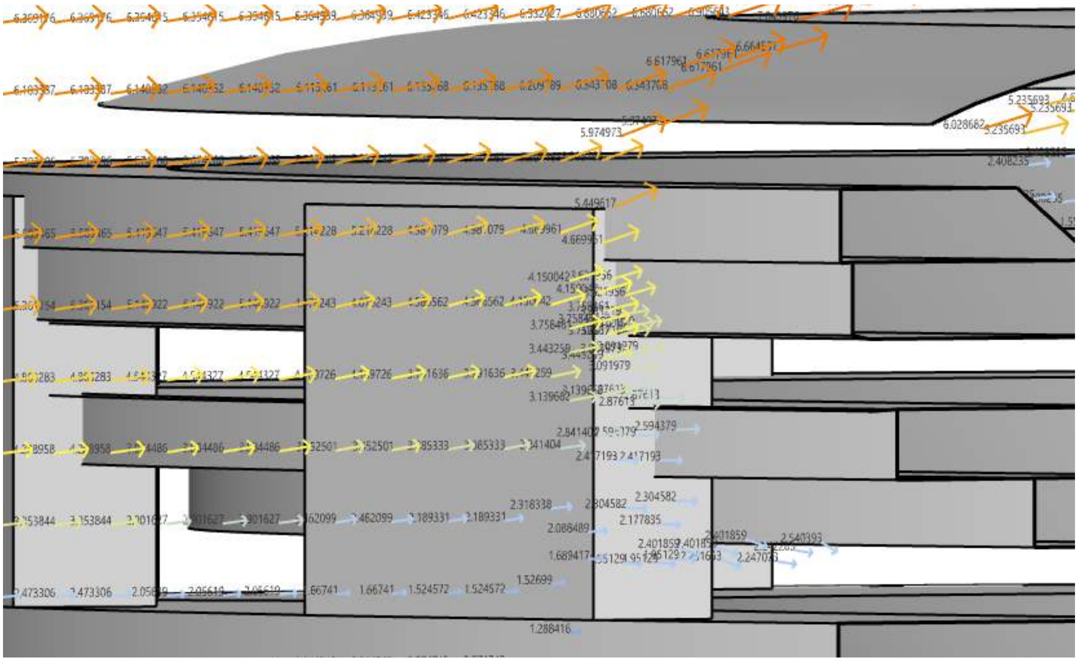


Figure 5.2.12: Cfd simulation with butterfly - outdoor wind flow

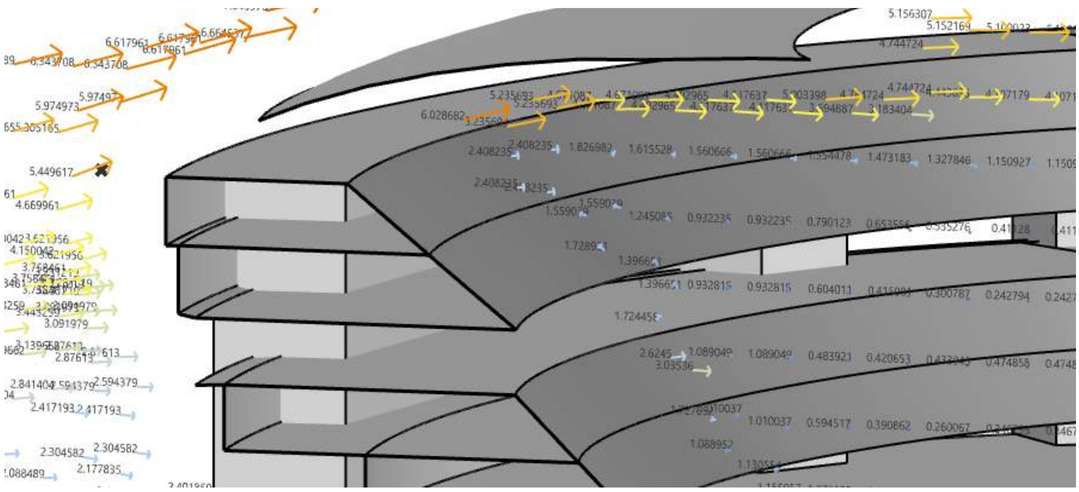


Figure 5.2.13: Cfd simulation with butterfly - indoor wind flow

Other potentials are represented by the building structure: the stadium is made of a large amount of concrete, therefore thermal mass can be exploited.

5.3 CLIMATE CONCEPTS

All these aspects considered, three climate proposals were developed to fully exploit the potentials of the surrounding built environment, as well as of the buildings itself. Proposals also refer to previously explored adaptation and extra measures.
All the concepts aims at exploiting natural ventilation by means of an operable façade and a retractable roof. They also include green either on the façade or in the surroundings, high albedo materials to reduce UHI and take into account the thermal mass.
The first concept, however, focuses on the stadium itself, whereas the second and the third, on the district connections, especially in terms of energy production.

Figure 5.3.1 shows the first concept. Here, electricity is produced by BIPV integrated on the façade, while heating and cooling are provided by the solar collectors placed on the roof. Green is integrated in the lower part of the façade to reduce UHI and purify air at street level.

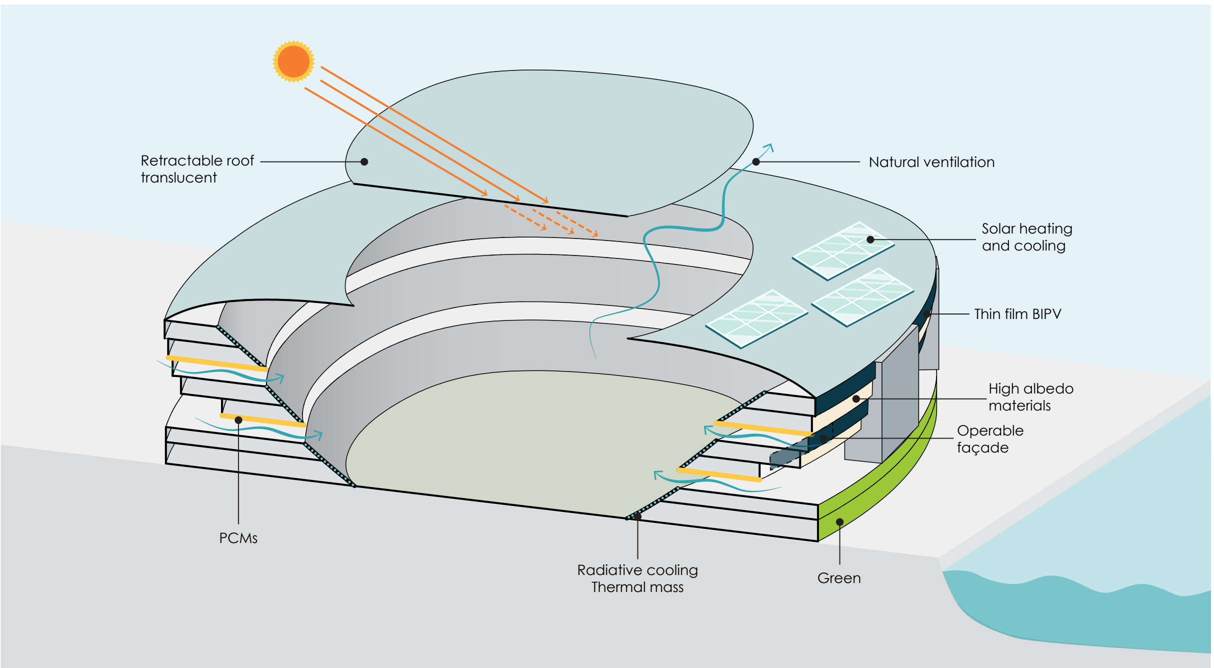


Figure 5.3.1: Climate concept 1

Figure 5.3.2 shows the second concept. In this case, both electricity and heating and cooling production are at district level. Green as well, is located in the immediate surroundings. The roof, which is free, is translucent to allow for daylight to enter.

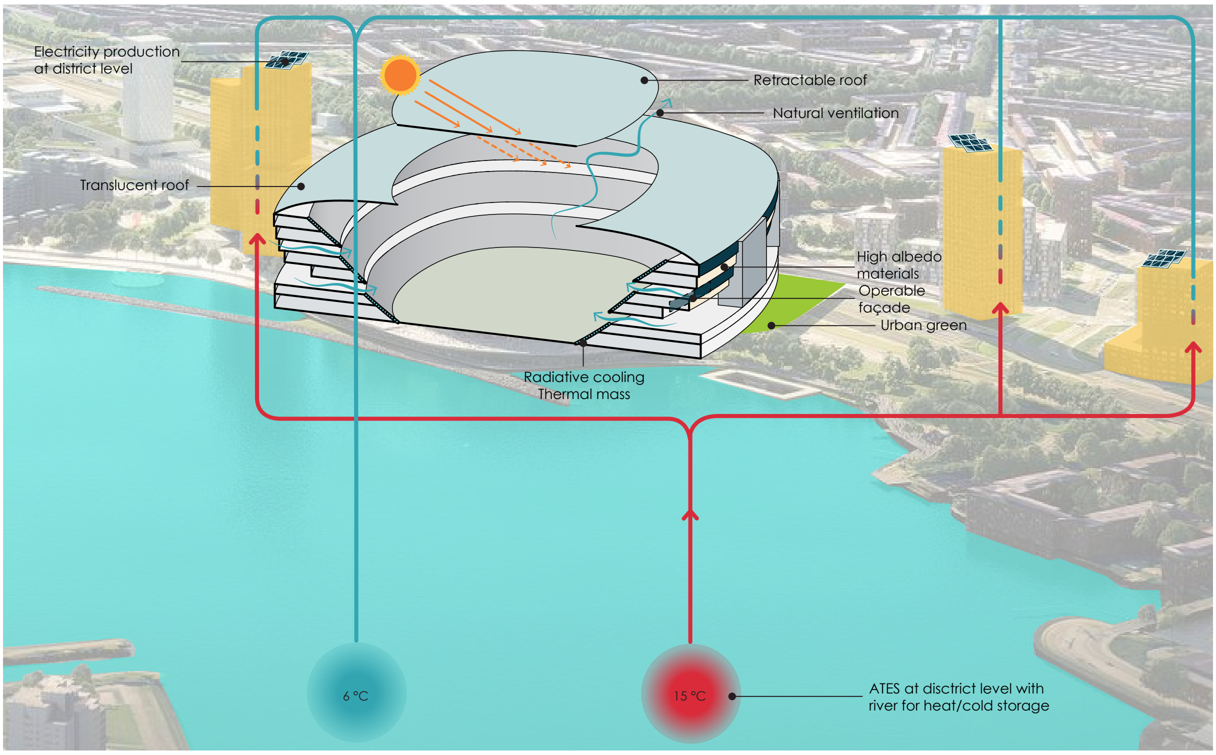


Figure 5.3.2: Climate concept 2

Figure 5.3.3 shows the third concept. This one, like the second one, focuses on the district level, with the main difference being that the PVs are placed on the stadium roof, thus not having a translucent roof.

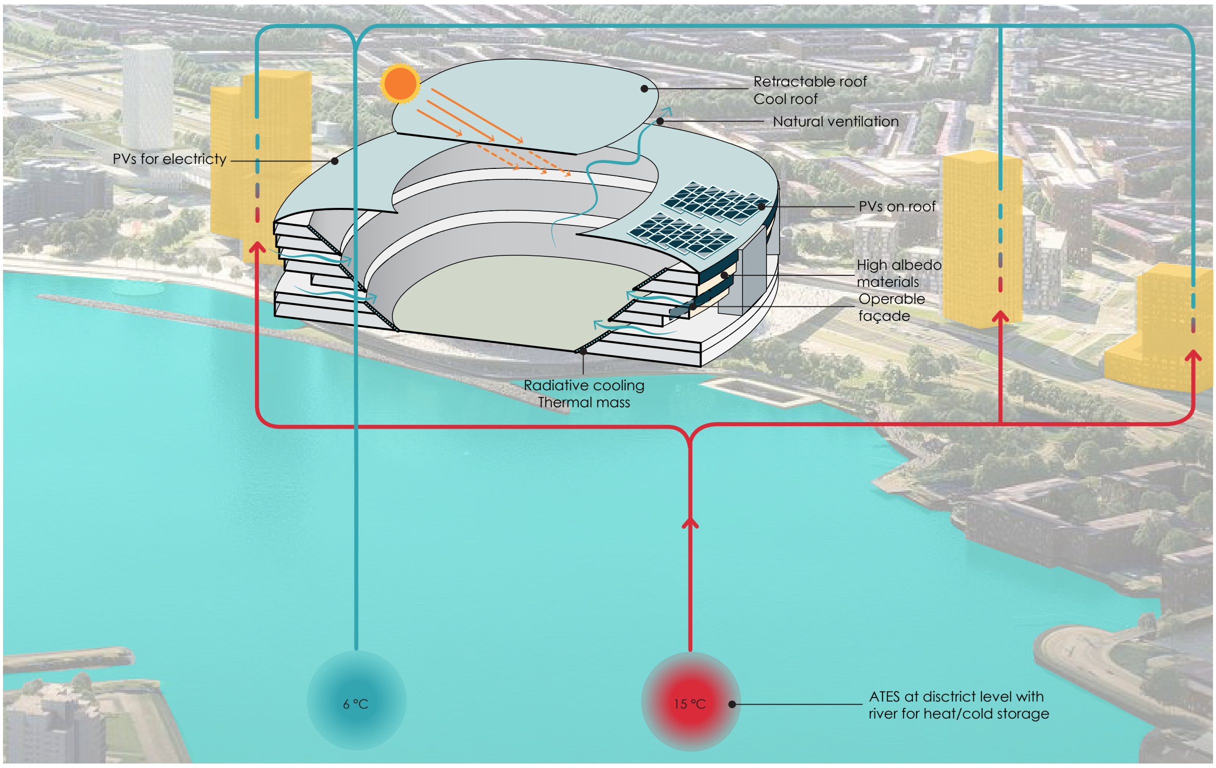


Figure 5.3.3: Climate concept 3

5.4 CLIMATE ADAPTATION CONCEPT

Calculations performed in chapter 4 and more detailed simulations introduced in the previous section of this chapter, support the final design decisions. In section 5.3 “Climate concepts”, three proposals were shown, having common elements as well as unique ones. The final concept aims at combining those that could result being the most efficient within the given context.

All the calculations and simulations outcomes considered, the design focuses on the envelope of the stadium and the concourses to improve the indoor thermal comfort by introducing passive solutions. In particular, the roof design focuses on the provision of shading and daylight, but it also aims at improving the effect of natural ventilation.
The façade, instead, focuses mainly on natural ventilation, to guarantee enough airflow, as well as temperature control of the air entering the stadium, through a proper design of the concourses levels. Regarding the other levels, which are in contact with the conditioned spaces, materials will be chosen in order to mitigate the urban heat island effect in the surrounding environment.

Heating and cooling production is analyzed and a system proposal is given to further improve the comfort when passive measures are not effective anymore.

5.4.1 Roof

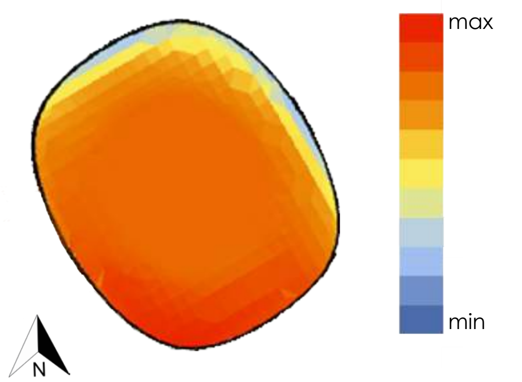
SHADING / NATURAL VENTILATION

The design of the roof took into account several factors. First, the calculations outcomes of chapter 4 (section 4.8.1.1 “Solar irradiance”), where solar irradiance hitting the roof was considered as a parameter. Here, the results shown that in summer the effect of sun on the indoor temperature is very high, thus raising the need for sun-shading. Outcomes are shown in the following table.

		q_{sun}	1000	750	500	250	0	q_{sun}	1000	750	500	250	0
Te [°C]	38	**Ti**	113.1	99.2	85.3	71.5	57.6	**Ti**	94.3	80.4	66.5	52.6	38.7
	35	*max ppl*	110.3	96.4	82.5	68.6	54.7	*min ppl*	91.4	77.6	63.7	49.8	35.9
	30	*max app*	105.5	91.6	77.7	63.8	50.0	*min app*	86.7	72.8	58.9	45.0	31.1
	25		100.8	86.9	73.0	59.1	45.2		81.9	68.0	54.2	40.3	26.4
	20		96.0	82.1	68.2	54.3	40.4		77.2	63.3	49.4	35.5	21.6
	15		91.3	77.4	63.5	49.6	35.7		72.4	58.5	44.6	30.8	16.9
	10		86.5	72.6	58.7	44.8	30.9		67.7	53.8	39.9	26.0	12.1
	5		81.7	67.9	54.0	40.1	26.2		62.9	49.0	35.1	21.3	7.4
	0		77.0	63.1	49.2	35.3	21.4		58.2	44.3	30.4	16.5	2.6
	-5		72.2	58.4	44.5	30.6	16.7		53.4	39.5	25.6	11.7	-2.1

Table 5.4.1: Summer case with solar irradiance as parameter – maximum people/maximum appliances and minimum people/minimum appliances

Then, solar irradiance analysis and sun-path (section 5.2.2) obtained with Ladybug for grasshopper were considered. The portions of the roof that should be provided with the most shade are, indeed, those that are hit the most by sun. These are shown in the following figures.



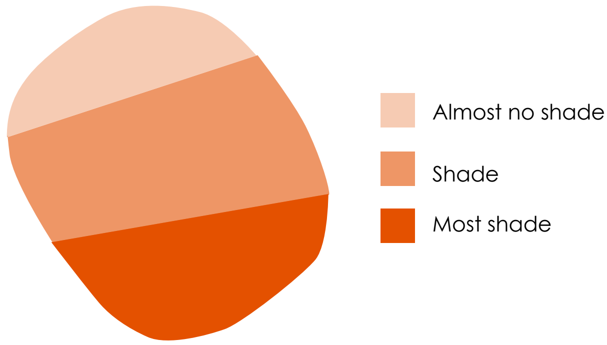


Figure 5.4.1: Solar irradiance on the roof in spring/summer
Figure 5.4.2: Shade requirement based on solar analysis

Last, orientation of the roof panels should take into account the prevailing wind direction, which is South-West, to facilitate the indoor airflow and the stack effect expected to occur inside the stadium.
The list of requirements is shown in table 5.4.2.

Requirements
Shading
Daylight
Acoustic
Rain protection
Adaptability
Visual comfort
Ventilation

Table 5.4.2: Roof design requirements

The existing roof truss structure, which is shown in figure 5.4.3, was analyzed to understand the possibility in terms of use to integrate the new roof panels. In the current design the roof is operable so that the football pitch can get sufficient daylight, and acoustic insulation and rain protection can be provided when needed.

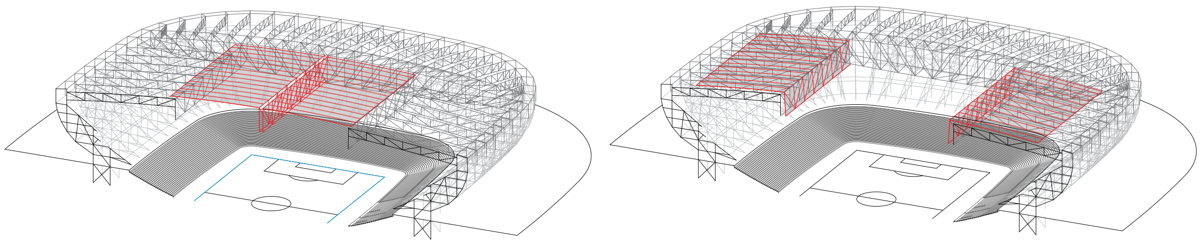


Figure 5.4.3: Roof structure
OMA,2018

The design of the roof system went through several steps, developing according to the requirements set by simulations and calculations, to get to a final design able to meet as many requirements as possible.

Initial proposal implied the use of different materials to provide either shade or sun by means of roof panels design to fit the existing structure. The process is shown in the following diagrams.

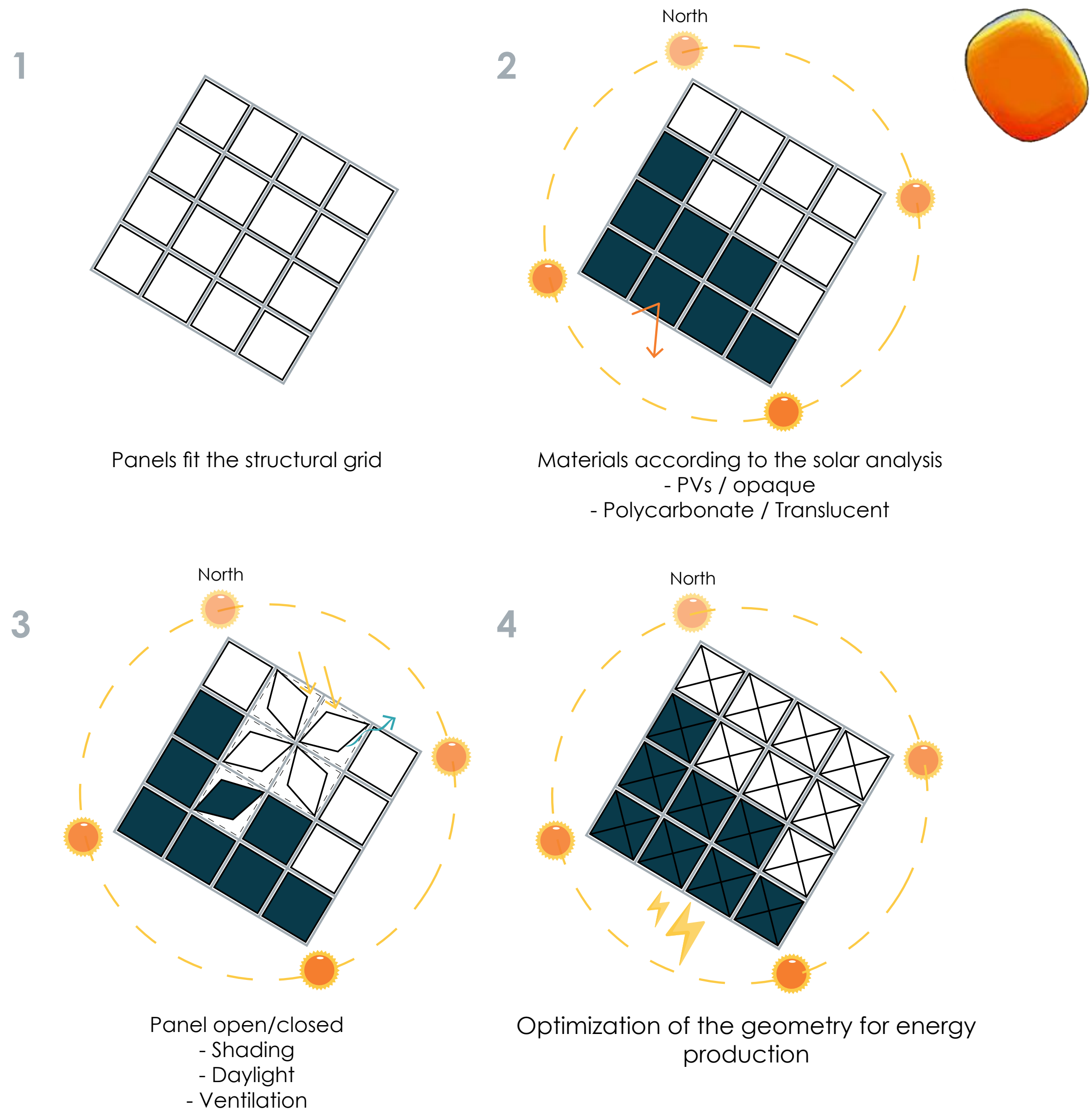


Figure 5.4.4: Roof - design process part 1

The first proposal, indeed, show pyramid-like shaped panels, either made of polycarbonate or integrated with PVs, based on the solar irradiance analysis. Panels are transparent where the sun hitting the roof is less strong, whereas they are opaque where screening the sun rays is more needed. This design allows for daylight, shading, energy production and ventilation, as shown in figure 5.4.5.

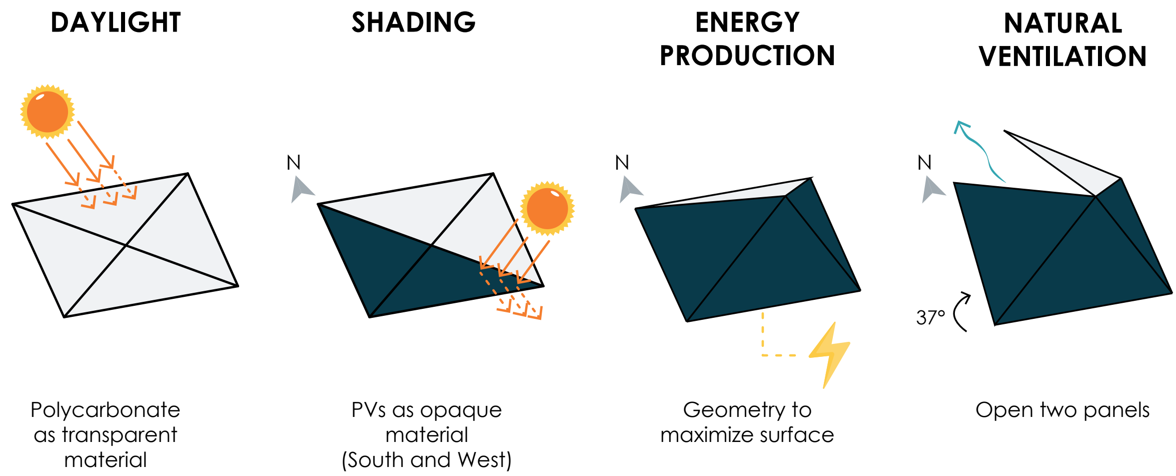


Figure 5.4.5: Roof - initial design

However, this system still does not allow for maximizing the daylight reaching the field and might show some issues in terms of shading.

Therefore, further development in the roof design has been carried out, through the following steps.

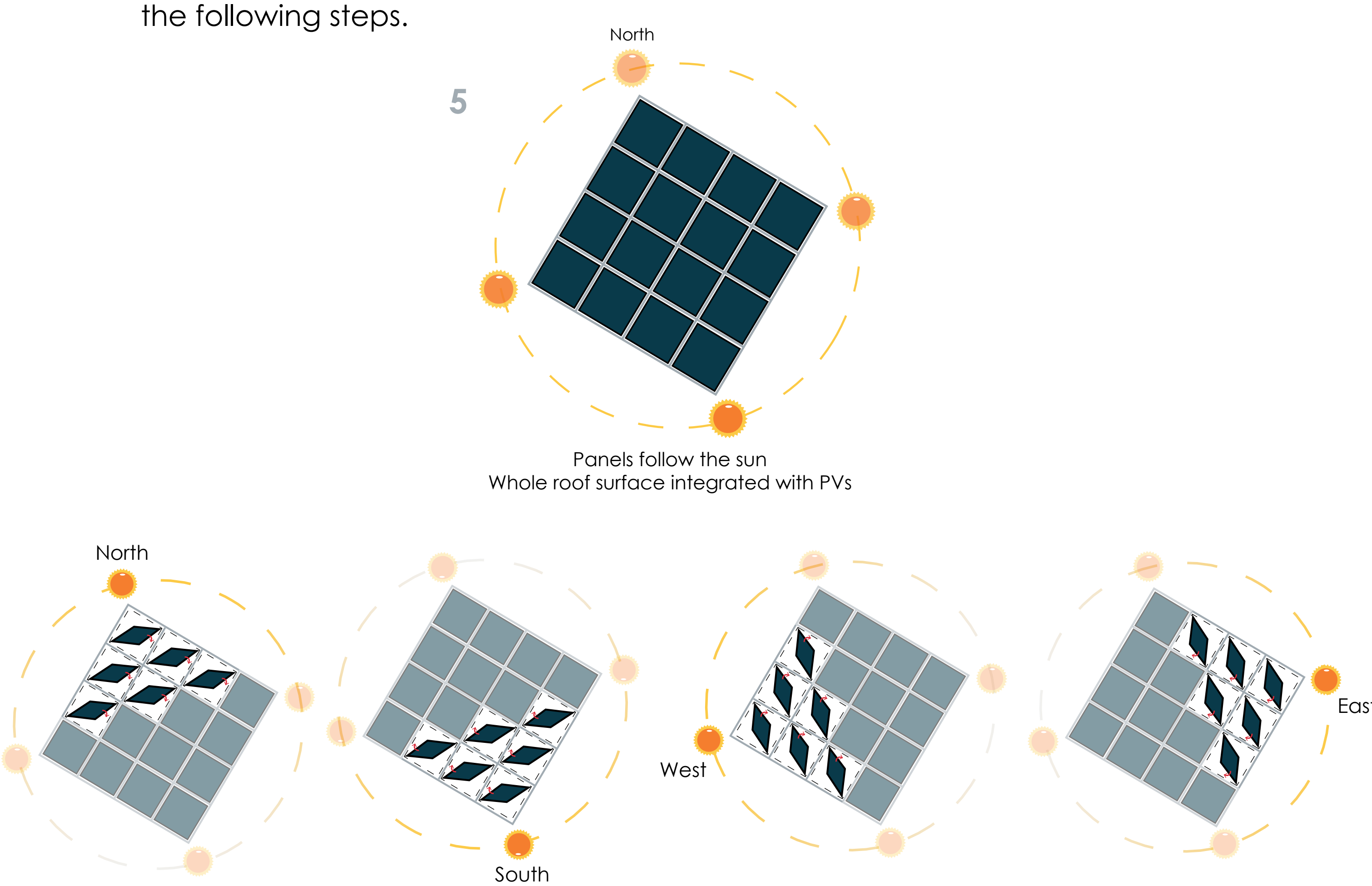


Figure 5.4.6: Roof - design process part 2

In the final design of the roof, given the architectural language of the stadium, with the structure being placed on the façade, the new proposal aims at integrating roof and façade by using a unique language. This is possible by connecting the roof structure to the one of the façade, thus repeating the same massive grid on the top part of the stadium, where the new panels are located.

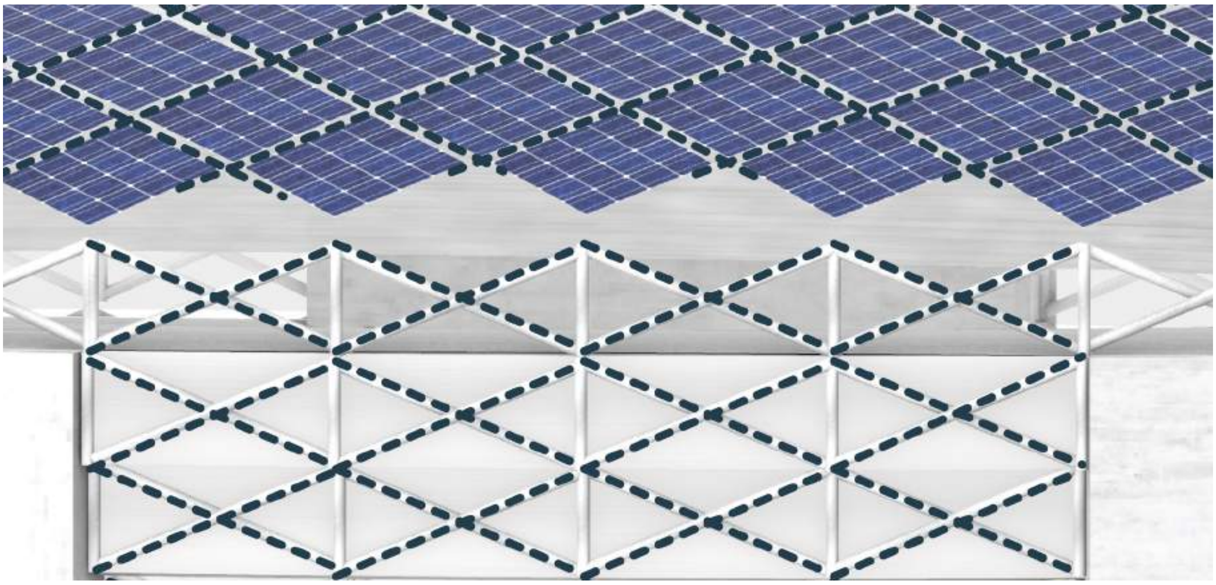


Figure 5.4.7: Roof -facade grid

The roof is made of panels which are attached to the structure. Each element is integrated with photovoltaic panels for energy production in situ. Each panel is free to move into two main directions: North-South and West-East. In this way the panel can follow the sun and screen the solar radiation to provide shade and reduce the solar heat gains. In addition, this solar tracking system maximizes the system's electricity production by moving in such a way that it follows the sun throughout the day. The operability of the panels also allow for natural ventilation to occur and to make the stadium adaptable to different activities. Daylight and shadow are, indeed, provided during the day in case of a match, whereas the closed roof guarantee acoustics insulation in case of a concert.
Next to this, being the panel operable they can allow for as much daylight as possible in, to guarantee enough illuminance on the field.
The system design is shown in the following schematic views.

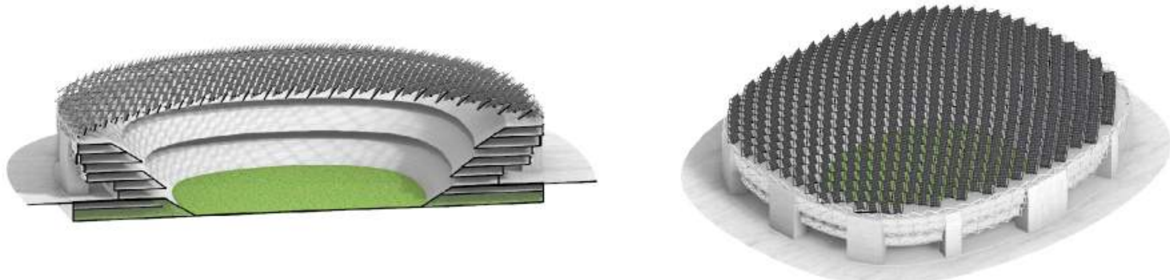


Figure 5.4.8: Roof - general view

Every individual panel is connected to the structure and operated by a motor to move following the sun.

In particular, as shown in figure 5.4.9, the panel system consists of two frames: the outer one, which is connected to the roof structure, allows for rotation of the panel in one direction, whereas the inner one, which also support the PV, can rotate in the other direction.

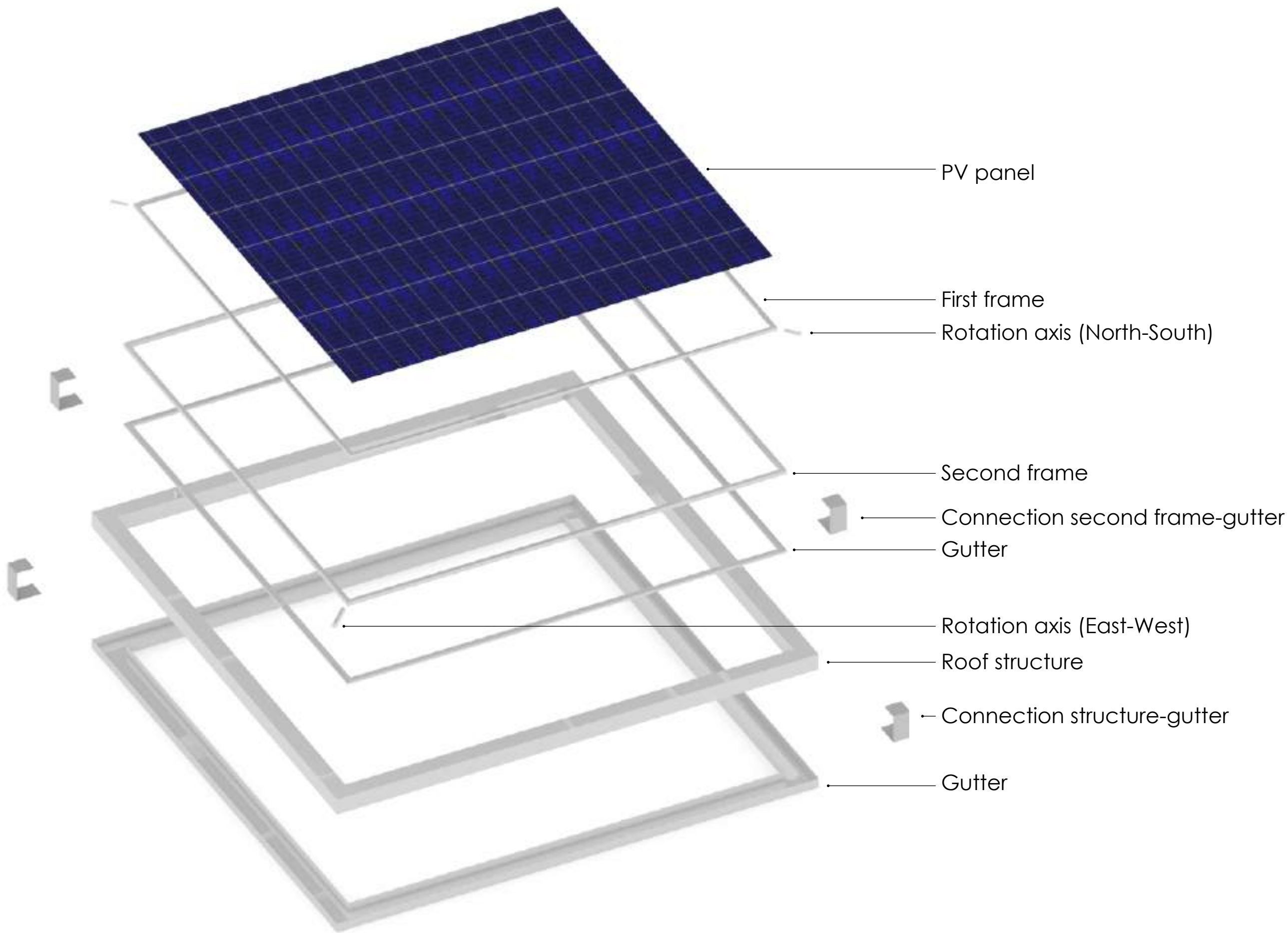
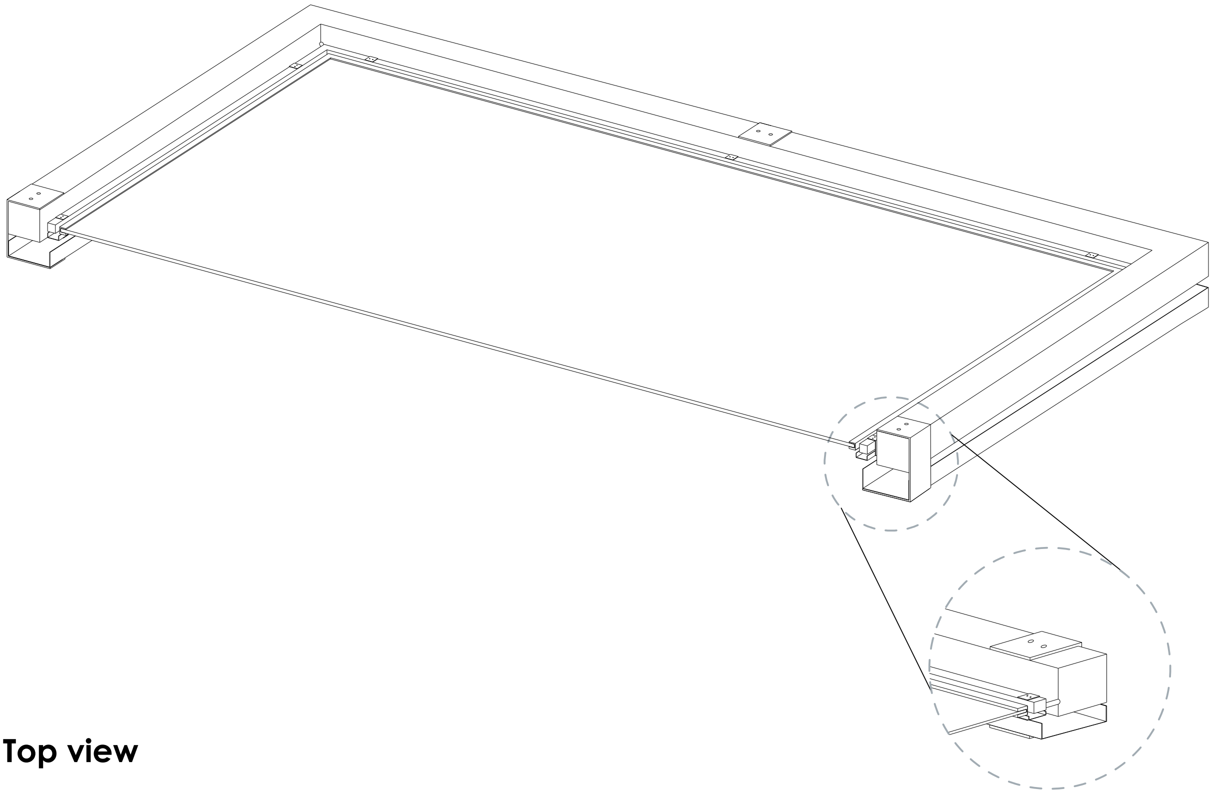


Figure 5.4.9: Roof - system

In addition, two gutters are integrated into the frames, so that in case of rain, the drops cannot filter through the gaps between frames, but they are collected and likely to be stored for rain water reuse.
A more technical detail of the system of frames and connections is shown in figure 5.4.10.

Axonometric view



Top view

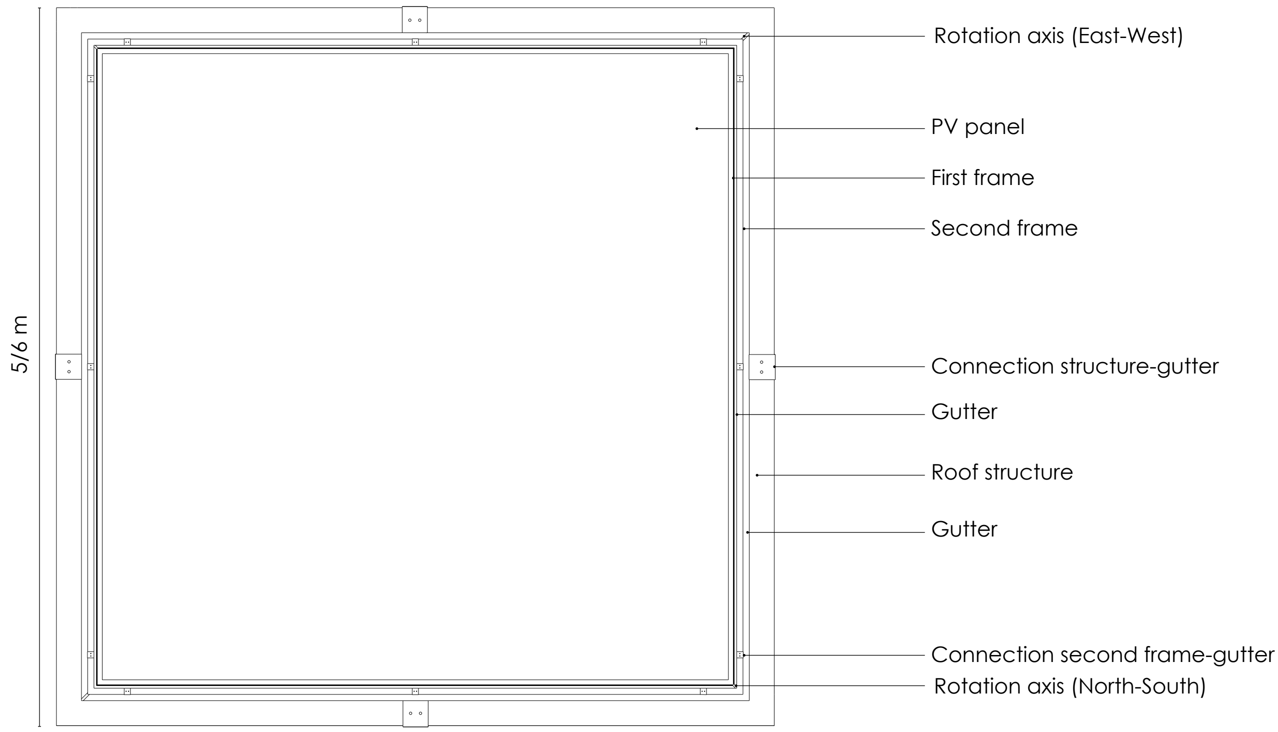


Figure 5.4.10: Roof panel - Construction system

Special requirements in terms of illuminance are, indeed, set by UEFA in the "UEFA Stadium Lighting Guide 2016". Targeting the highest class described, which is "UEFA Champions League - Finals", the average illuminance on the field should be higher or equal 2000 lux. Therefore, this value is verified by means

of daylight simulation with Honeybee for Grasshopper (Appendix E).
Two types of analyses were done: hourly and annual.
In the first case, three days where chosen, namely June 21st, December 21st, and March 21st. In this way it was possible to find the highest, lowest and average illuminance on the field. The hourly simulation was performed for 3 pm, as in general football matches are in the afternoon, either at 15h or at 18h. However, due to the early sunset in winter, it was preferred to run the simulation taking as reference 15h.
The annual simulation, instead, was performed to see the percentage of days throughout the year when the illuminance on the field is at least 2000 lux.
For each case, four simulations were run as the roof panels can open in four directions, to check if the target illuminance can be reached in all cases.
The following figures show the results both of the hourly and annual simulations for one of the four cases, with the roof panels opened towards North. Other outcomes can be found in Appendix A.

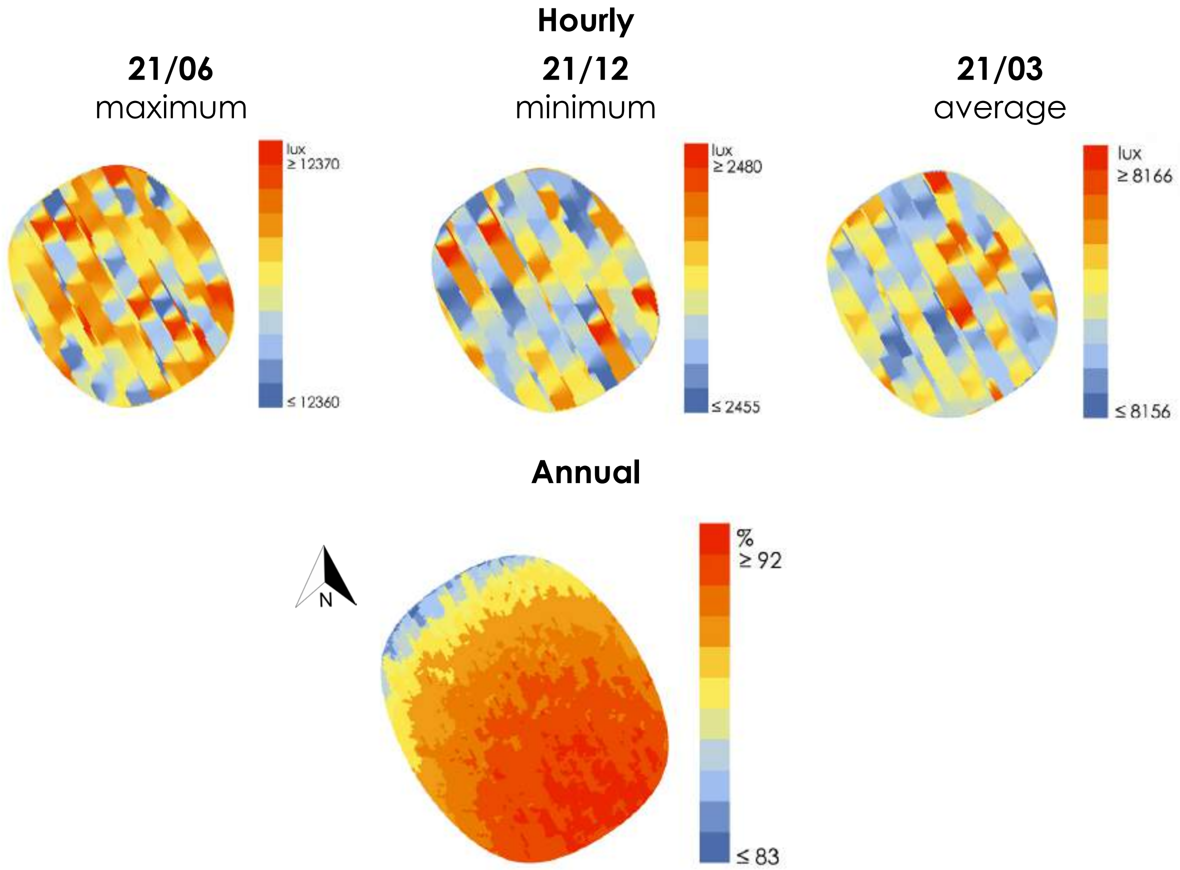


Figure 5.4.11: Hourly and annual daylight analysis on the field

As it can be observed from the figures above, illuminance on the field due to sun is overall quite high, being above 2000 lux for at least 83% of the time throughout the year. However, the weather file of Rotterdam was used, which might not always represent the worst case scenario. Therefore, in order to understand the amount of daylight reaching the field in case of overcast sky, the effect of the roof on illuminance has been analyzed. In order to do so, the same simulation as before was run for June 21st, considering as reference planes to calculate the illuminance both one the field and outside the stadium. In this way, it was possible to define the actual percentage of daylight that reaches the field. Results of the simulation are shown in figure 5.4.12.

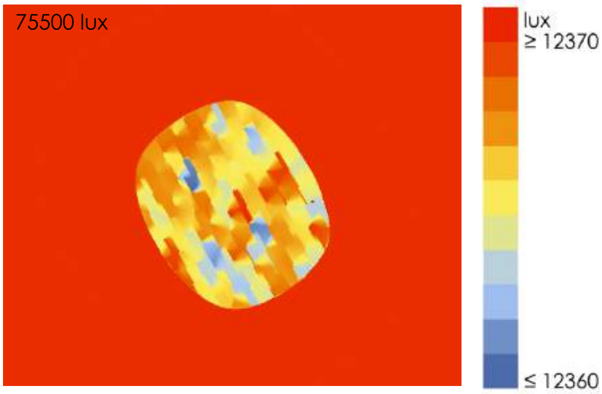


Figure 5.4.12: Hourlyaylight analysis inside and outside the stadium

Another aspect related to the light analysis is the shadows projected by the roof onto the field and the tiers. For visual comfort, it would be important not to have undesired strong shadows. A simple study was done by changing the sun position in Rhinoceros. All four direction of opening of the roof where considered. Shadows can be observed in figure 5.4.13, where it can be noticed that they should not cause visual discomfort.

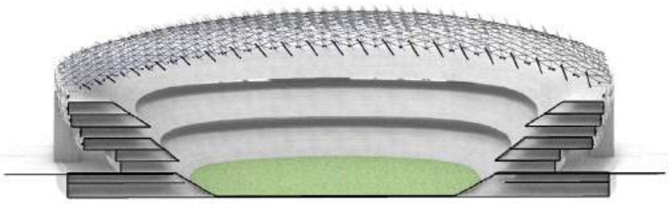


Figure 5.4.13: Shadows

In addition, being the panels operable, they can adapt to different requirements for different activities. In particular, during a concert, it would be preferred to keep the roof closed not to let the noise go outside. However, since the panels are openable towards different direction, this can allow to dissipate sound towards the river. By keeping the roof open to some extent also in case of a concert, natural ventilation can occur, avoiding overheating and allowing for fresh air.

All the analyses together give insights into the performance of the roof. At the beginning of this section, requirements were stated. In table 5.4.3 the performance of the design is rated based on its ability to tackle each requirement.

Requirements	
Shading	++
Daylight	++
Acoustic	+
Rain protection	+
Adaptability	++
Visual comfort	±
Ventilation	++

Figuure 5.4.3: Roof design - requirements achievement

As the roof is covered by PVs to produce electricity, PVs outputs was calculated by using the following formula.
The result shows 2527599 kWh/an could be produced.

$$E = A \times r \times H \times PR$$

Formula 5.4.1: PVs electricity output

E = Energy [kWh]	2527599	kWh/an
A = Total solar panel Area [m²]	39074	m²
r = solar panel yield [%]	15%	
H = Annual average irradiation on tilted panels	575	kWh/m²an
PR = Performance ratio, coefficient for losses (range between 0.9 and 0.5, default value = 0.75)	0.75	

Table 5.4.4: PVs electricity output

However, this formula does not take into account the orientation factor, therefore, the result is not very accurate.

Looking at the maintenance of the roof, this is eased by the panels configuration. Indeed, the whole system is made of individual panels connected to their own frame.
In this way, in case of damage or if they need to be cleaned, the specific panel could just be removed and then replaced or reassembled to the rest of the structure. However, the chosen materials do not require high maintenance levels. PV panels, in general, require very little maintenance to work. The only thing they might need is cleaning to avoid obstructions to sun rays.
In case of maintenance of the roof, this could be accessed by the bottom, as it would be better to avoid the top part due to PVs surface temperature.

For the roof design, reference case studies are shown in the following pictures.

Figure 5.4.14: Roof reference - National Stadium Taiwan
http://www.solar-inverter.com/in/656.htm
5.4.15: Roof reference - ETH Zurich Adaptive Solar façade
From "ETH Zurich", (2017). http://www.systems.arch.ethz.ch/research/active-and-adaptive-components/asf-adaptive-solar-facade.html

5.4.2 External façade

NATURAL VENTILATION / SOLAR REFLECTANCE

The external façade is the one in direct contact with the conditioned areas of the stadium, but not with the semi-outdoor space. According to the calculations performed in chapter 4 (section 4.8.1.2 "∑UA external façade"), whose outcomes are shown in table 5.4.3, the properties of this façade do not influence much the indoor temperature.

		∑Uf1Af1	24508.3	49016.6	73524.9	98033.2	122542	343116	∑Uf1Af1	24508.3	49016.6	73524.9	98033.2	122542	343116
T_e [°C]	38	**Ti**	113.1	112.3	111.4	110.6	109.7	102.0	**T_i**	94.3	93.4	92.6	91.7	90.9	83.2
	35	*max ppl*	110.3	109.6	108.8	108.1	107.4	101.0	*min ppl*	91.4	90.7	90.0	89.3	88.6	82.2
	30	*max app*	105.5	105.0	104.6	104.1	103.6	99.3	*min app*	86.7	86.2	85.7	85.3	84.8	80.5
	25		100.8	100.5	100.3	100.1	99.8	97.7		81.9	81.7	81.5	81.2	81.0	78.8
	20		96.0	96.0	96.0	96.0	96.0	96.0		77.2	77.2	77.2	77.2	77.2	77.2
	15		91.3	91.5	91.7	92.0	92.2	94.3		72.4	72.7	72.9	73.1	73.4	75.5
	10		86.5	87.0	87.5	87.9	88.4	92.7		67.7	68.1	68.6	69.1	69.6	73.8
	5		81.7	82.5	83.2	83.9	84.6	91.0		62.9	63.6	64.3	65.1	65.8	72.2
	0		77.0	77.9	78.9	79.8	80.8	89.3		58.2	59.1	60.1	61.0	62.0	70.5
	-5		72.2	73.4	74.6	75.8	77.0	87.7		53.4	54.6	55.8	57.0	58.2	68.8

Table 5.4.5: Summer case with thermal transmittance x surface as parameter – maximum people/maximum appliances and minimum people/minimum appliances

Therefore, it would be possible to propose different materials. In this research, the goal is to chose the materials in such a way that the stadium envelope help reduce the urban heat island effect in th surroundings.
In addition, ventilation is an important parameter in the control of the indoor temperature. In order to achieve as much air flow as possible, the façade should be operable. The airflow entering through the concourses was also shown in section 5.2.2 "Building", with the Butterfly for Grasshopper simulation.

The design of the façade, therefore, combines two strategies: the concourses levels (L02 and L05) are opened so that wind can enter and air circulates reaching the seating areas; the other levels, which are not in connection with the tiers, will be cladded with façade materials able to mitigate UHI, thus probably being characterized by high albedo.

5.4.2.1 Concourses levels

For the concourses levels a new design for the façade is proposed, which could fit the existing project. The façade of the Feyenoord stadium is, indeed, characterized by simple geometric shapes, mainly rectangular. In order for the new panels to be integrated into the existing architecture, their geometry should follow that of the existing ones.
In addition, as the concourses are the spaces through which natural ventilation occurs, a system to control the temperature of the air entering should be integrated. The location of these new panels is shown in figure 5.4.16.

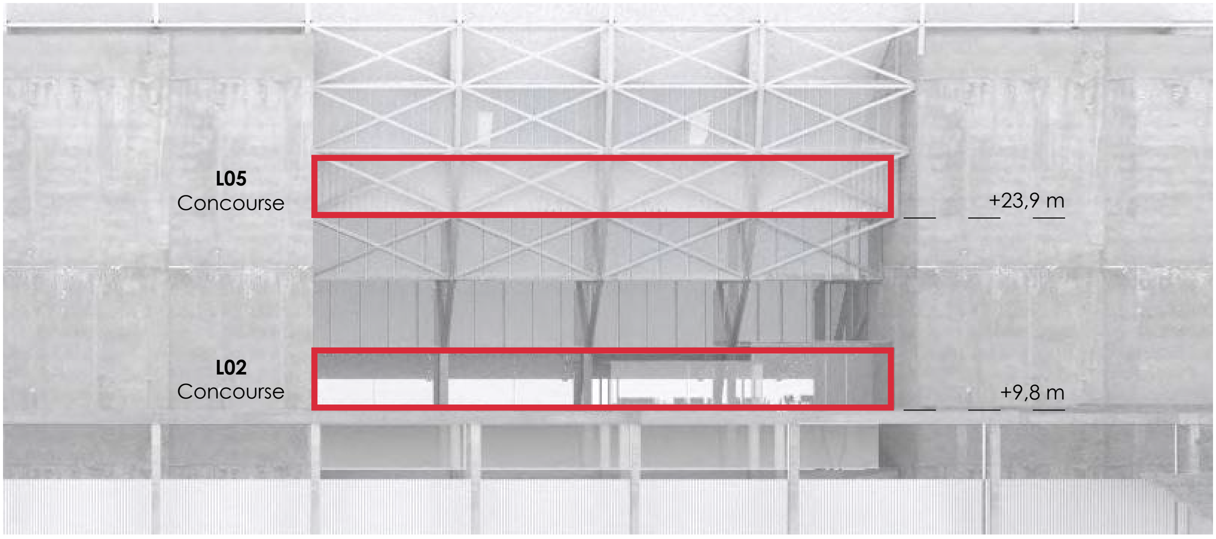


Figure 5.4.16: New façade panels location on levels
OMA, 2018.

Also in the façade product design, several steps were followed. The design process is shown in the next sequence of figures.

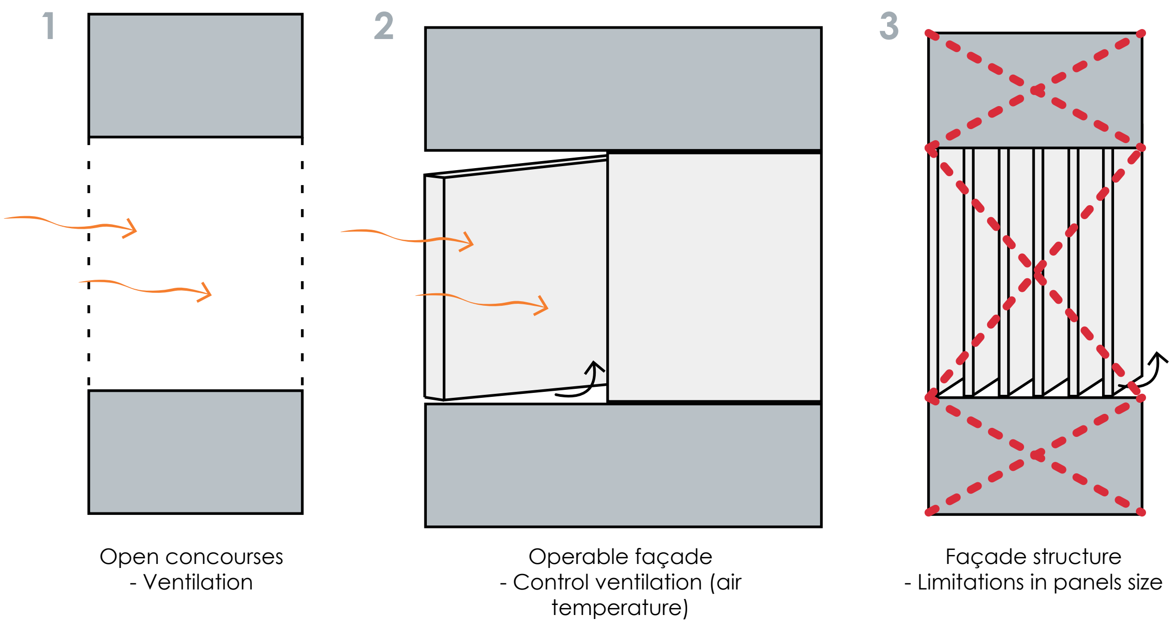


Figure 5.4.17: Façade - design process

In the final design proposal, the façade panels are made of phase change materials, which help pre-cool or pre-heat the air entering the stadium. The selected PCM is SP21 EK by Rubitherm, whose melting point corresponds to the summer average temperature obtained from the modified Weather file. Further information about the PCM are in appendix B. The PCM material is also chosen as it is translucent, thus allowing for view to the outside and daylight to enter. The PCM panel is enclosed by a glass box not to be into direct contact with the metal frame, as PCMs tend to be corrosive. The frame is connected to a central axis which allows for rotation. These panels, indeed, are operable and can open by rotating around a central axis connected to the floor and ceiling of the specific level. They are not in line with the other levels façades as the structure bracing is placed in front of them and the need space to freely rotate. Therefore, the panels are moved a bit back and they are not very large. There is one panel on each side of the axis, so that the façade always allow for small air infiltration, even when it is closed. In terms of safety, it is important to integrated a fence or a support element near the façade, to avoid people or objects to fall.
In case of maintenance, each façade panel can be removed and replaced by accessing it from the interior.

The schematic working principle of the panels is shown in figure 5.4.18, whereas the components of the panel are shown in figure 5.4.19.

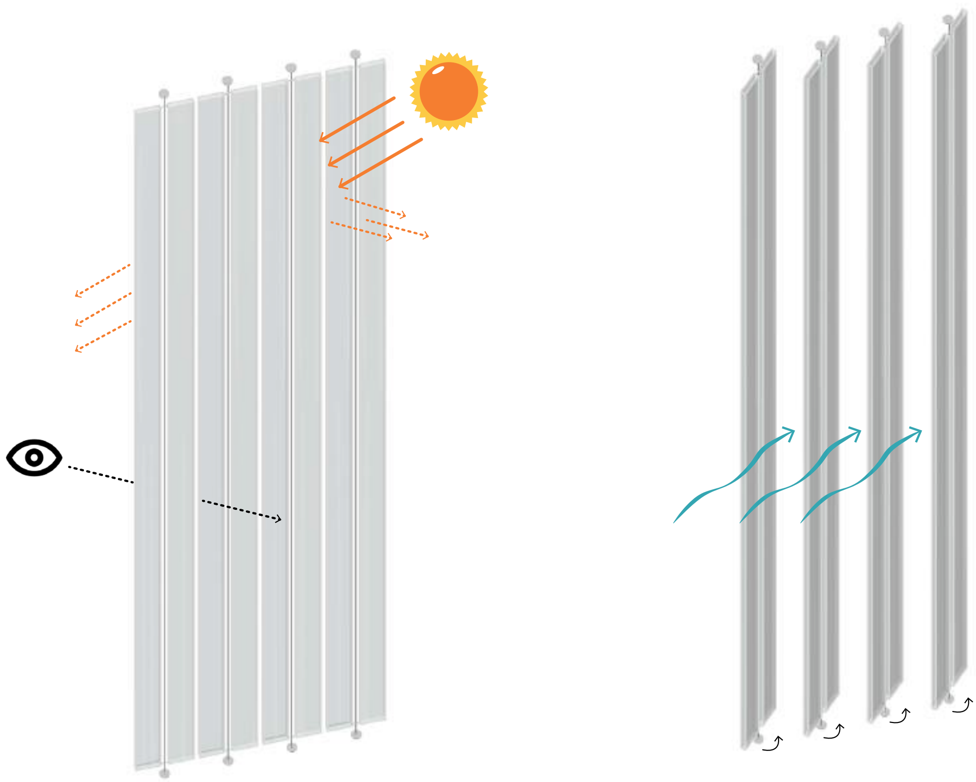


Figure 5.4.18 New façade panels working principle

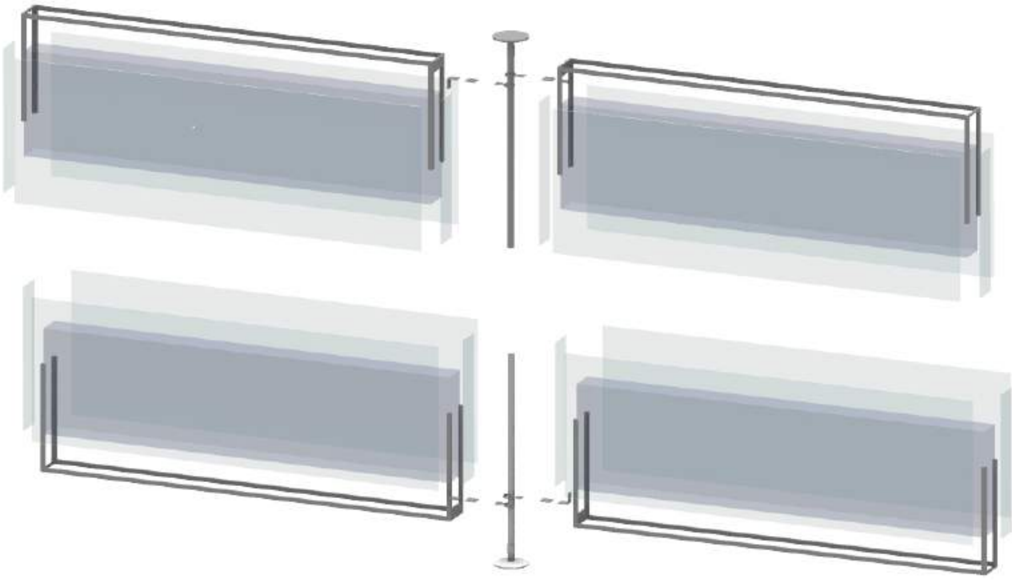


Figure 5.4.19: New façade panels components

The metal frame is connected to a pivoting element, which is the support of the panel connected to the ceiling and floor slabs. The system is shown in figure 5.4.20.

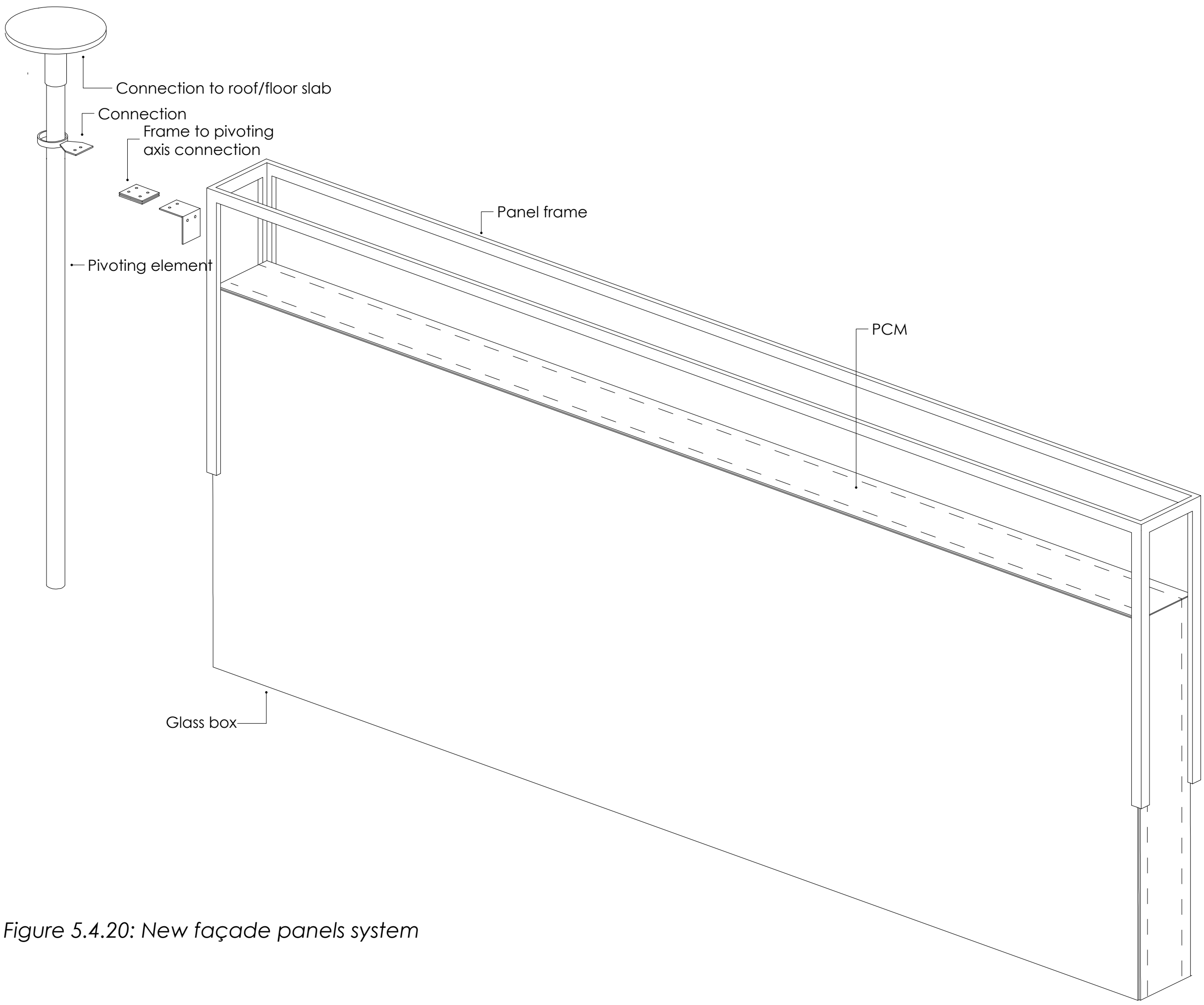


Figure 5.4.20: New façade panels system

An example of similar system for pivoting panels is shown in figures 5.4.21 and 5.4.22.

Figure 5.4.21: House in Montevideo, Uruguay
From "Casa de arquitectura Rifa", (2008). http://www.fadu.edu.uy/casa/historia/casa-2008/
Figure 5.4.22: Aalen University extension
From "Archdaily", (2008). https://www.archdaily.com/948/aalen-university-extension-mgf-architekten/500ec1e628ba0d0cc70002a8-aalen-university-extension-mgf-architekten-image

In order to verify the performance of the open concourses, a Design Builder model was set up. This allows to check air temperature in the different areas of the stadium, as well as the air change rate.
First, the basic models for football match and concert, were defined by creating the levels and dividing them into zones according to the different activities. Materials for roof and façade where assigned based on those indicated in the OMA's report. Then, the activity template was defined for each zone according to the schedule and the occupancy. Two different templates were created, referring to the football match and concert cases, considering both occurring on Saturdays.
The simulation for the football match case was performed for the period of August-May, whereas the one for the concert for the whole year. Results were visualized as hourly to get more specific number related to the input schedule. The reference day analyzed was 3rd of August, which resulted to be the warmest day from the Weather File, as previously mentioned.
The set up of schedules, HVAC and ventilation for the different zone for both cases can be seen in table 5.4.6.

ACTIVITIES	SCHEDULE	MECHANICAL VENTILATION	NATURAL VENTILATION	COOLING	HEATING
Field	17.30-20	NO	YES	NO	NO
Tiers	17.30-21	NO	YES	NO	NO
Concourses	17-21	NO	YES	YES	YES
Media	17-18	YES	NO	YES	YES
Staff	17-21	YES	NO	YES	YES
Business	17.30-21	YES	NO	YES	YES
Facilities	17-21	YES	NO	YES	YES
Parking	6-24	YES	NO	YES	YES
Players area	17-21	YES	NO	YES	YES
Circulation	17-21	YES	NO	YES	YES

ACTIVITIES	SCHEDULE	MECHANICAL VENTILATION	NATURAL VENTILATION	COOLING	HEATING
Field (stage)	20-24	NO	YES	NO	NO
Tiers	20-24	NO	YES	NO	NO
Concourses	20-24	NO	YES	YES	YES
Media	20-24	YES	NO	YES	YES
Staff	20-24	YES	NO	YES	YES
Business	20-24	YES	NO	YES	YES
Facilities	20-24	YES	NO	YES	YES
Parking	6-24	YES	NO	YES	YES
Players area	20-24	YES	NO	YES	YES
Circulation	20-24	YES	NO	YES	YES

Table 5.4.6: Templates set up for Design Builder

In order to understand how the airflow and indoor temperature vary when the concourses are open, the model was modified.
Outcomes show that if natural ventilation occurs at day time due to open concourses levels, when outside air is pretty warm, it has no or little effect on the indoor temperature of tiers and field. Air change rate, instead, increases.
Comparison of basic model and improved model simulations is shown in tables 5.5.7 and 5.5.8.

Match September-May August 3rd	Fuel	CO2	Ventilation	Max air temperature	Gains
	Wh/m2	**kg/m2**	**ac/h**	**°C**	**Wh/m2**
Basic - stadium	10,8	6,5	1,3	28,2	15,8
Field	-	-	0,7	26,5	--
Tiers	-	-	0,7	34,9	--
Open concourses - stadium	10,8	6,5	2,2	28	15,3
Field	-	-	0,7	26,4	--
Tiers L02	-	-	5,8	34,1	--
Tiers L05	-	-	5,8	34,1	--

Table 5.5.7: Simulations outcomes comparison - Football match

Concert All year August	Fuel Wh/m2	CO2 kg/m2	Ventilation ac/h	Max air temperature °C	Gains Wh/m2
Basic - stadium	10,3	6,2	1,4	28,7	24
Field	-	-	0,7	36	--
Tiers	-	-	0,75	36	--
Open concourses - stadium	10,3	6,2	2,2	28,4	38,6
Field	-	-	4,5	36,1	--
Tiers L02	-	-	5,8	32,8	--
Tiers L05	-	-	5,8	32,8	--

Table 5.5.8: Simulations outcomes comparison - Concert

Looking at the results, which focus on the tiers of the open concourses and the field, it is, therefore, recommended to open the concourses only at night, when the outside air is cooler, also to have night flushing and cool down the thermal mass of the stadium and recharge the PCM. Another option is to have the façade activated by sensors and able to open when the temperature is, for example, below 24°C.

However, the information obtained from OMA report, where not sufficient to set up a accurate model. Materials were not clearly specified and used HVAC and ventilation systems not mentioned. Therefore, the simulations outcomes did not result to be precise. In addition, the model automatically builds wall as boundaries for each zone, so areas such as the tiers where not fully open and the air could not properly flow.

5.4.2.2 Other levels

The main focus here was on the materials to be used for the façade, rather than designing a new system. In the previous chapter, it was proved by calculations that the external façade composition does not affect much the semi-outdoor area of the stadium, as there is not direct contact between them. The proposal was, indeed, to focus on the material in such a way that they could help improve the outdoor comfort around the build by reducing UHI. So, in this case, the effect of the component would not be on the inside but on the outside of the building.
In order to check the effect of different materials on the UHI, the software ENVI-met has been used as it allows for simulations at urban scale. In order to get final results, it is necessary to go through some specific steps.

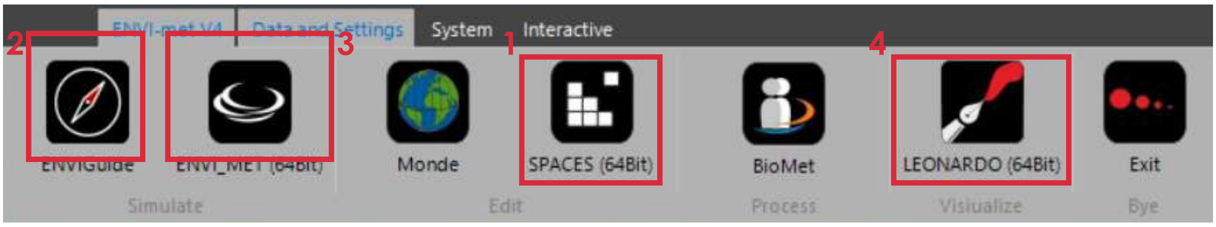


Figure 5.4.230: ENVImet interface and steps

First, in "SPACES" the model has been built considering the stadium and the nearby buildings, which are four towers and another block.
Soil configuration was then set up: water for the river area, and standard soil for the rest of the surface.
Materials as well have been assigned. For the surroundings buildings the basic material provided by the software was kept, whereas the stadium's façade material has been changed in every simulation.
Model configuration is shown in figure 5.4.24. River boundaries are also highlighted. In the model, each cell has dimensions of 10x10 m.

The second step was to set up the simulation in "ENVIGuide". Also in this case, 3rd of August, which is the warmest day, was taken into account. Weather data relative to this day were used as input for the simulation as it follows:

- Temperature range: 20 - 35°C
- Wind speed: 3.8 m/s
- Prevailing wind direction: South-West

To run the simulation the ENVI_MET component was used. Simulation was run for 24 hours to check the variation in surface temperatures throughout the day.

Last, "LEONARDO" allowed to visualize the results.

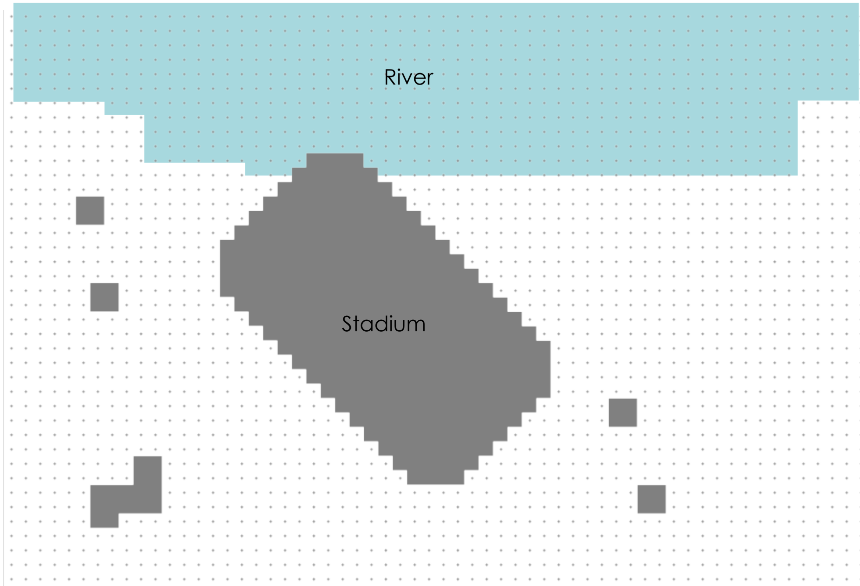


Figure 5.4.24: Model configuration

In total, six simulations for the façade materials were run, whereas two additional simulations were needed to check what would happen is paving materials in the area are changed.

The materials were chosen based on research on their possible ability to reduce UHI. In particular, materials with high albedo were preferred. However, some other options were tested.

The chosen configurations were:

1) Basic material provided by the software
2) Aluminium
3) White painted wall
4) Glass
5) Ceramic
6) Green

The following groups of figures show the outcomes of simulations at 8,12,18 and 22 hour for the different façade materials.

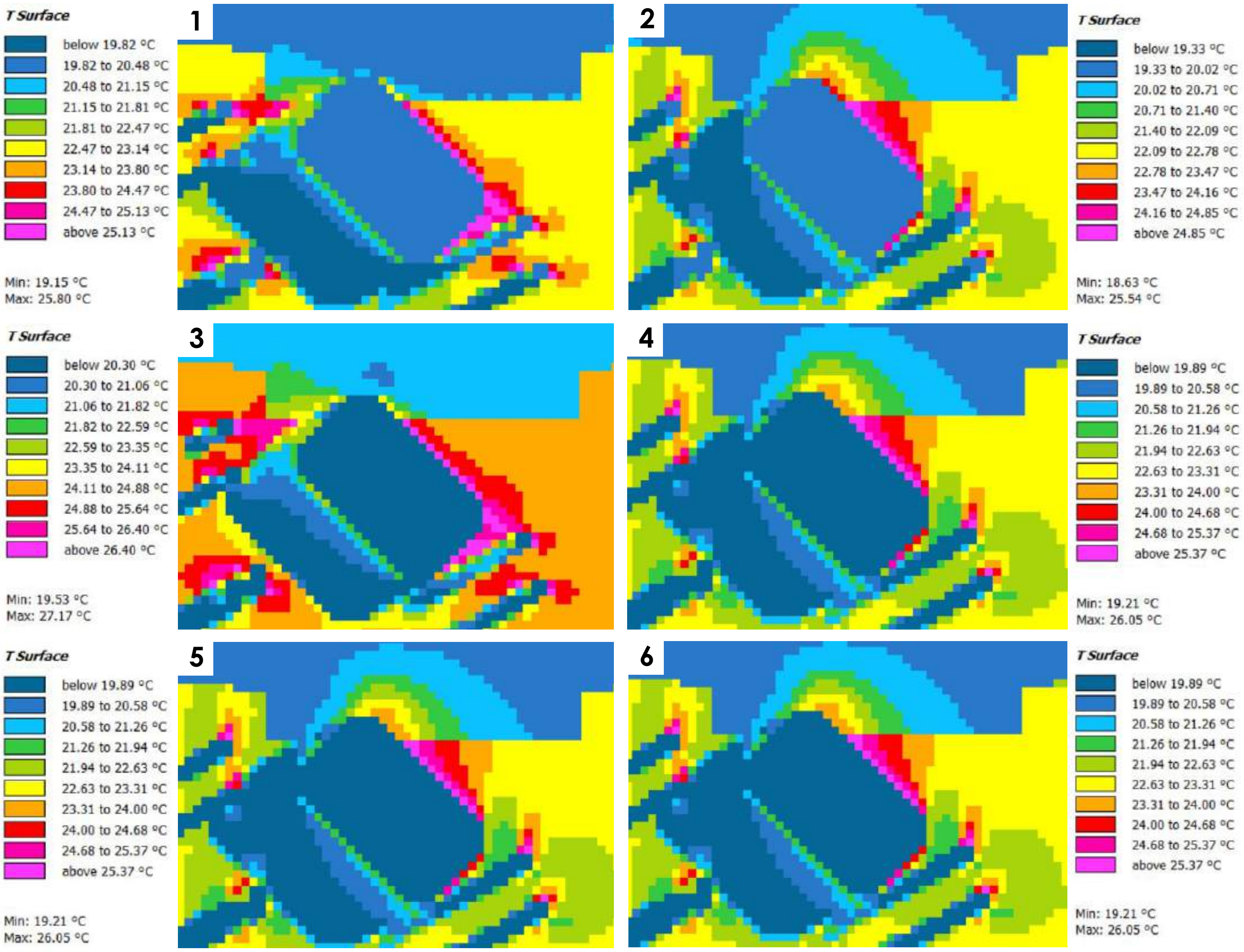
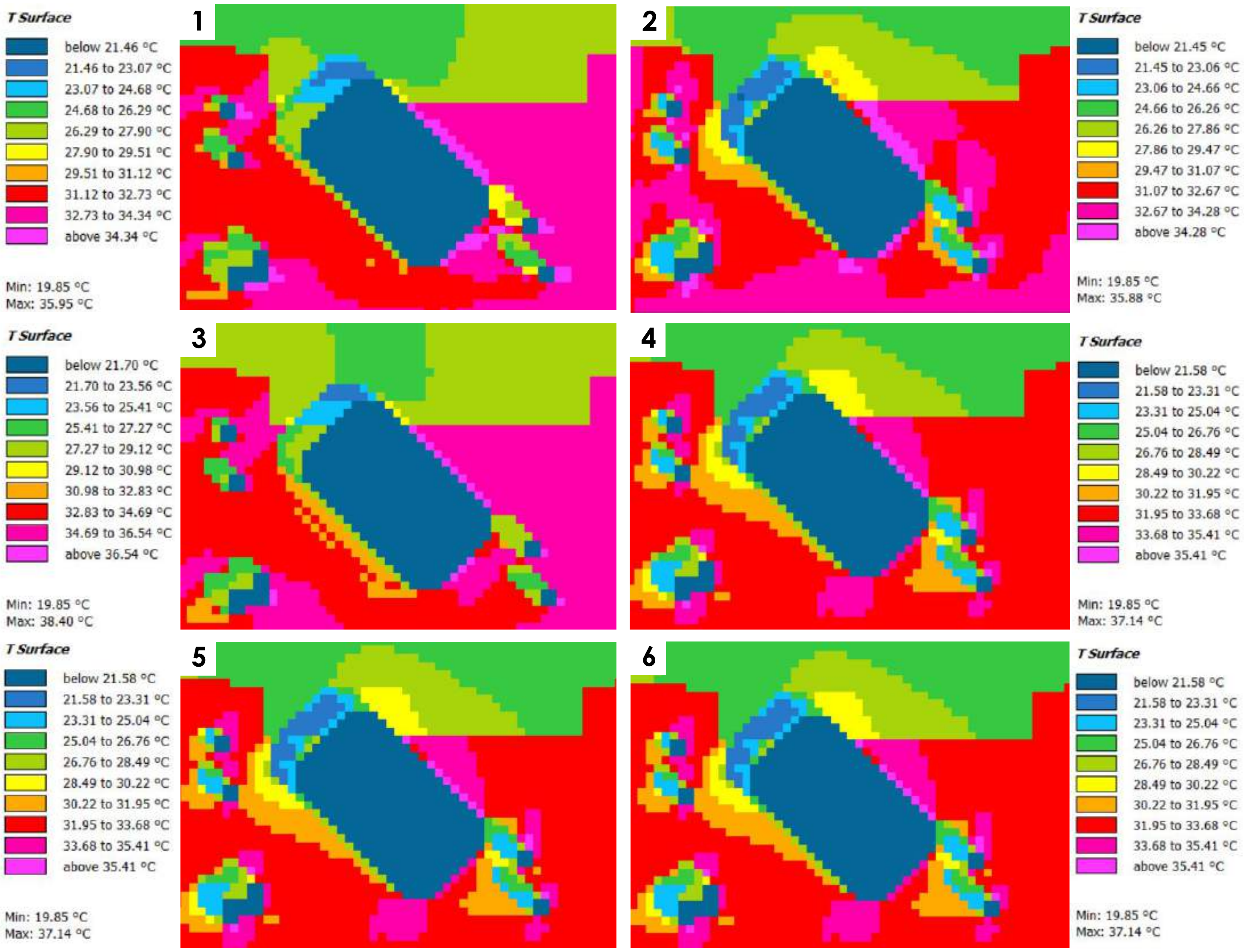


Figure 5.4.25: Surfaces temperature at 8h

At 8 the lowest average surfaces temperature is in case of aluminium, with a minimum temperature of 18,63°C and a maximum of 25,54°C.
In addition, if we look at the immediate surroundings, the temperature is also lower on both sides. It can be observed that the Eastern side is warmer due to sun.
On the other hand, the configuration increasing surfaces temperature the most is white painted wall with a minimum temperature of 19,53°C and a maximum of 27,17°C.



Figuree 5.4.26: Surfaces temperature at 12h

At 12 the lowest average surfaces temperature is in case of aluminium, as at 8 am. The minimum and maximum values are respectively 19,85°C and 35,88 °C. The worst configuration in terms of UHI reduction is always white painted wall (Maximum temperature of 38,40°C).

It is possible to observe that temperature of surfaces starts increasing quite a lot at this time of the day.

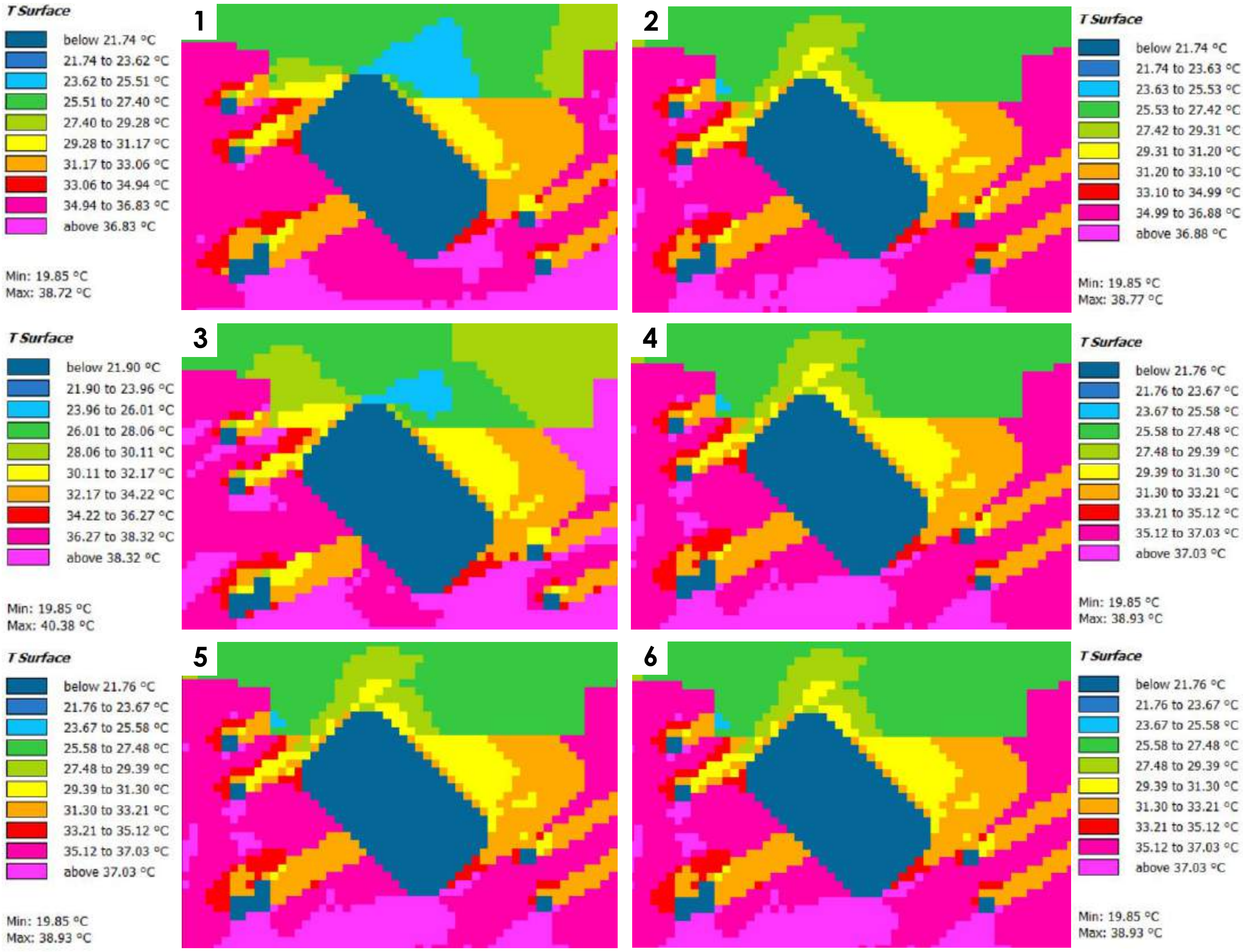


Figure 5.4.27: Surfaces temperature at 18h

Differently from previous hours, at 18 the lowest average surface temperature is observed in the basic configuration case. Minimum temperature is here 19,85°C and maximum temperature is 38,72°C. However, aluminium case's maximum temperature is almost the same, being 38,77°C. The configuration performing the worst is white painted wall, reaching a maximum temperature of 40,38°C. At 18 the warmest surfaces temperature is registered, probably due to the heat accumulated throughout the day.

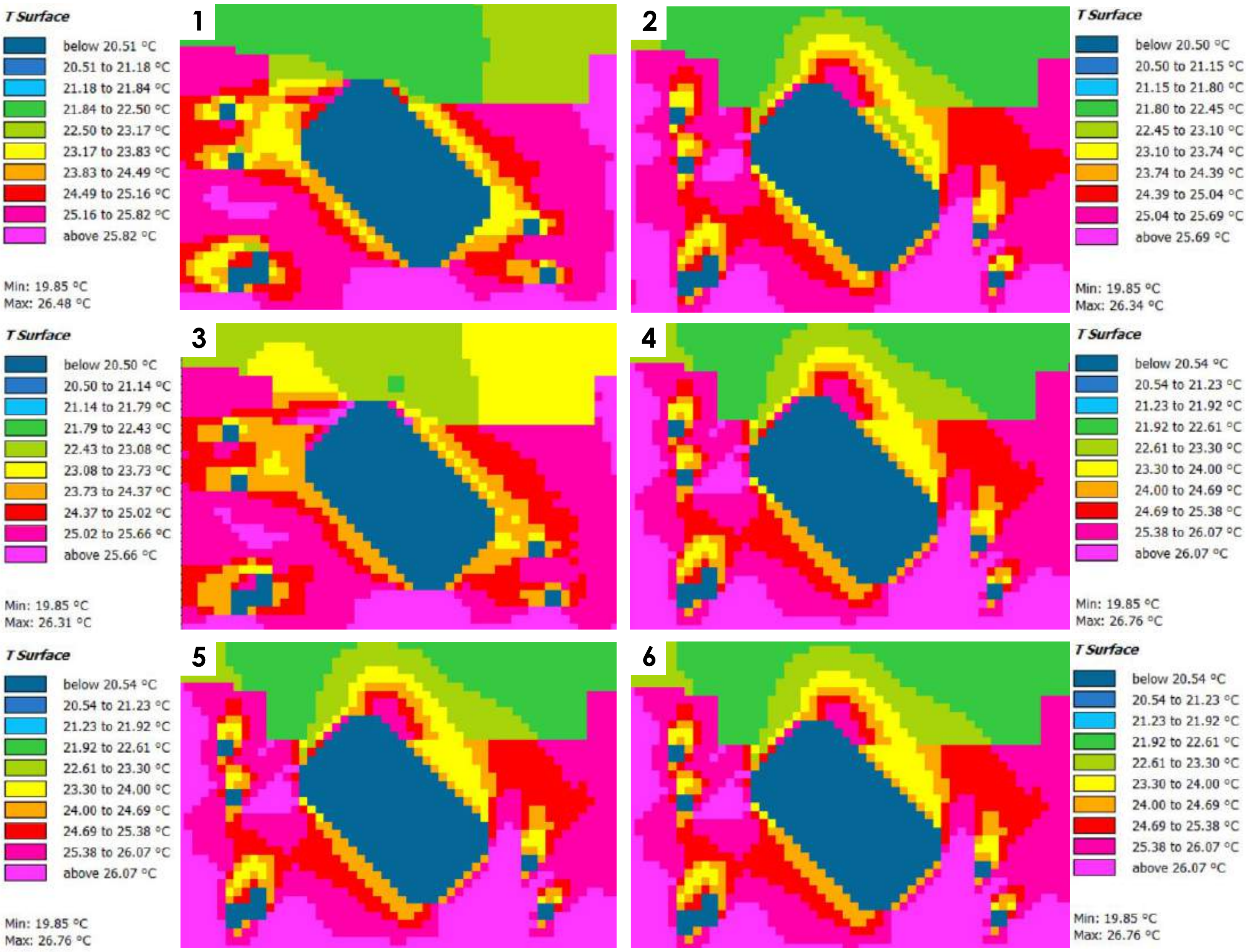


Figure 5.4.28: Surfaces temperature at 22h

Last, the surfaces temperature was checked at 22h. Also here, aluminium is the material bringing the most benefits. Indeed, the minimum temperature is 19,85°C and the maximum is 26,34°C. All the other configurations result to be worse than aluminium but in this case the temperatures are quite similar.
From the results, it can be seen that at this time of the day, surfaces temperature start to decrease as sun has gone down and the warmth accumulated throughout the day is slowly released.

All the outcomes considered, aluminium is the material performing the best in terms of UHI reduction. On the other hand, such a highly reflective material makes the river water temperature increase as it reflects sun onto the river surface, where the water tends to store heat. However, from the figures it is visible that this increase in temperature is limited only to a small portion of the river, whereas the soil temperature is still lower compared to other cases.
Although it is not very sustainable, the project for the new stadium already sees this material being integrated in big portions of the façade, therefore the original design by OMA would not change much.

However, being the impact of the material on UHI not very high, some changes have been brought to the soil configuration as well. Two cases were simulated: greenery and light colored concrete. Greenery was placed on the South-West side of the stadium, where the wind mainly comes from. In this way, benefits are brought not only to the surrounding but also to the stadium itself by using the green as element to cool down the wind. Concrete, instead was placed on the whole surface of the area. The façade material remain aluminium. Location of the new proposed paving materials is shown in figure 5.4.29 and 5.4.30.

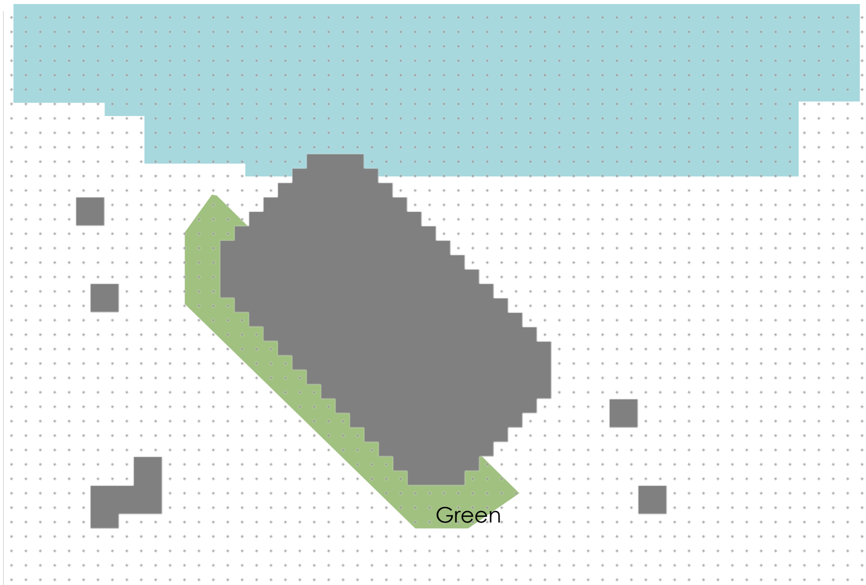


Figure 5.4.29: Greenery location

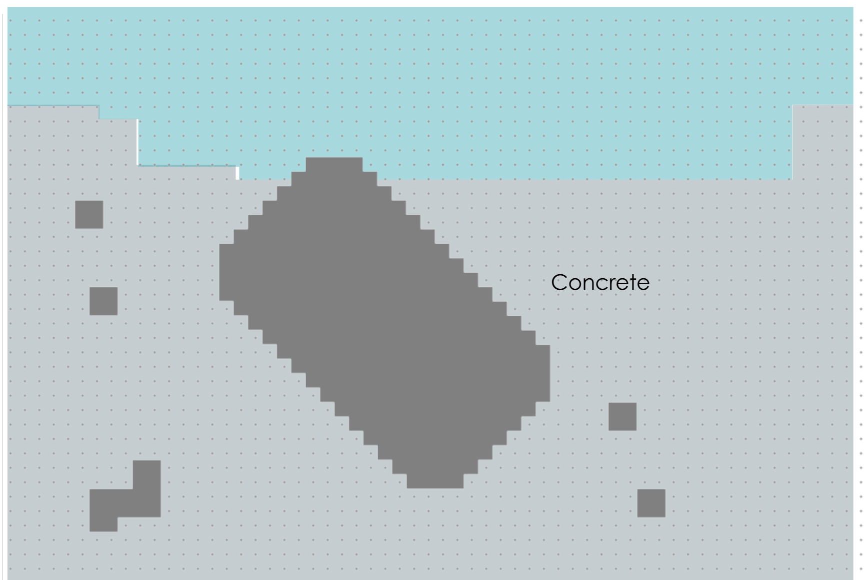


Figure 5.4.30: Light colored concrete location

Simulations outcomes at 8, 12, 18 and 22 hour are shown in the following group of figures.

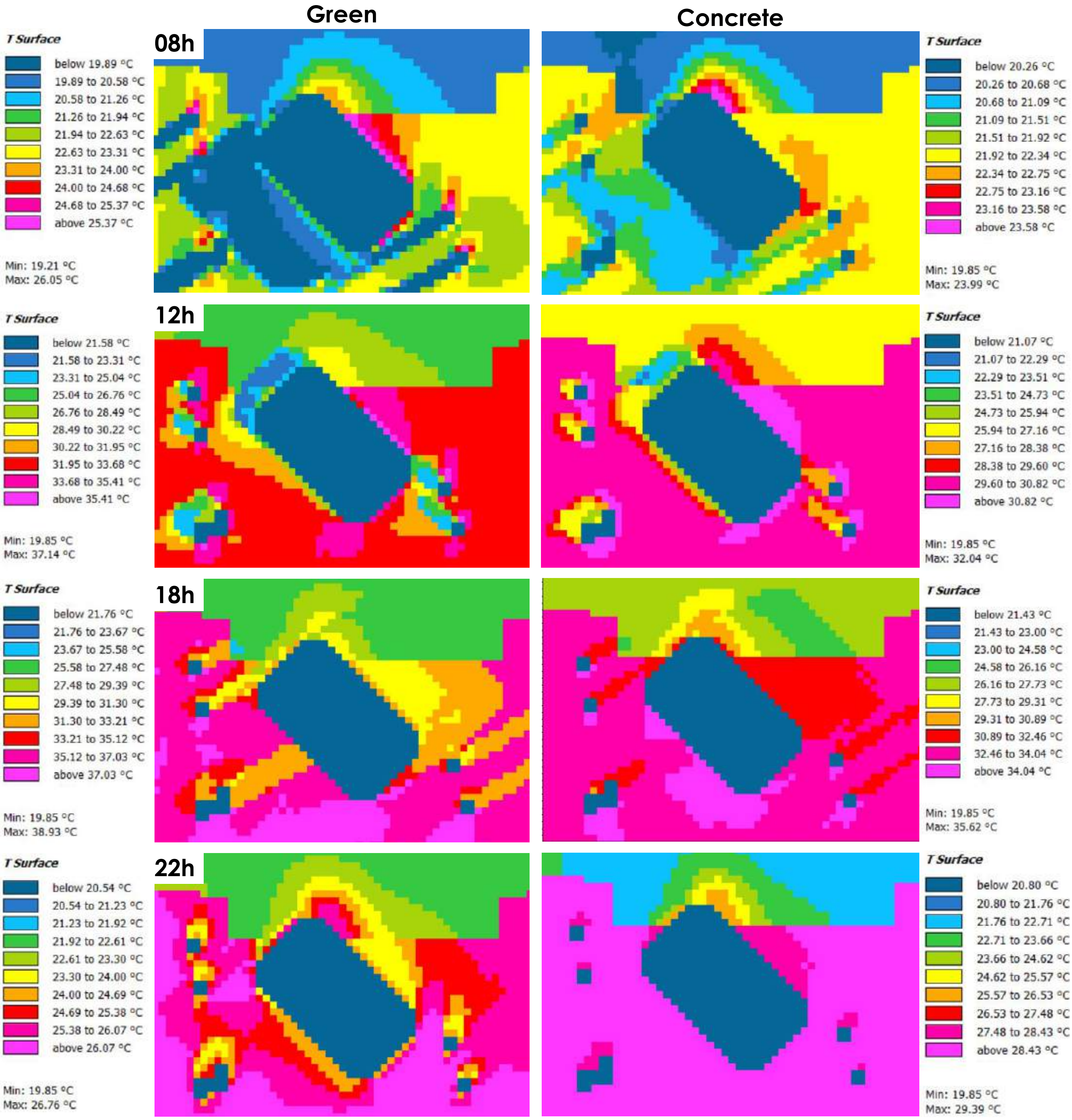


Figure 5.4.31: Surfaces temperature at 8, 12, 18 and 22 - Green vs Light coloured concrete with aluminium façade

Outcomes of simulations show that by using light colored concrete as paving material minimum and maximum surface temperature could be further reduced. However, greenery performs better in reducing UHI in the immediate surroundings of the stadium. Therefore, this is preferred over concrete.

To conclude, an overview of the design of façade is given. Here, the requirements were: natural ventilation, daylight, cooling and UHI reduction.
Steps are shown in figure 5.4.32.

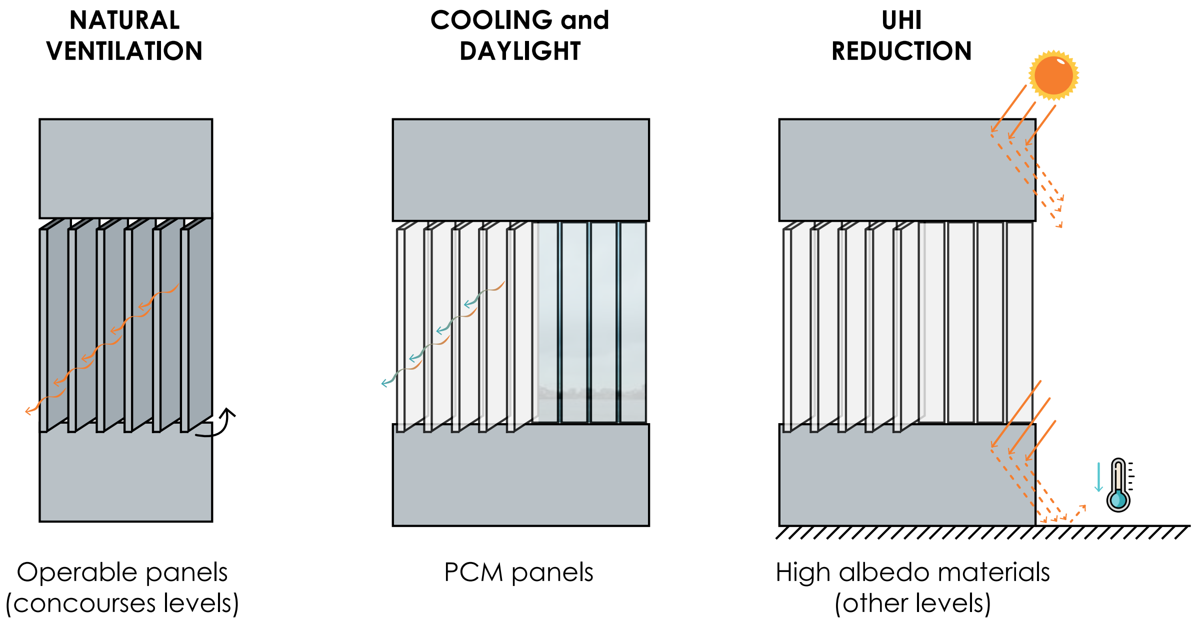


Table 5.4.32: Façade design - steps

5.4.3 Concourses

EVAPORATIVE COOLING / RADIATIVE COOLING

The concourses correspond to the levels where the new façade panels made of PCM are integrated. The design aims at naturally ventilate these spaces, therefore measures to cool down the air and improve comfort are necessary. The proposal is to introduce evaporative cooling at concourses level such that the air that enter could be cooled down.
Evaporative cooling occurs when air comes in contact with water, thus absorbing it and becoming humid air. In order for this to happen in a space, this must be ventilated, and the less the relative humidity of the air is, the more effective the system is. In this case, from Design Builder simulation, it can be observed that air relative humidity in the concourses is around 60%. The process of evaporative cooling allows the cooling of air (incoming or exiting air) or of thermal masses (roofs, walls, ceilings). It uses the natural effect of evaporation to remove heat from the air. Sensible heat from the air is absorbed as latent heat necessary to

evaporate water: arm dry air is changed to cool moist air - heat in the air is used to evaporate water. The amount of sensible heat absorbed depends on the amount of water that can be evaporated in the system (Bokel, 2017).
Therefore, evaporative cooling panels are proposed which will be located on the partition walls that are in the concourses. The panels will not cover the whole surface of the walls due to risk of damages. Therefore the first 2,2 m should be left free. The panels, will be, indeed, placed on the top half part of the walls, which are around 4,5 m high. Ideally, in order to have as much surface as possible for the evaporative cooling to happen, thus increasing the effect, the ceiling area should be exploited. However, this would lead to thermal mass to be covered, which is not convenient due to its good cooling effect.
In addition, the system will be integrated in the floor of level 07, which the bottom part of the roof. Here, the whole surface can be exploited. Figure 5.4.33 shows the location of the evaporative cooling panels.

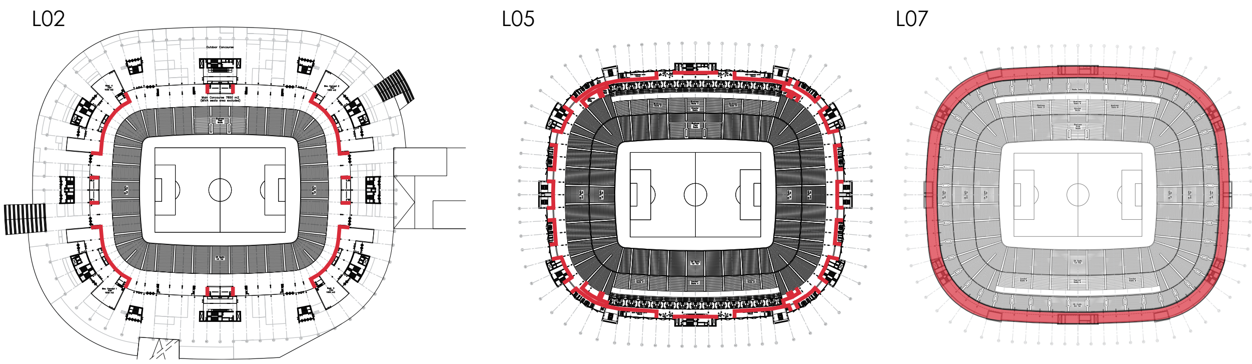


Table 5.4.33: Evaporative cooling panels location

The new panels are made of CELdek media, which is made of specially engineered cellulose. Its properties are similar to the ones of a normal sponge when it comes to evaporative cooling, but it is more resistant in terms of deterioration. CELdek is shown in figure 5.4.34. Also, this material is safe in terms of fire resistance. Information are provided in Appendix B.

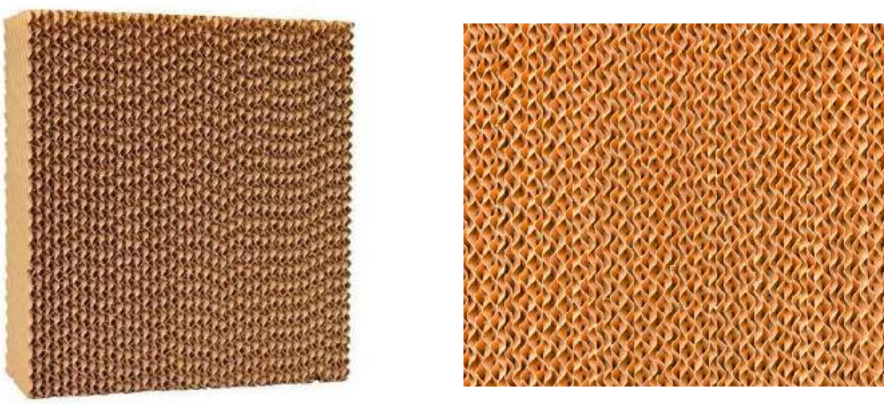


Figure 5.4.34: New façade panels system

The panel system consists of a CELdeck layer, irrigation system to keep the CELdek wet, and a box to cover the irrigation system and connect the panel to the existing wall or floor.

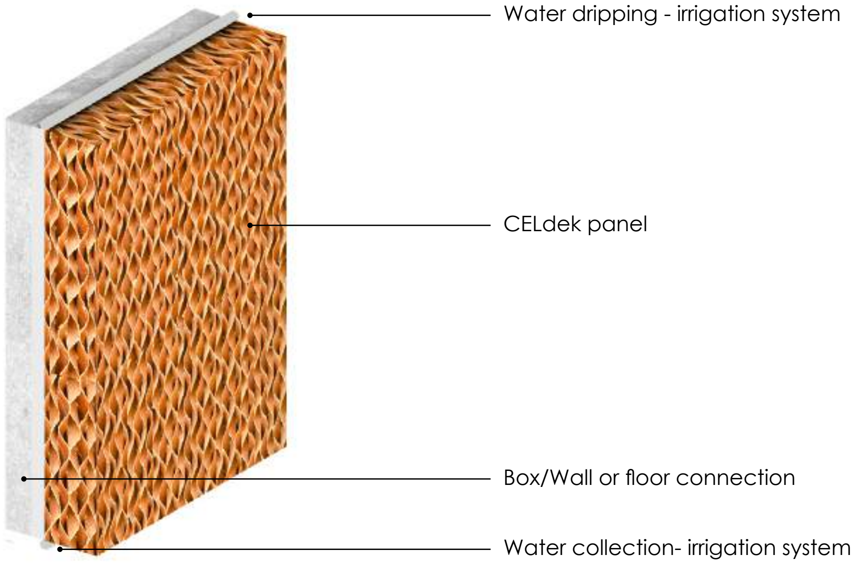


Figure 5.4.35: CELdek panel system

In this picture, the air will enter flowing through the new façade, thus being cooled down by the PCMs, where further cooling is provided by the thermal mass and the wall panels.

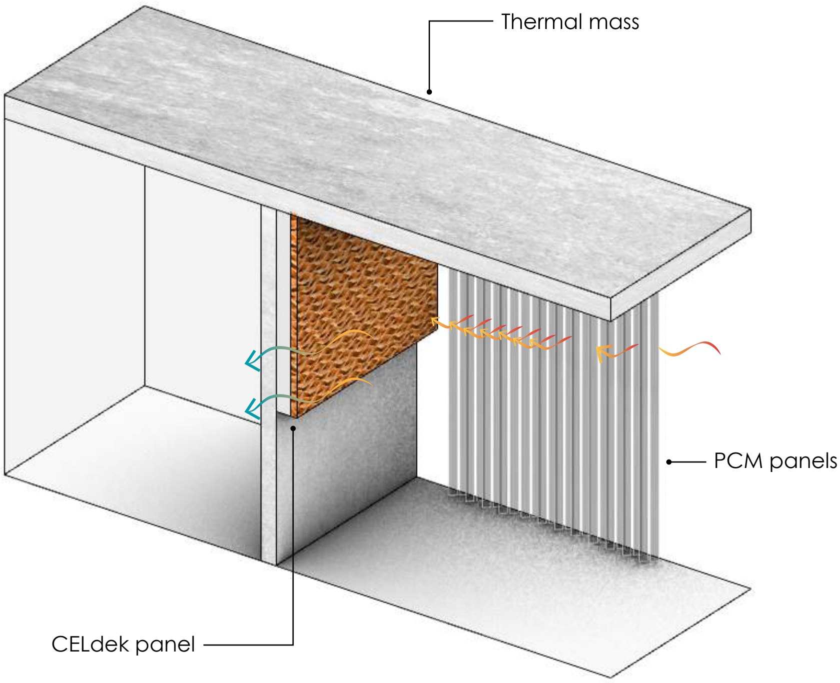


Figure 5.4.36: PCM, CELdek panel and thermal mass cooling system

To check the effect of evaporative cooling on the air entering from outside, the Psychrometric chart is used. As data about the effective power of the product in terms of evaporation are missing, the chart will help see what happens when air becomes saturated, through various steps.

The worst case scenario is considered, corresponding to the 3rd of August, which is the warmest day in which the stadium will be likely to be used both for football and concert. Data are obtained from Design Builder, showing a maximum temperature of 35°C and relative humidity of 60%.
Starting from these values, on the chart, the change in temperature is read for relative humidity increasing to 70%, 80%, 90% and 100% due to evaporative cooling from the CELdeck panels.
Values are shown in the following Psychrometric chart.

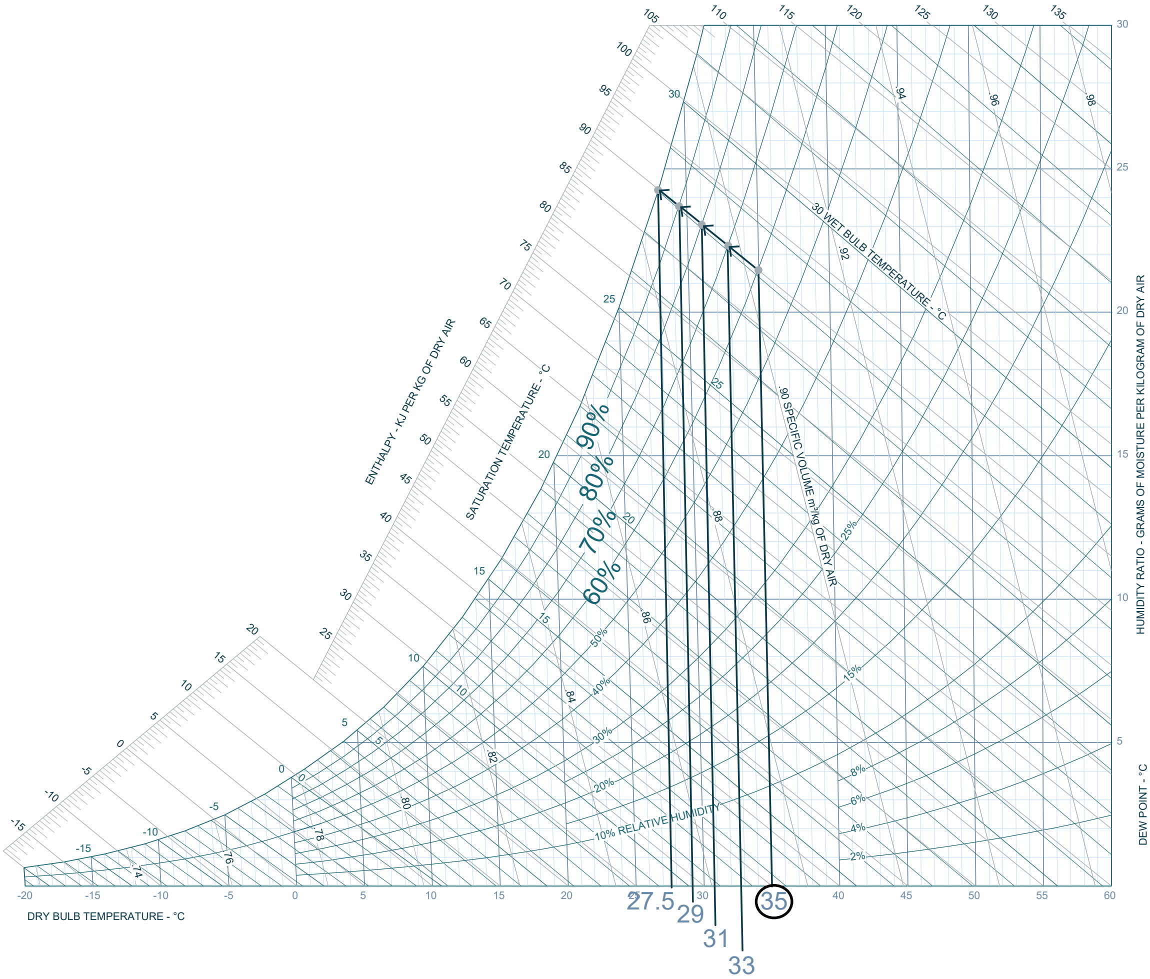


Chart 5.4.1: Psychrometric chart

From the chart, the following values are observed:

- if r.h increases to 70%, dry-bulb temperature decreases to 33°C;
- if r.h increases to 80%, dry-bulb temperature decreases to 31°C;
- if r.h increases to 90%, dry-bulb temperature decreases to 29°C;
- if r.h increases to 100%, dry-bulb temperature decreases to 27,5°C.

Therefore, if the air entering the stadium becomes saturated due to the evaporative cooling effect of the panels, it can decrease up to 7,5°C. However, in this case, not the whole amount of air entering will get in contact with the panels, as they covering relatively small surface. Only some amount of air is cooled down, then it mixes with warmer air so the final temperature will not be 7,5°C lower than the initial one. In addition, the air skims the panels and do not go through them as it normally happens in an evaporative cooler, thus reducing the effect.
On the other hand, it must be considered that the air that enters is pre-cooled by the PCM panels, therefore will not be 35°C.
All these aspects considered, evaporative cooling results to be effective in terms of reduction in air temperature, allowing for natural ventilation to occur even if outdoor air temperature is high, but, in this context, to increase the effect, the panels surface must be increased.

Figure 5.4.37: Stadium render - interior view

5.4.4 Performance evaluation

To evaluate the performance of the final design, calculations were done, starting from the same heat balance equations defined for the football match and concert case in chapter 4.
Here, the new input parameters are those obtained from the final design.

First, the heat balance equation was defined and indoor temperature isolated as it follows.

$$Q_{sun} + Q_{people} + Q_{appliances} = Q_{transmission} + Q_{ventilation}$$

$$Q_{sun} = q \times g \times A_{roof,polycarbonate} + q \times g \times A_{roof,PV} + q \times g \times A_{roof,open}\ [W]$$

$$Q_{people} = n. of\ people \times metabolic\ rate\ [W]$$

$$Q_{appliances} = power\ of\ appliances\ [W]$$

$$Q_{transmission} = \sum UA_{facade\ 1} \times (T_e - T_{cs}) + \sum UA_{facade\ 2} \times (T_i - T_{cs}) + \sum UA_{roof} \times (T_i - T_e)\ [W]$$

$$Q_{ventilation} = 0{,}35 \times n \times V \times (T_i - T_e)\ [W]$$

$$T_i = \frac{Q_{sun} + Q_{people} + Q_{appliances} + T_e \times \left(\sum UA_{roof} - \sum UA_{facade\ 1} + 0{,}35 \times n \times V\right) + T_{cs} \times (\sum UA_{facade\ 1} + \sum UA_{facade\ 2})}{\sum UA_{facade\ 2} + \sum UA_{roof} + 0{,}35 \times n \times V}\ [°C]$$

Formula 5.4.2: New heat balance equation

Then both the values for the case of the football match and concert were considered and indoor temperature calculated.
Differently from chapter 4, outdoor temperature now varies between 35 and -3. These are, respectively, the highest and lowest temperature observed in the new Weather file.

T [°C]	max	35
	min	-3
Solar irradiance [W/m2]	summer	1000
	winter	150
ACH [1/h]	5.8	
Volume [m3]	2347967.7	
Metabolic rate [W/m2]	Football match	167.4
	Concert	522
New materials	External façade	aluminium
	Roof	PVs

Table 5.4.9: Input and outcomes - Football match

Q_{tr} (FACADE 1) [W]	9800	$*(T_e-T_{cs})$
Q_{tr} (FACADE 2) [W]	919	$*(T_i-T_{cs})$
Q_{tr} (ROOF) [W]	115659040	$*(T_i-T_e)$
Q_v [W]	4766374	$*(T_i-T_e)$
Q_{sun} summer [W]	0	
Q_{sun} winter [W]	0	
Q_{ppl} [w]	10546200	
Q_{app} [w]	9000	

T_e	T_i
35	35.2
30	30.2
25	25.2
20	20.2
15	15.2
10	10.1
5	5.1
0	0.1
-3	-2.9

Table 5.4.10: Input and outcomes - Football match

Q_{tr} (FACADE 1) [W]	9800	$*(T_e-T_{cs})$
Q_{tr} (FACADE 2) [W]	919	$*(T_i-T_{cs})$
Q_{tr} (ROOF) [W]	115659040	$*(T_i-T_e)$
Q_v [W]	4766374	$*(T_i-T_e)$
Q_{sun} summer [W]	0	
Q_{sun} winter [W]	0	
Q_{ppl} [w]	32886000	
Q_{app} [w]	10000	

T_e	T_i
35	35.3
30	30.3
25	25.3
20	20.3
15	15.3
10	10.3
5	5.3
0	0.3
-3	-2.7

Table 5.4.11: Input and outcomes - Concert

Results show that in both cases indoor temperature in the semi-outdoor area of the stadium is likely to follow the outdoor temperature.
In general, comparing new results with those obtained from calculations in chapter 4, the new design makes the stadium perform better in terms of temperature control. To prove that, the same calculations have been performed considering the same gains, solar irradiance, air change and temperature range, but having the old design for input values.
Comparison is shown in the following tables and graphs.

Football match

	NEW	OLD
T_e	T_i	T_i
35	35.2	47.8
30	30.2	42.8
25	25.2	37.8
20	20.2	32.8
15	15.2	22.8
10	10.1	17.8
5	5.1	12.8
0	0.1	7.8
-3	-2.9	4.9

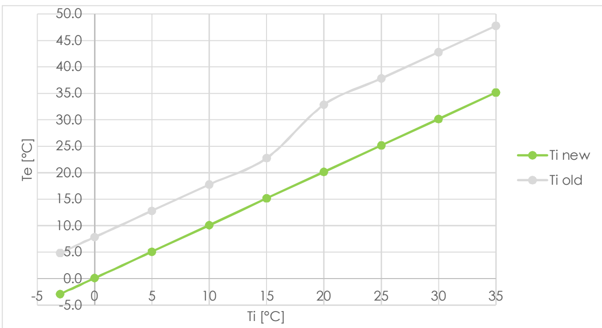


Table 5.4.12: Indoor temperature - football match - new vs old
Graph 5.4.1: Indoor temperature - football match - new vs old

Concert

	NEW	OLD
Te	Ti	Ti
35	35.3	41.8
30	30.3	36.8
25	25.3	31.8
20	20.3	26.9
15	15.3	21.9
10	10.3	16.9
5	5.3	12.0
0	0.3	7.0
-3	-2.7	4.0

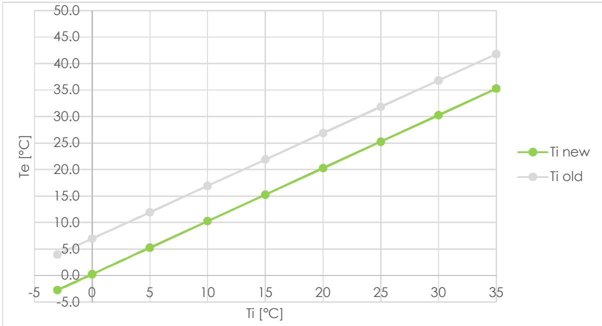


Table 5.4.13: Indoor temperature - concert - new vs old
Graph 5.4.2: Indoor temperature - concert - new vs old

Even though according to the adaptive thermal comfort model, which is shown in figure 5.4.38, the new indoor temperatures would not be very comfortable for users, it could also be said that model is representative for an indoor environment, whereas the stadium is a semi-outdoor space.
Therefore, comfort requirements from users would be less strict and their bodies might be easily able to adapt to temperatures similar to the external ones.
Furthermore, it is very important to consider that in this type of calculations, the cooling provided by the PCM and the CELdek are not taken into account as they would have effect over time. By considering these elements, indoor temperature would be even lower.

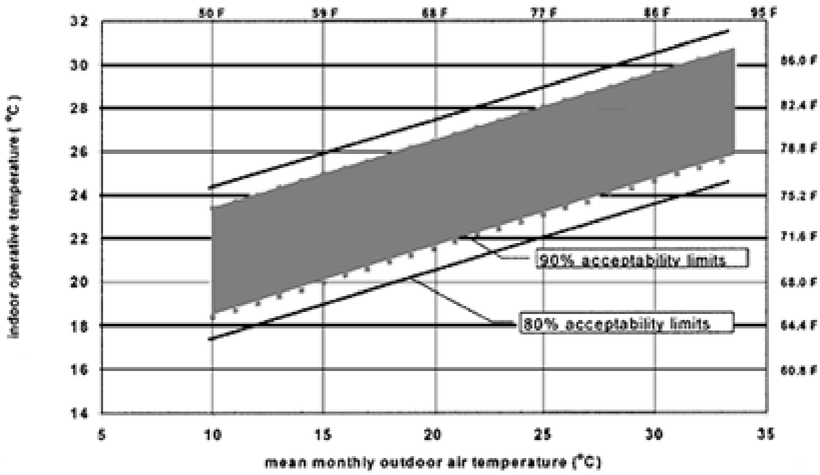


Figure 5.4.38: Adaptive thermal comfort model - ANSI/ASHRAE Standard 55-2004, Thermal Environmental standard Conditions for Human Occupancy
Nicol J.F., Humphrey M. A.,2002.

In addition, from the modified weather file (+3°C monthly average) it can be observed that temperature almost never reaches 35°C, and almost never goes above 25°C.
35°C are, indeed, reached only for a few days throughout the year and mainly in June. In this month, however, the stadium would not be used for football matches but only for events or concerts, therefore at night when outdoor temperature is lower.
Temperatures,obtained from Design Builder, are shown in figure 5.4.39.

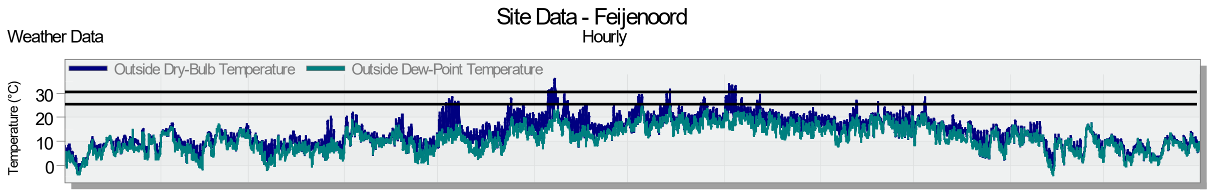
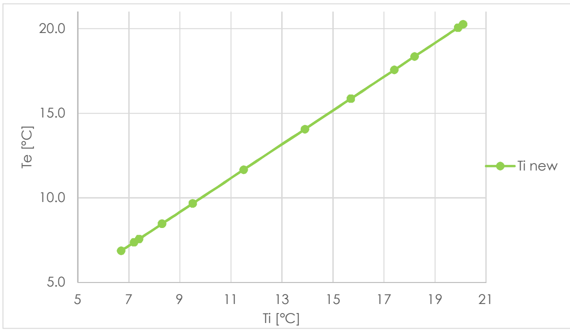


Figure 5.4.39: Temperature data
Design Builder

Therefore, new calculations were performed also considering the monthly average temperatures given by the weather file, which are usually lower than the previously considered extremes.
Results are shown the following tables, both for football match and concert.

Football match

	Te	Ti
JAN	7.2	7.4
FEB	6.7	6.9
MAR	8.3	8.5
APR	11.5	11.7
MAY	15.7	15.9
JUN	18.2	18.4
JUL	19.9	20.1
AUG	20.1	20.3
SEP	17.4	17.6
OCT	13.9	14.1
NOV	9.5	9.7
DEC	7.4	7.6



Concert

	Te	Ti
JAN	7.2	7.5
FEB	6.7	7.0
MAR	8.3	8.6
APR	11.5	11.8
MAY	15.7	16.0
JUN	18.2	18.5
JUL	19.9	20.2
AUG	20.1	20.4
SEP	17.4	17.7
OCT	13.9	14.2
NOV	9.5	9.8
DEC	7.4	7.7

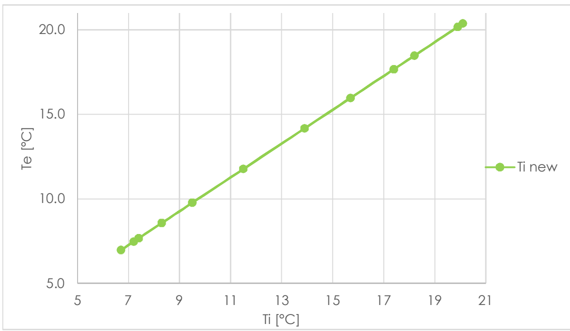


Table 5.4.14: Comparison outdoor monthly average temperature and indoor temperature - football match
Graph 5.4.3: Comparison outdoor monthly average temperature and indoor temperature - football match
Table 5.4.15: Comparison outdoor monthly average temperature and indoor temperature - concert
Table 5.4.4: Comparison outdoor monthly average temperature and indoor temperature - concert

Considering the average temperatures, the stadium will never result to be overheated, and comfort will be guaranteed in the warmest month. However, in winter period it might result to be a bit cold for users.

To conclude, it can be said that, in general, with the new additions and changes brought the design, indoor temperature can be controlled and overheating is avoided.

Whereas indoor temperature was evaluated by means of calculations, as the not detailed information about materials would have not allowed to get a proper temperatures map, for ventilation a new simulation with Butterfly was performed. The focus was on the combined behaviour of concourses and open roof panels in terms on air flow.
Results are shown in figure 5.4.40, 5.4.41 and 5.4.42.

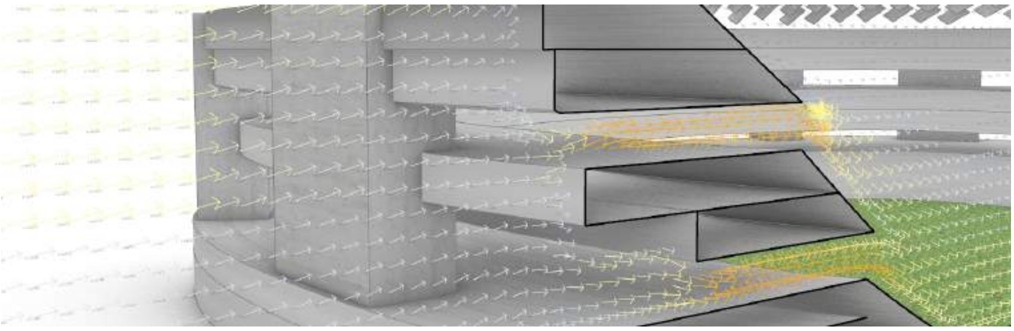


Figure 5.4.40: CFD simulation - view from outside

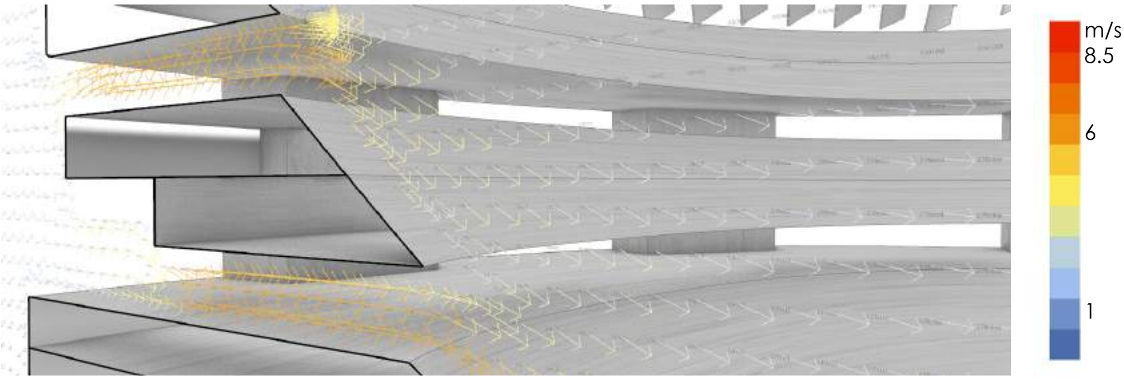


Figure 5.4.41: CFD simulation - view from inside (concourses)

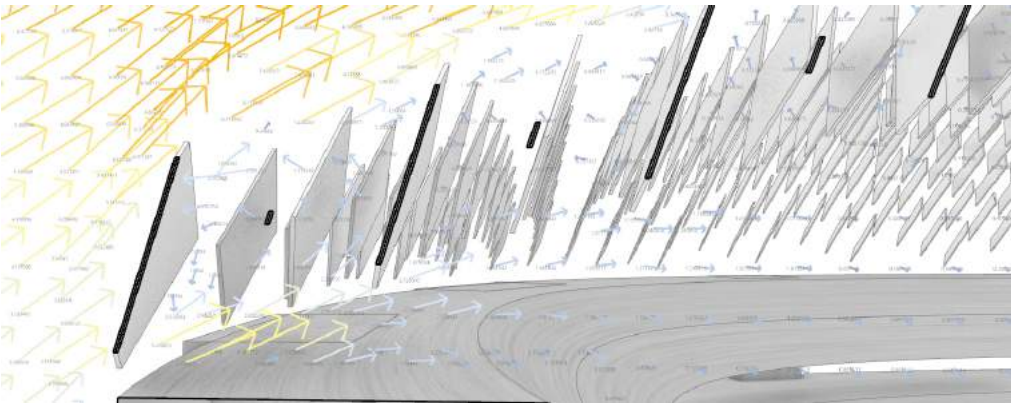


Figure 5.4.42: CFD simulation - roof

From the pictures it can be observed that when wind enters the open concourses its speed increases. Inside the stadium, then, the airflow tends to go downwards on the tiers area. Regarding the roof, the air velocity is reduced but there is still some airflow, therefore natural ventilation can occur.

5.4.5 Extra measures

In order to supply the stadium with the remaining cooling demand to improve comfort when the passive measures are not enough, a proposal for active systems is developed, always looking at the site potentials.
In section 4.5.2 "Extra measures", some active measures to be applied to the Feyenoord case study were introduced.
In particular, the aquifer thermal energy storage (ATES) combined with energy exchange with water from the river seems to be the most suitable withing the context.

ATES principle consists in the extraction and injection of ground water into two separate storage wells.
In summer, water is extracted from the coldest well and used to cool the building. This heats the water from approximately 8 to 16 °C. The heated water is injected at the warm well and stored. During winter, instead, the extraction/injection flow is inversed and the heated water (with a temperature of approximately 15 °C) is pumped back to the building. Using a heat pump the heat is extracted from the water and the cold water (6°C) will be injected in the cold well. (Zeiler,2017).
This system can be implemented by using the water from the nearby river, the Nieuwe Maas, in specific periods of the year, when the water temperature is favorable to provide either heating or cooling for the building. Ideally, the combined ATES-River system works at the beginning of the warm season, when the water is still cold enough to provide cooling, or in autumn, when the water is still quite warm due to the accumulated summer heat.
The water of the river is led past a heat exchanger which is connected to the building's climate control system. This allow for the building to absorb the heat or the cold still present in the river. After passing through the heat exchanger the warm/cold river water is stored into the warm/cold well.
When the river water is too warm or too cold to be used, water is pumped up from the two wells, depending on the season.

In order to make the whole system more efficient also in terms of cost and feasibility, heat and cold exchange at district level is introduced. This is possible due to the fact that Feyenoord City project does not only focus on the New Stadium but also on the construction of new buildings with different functions, such as commercial, hotel and residential.
In particular, residential buildings are favorable for heat and cold exchange because their heating demand is higher than the cooling demand. On the other hand, the stadium requires more cooling than heating.

Therefore, heating and cooling will be provided to the stadium through a aquifer thermal energy storage system combined with the river, which sees thermal exchange between the stadium and the surrounding residential buildings.

The system is shown in figures 5.4.43 and 5.4.44.

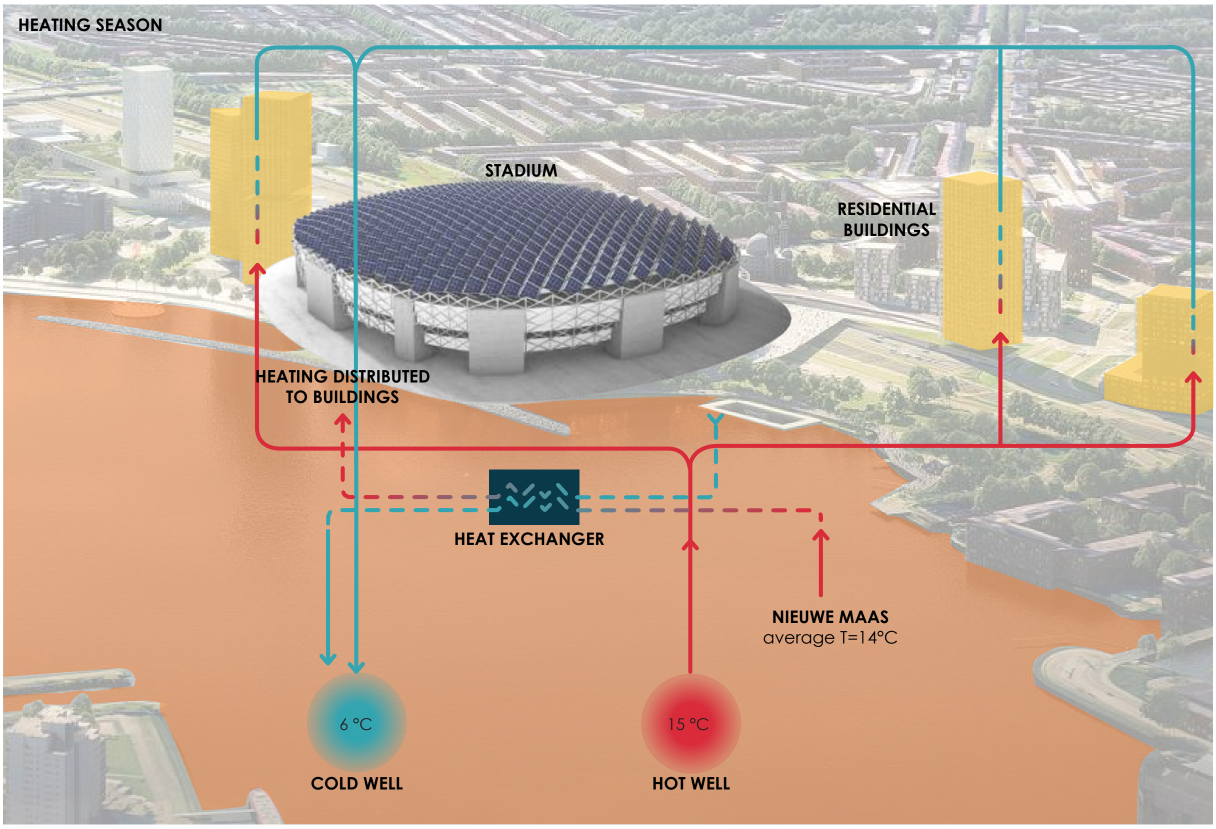


Figure 5.4.43: ATES+Nieuwe Maas - heating period

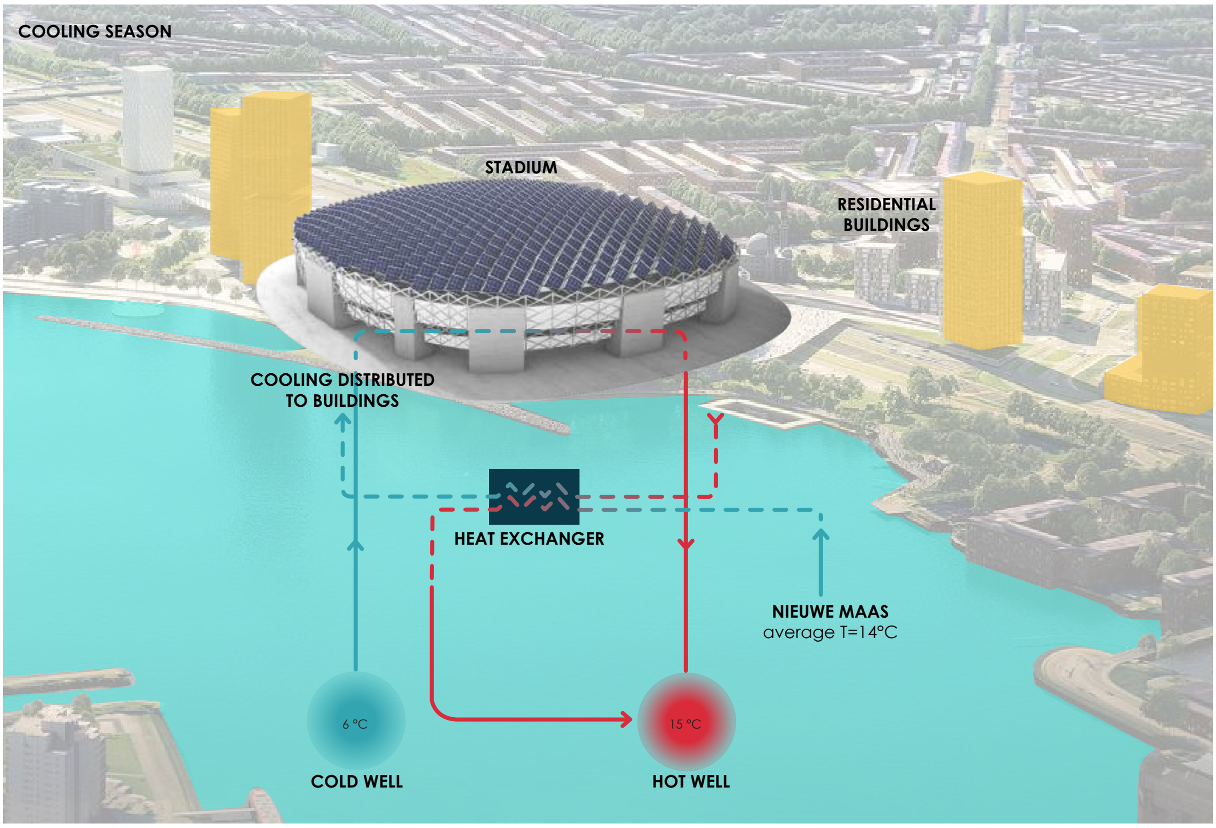


Figure 5.4.44: ATES+Nieuwe Maas - cooling period

Local cooling measures are also proposed, with the focus on the seating areas. From section 5.2.2 "Building", the CFD simulation run with Butterfly for Grasshopper shown that when the wind coming from South-West is channeled through the open concourses when it hits the façade. Then, when the air flows into the semi-outdoor space of the stadium, it tends to go downwards, following the tiers.

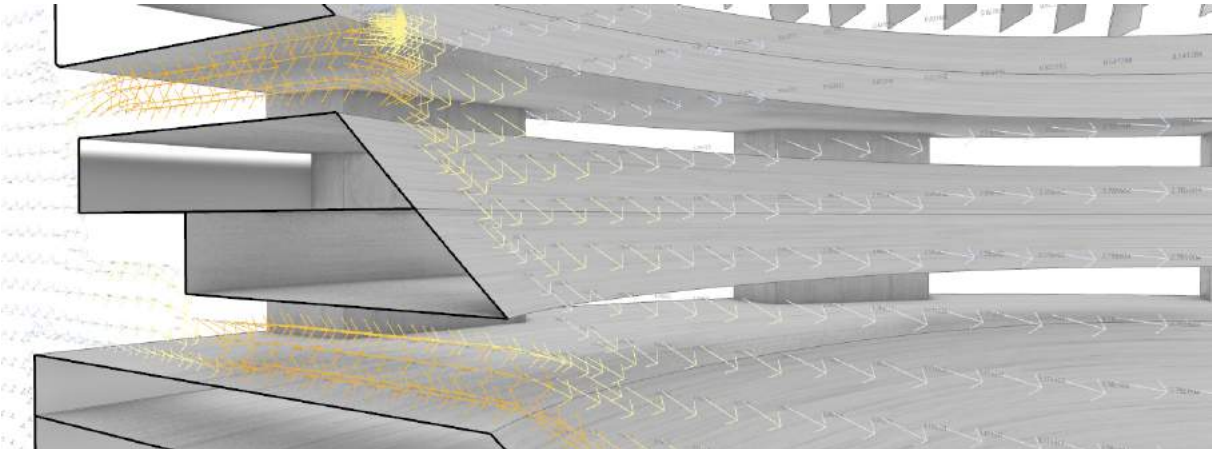


Figure 5.4.45: Cfd simulation with butterfly - indoor wind flow

In addition, the study of local measures in section 4.5.2 "Extra measures", shown that local cooling could be effective to reduce the temperature, if properly designed and located.
Here, the proposal is to introduce air nozzles at the top of the tiers in correspondence of the open levels, namely the concourses and the bottom part of the roof. These supply cold air to the tiers. With this system it would be possible to naturally ventilate the building, by opening the defined levels, also when the outdoor temperature is not very favorable. The air coming from outside through the concourses mixes with the colder air supplied by the nozzles, and since the air flow tends to go downwards, the cooled air will be supplied to the tiers.

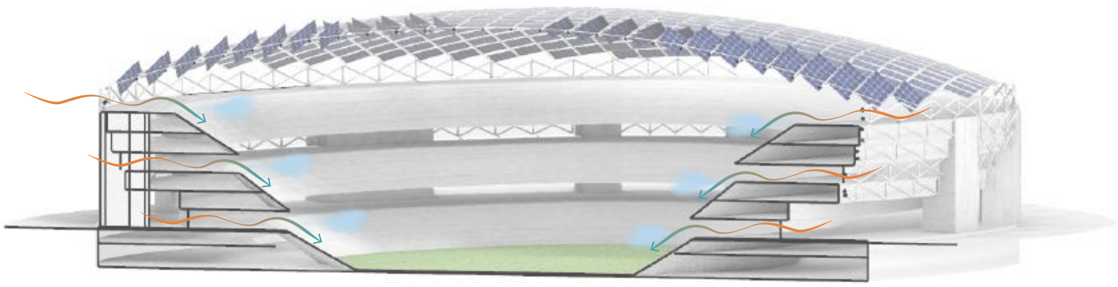


Figure 5.4.46: Local cooling measures

5.5 DESIGN APPROACH

This research aims at creating guidelines for the design of climate adaptive stadia around the world, taking the New Feyenoord stadium as case study. In this chapter, all the steps to get to a final design to make a stadium adaptable to climate and, in particular to climate change, are explained.
The new Feyenoord stadium was here analyzed, and outcomes of the research focus on this specific case. However, the method could be replicated for the design of other stadiums.
The design phases find validation in the paper "Smart and Bioclimatic Design: an effective approach to the sustainable use of resources and deployment of local qualities" (van den Dobbelsteen, van Timmeren, Mensinga, 2008).

The design approach should be as it follows:

1) **Context and site analysis - Local characteristics**
 a) Climate
 b) Orientation
 c) Sun
 d) Wind
 e) Surroundings
 f) Local resources

Understanding the context means to create connections between the stadium and its surroundings and develop a coherent design which fits a bigger framework. The analysis can affect the stadium at building scale, or its relation with the surroundings.
Climate influences the design as it helps understand the focus of the research by having specific data. In particular temperatures information give an idea about the comfort or discomfort of users, whereas sun and wind influence the design based on the possibility to integrate or avoid them. Next to this, orientation is important as it might allow to exploit more or less resources such as sun and wind. By determining the orientation and the effect of the sun on the building, it is possible to define if and where shading is needed, or where the building should let sunlight enter. Orientation and wind analysis allow to design for natural ventilation in such a way that wind does not cause discomfort to users.
The study of surroundings helps create connections with nearby buildings, understand their effect on the stadium, and find potential resources in the area, such as water.
The analysis of the context actually helps define the issues and potentials of the areas, therefore determine the goals of the design in such a way that it fits the context and improve itself.

2) **Objectives - Starting points**

Defining the goals of the design helps keep focused in the analysis phase. When the aim is clear, calculations, simulations and design choices follow it.
In this case, the main objectives were to improve the comfort, reduce the cooling demand and mitigate urban heat island effect.

3) **Parameters - Boundary conditions**

Definition of the context is not the only element to consider for the design of the building. It is, indeed, necessary to understand which are the parameters, or elements, affecting it the most. In order to analyze the parameters, it is necessary to keep the goal of the design clear.
Calculations or basic simulations can be performed to have a first insight into what would be the behaviour of the building if one or more parameters are changed. Outcomes allow to define on which elements the design should focus on in order to achieve the previously stated goals.

4) **Design - Smart solution**

Once the relations with the surroundings and the effect of parameters are defined, it is possible to proceed with the actual design of the building. It is important to take into account all the previous analyses and outcomes to come up with a coherent proposal, able to fit the context.

Table 5.5.1 gives an overview of possible measures and the goals that could be achieved by integrating them.

5) **Validation**

The overall design can be tested with different tools: calculations, simulations or real measurements, with the last being possible only if the final product is already built.
Calculations are more useful for a fast check, but they are not as accurate as simulations with specific softwares.
On the other hand simulations give more accurate results but to get them it is necessary to also have detailed and precise inputs.

By following these steps it should be possible to get to a design proposal that exploit the site potentials as much as possible to achieve the defined goals.

			Shade	Daylight	Ventilation	Rain	Acoustic	Heat gains reduction	UHI reduction	Cooling demand reduction	Heating demand reduction	Electricity demand reduction
CONTEXT												
Site analysis	Orientation		■	■	■			■	■	■	■	■
	Sun		■	■				■	■	■	■	■
	Wind				■					■	■	
	Water								■	■		
DISTRICT SCALE												
Surroundings	Relation with other buildings		■	■	■	■		■	■	■	■	■
	Greenery		■					■	■	■		
	Paving material								■			
BUILDING SCALE												
Building geometry			■	■	■	■		■	■	■	■	■
Passive measures	Natural ventilation				■					■	■	
	Shading		■	■				■	■	■		
	Materials	Thermal mass								■	■	
		PCMs								■	■	
Openings			■	■	■			■		■	■	■
Roof	Material	High albedo	■					■	■	■		
		Opaque	■									
		Translucent or transparent		■							■	■
	Green		■					■	■	■		
	Operability	Retractable	■	■	■	■	■			■	■	■
Façade	Material	High albedo	■					■	■	■		
		Opaque	■									
		Translucent or transparent		■							■	■
	Green		■					■	■	■		
	Operability	Operable	■	■	■	■	■			■	■	■

Table 5.5.1: Measures and effects

6 CONCLUSIONS

In chapter 2 “Research framework”, research questions and objectives were defined to clarify the goal of the research. In this chapter, answers will be given.

The goal of the research is to develop a design approach to make stadia adaptable to climate change and to the specific climatic conditions of their location. The focus, here, is on the semi-outdoor area of the stadium, namely the field and the tiers, which are the most exposed to outdoor conditions, thus being harder to control the comfort of users.
This research helps define guidelines for stadia to be designed in such a way that a comfortable indoor micro-climate can be created by controlling the temperature. In addition, being the stadium such a big infrastructure, the design can also bring effect on th surroundings, in particular on the urban heat island effect in the area.
By introducing adaptation measures, indeed, the stadium can guarantee proper livability of users in a future warmer scenario.
Based on the defined goals, the research questions were introduced.

Main research question

How can the envelope of a large-scale stadium be designed to integrate passive strategies to provide cooling in a future warmer scenario and guarantee a comfortable micro-climate to users, while reducing the UHI in the surroundings?

Sub-questions

1) ***How are the stadium and its surroundings affected by climate change, in particular by rising temperatures?***

2) ***How do users’ comfort requirements vary according to the carried-out activity?***

3) ***Which are the parameters affecting the indoor comfort the most?***

4) ***How can the design allow for shading in such a way that daylight is still provided?***

5) ***How can natural ventilation be implemented in the design? What would be the effectiveness of the measure?***

6) ***How can cooling be provided to the space?***

7) ***Which materials can be used in the design of the envelope so that the indoor comfort is improved? How they help mitigate UHI in the surroundings?***

First, the sub-questions will be answered as these have helped answer the main research question.
The first two sub-questions got an answer in the first part of this research, when the framework was defined. The answer helped define the goals of the research as they gave a clear overview of the issues related to climate change and global warming.

1) ***How are the stadium and its surroundings affected by climate change, in particular by rising temperatures?***
Climate change is leading to shifting weather pattern, with associated increasing heat waves and droughts periods, as well as extreme events.
Buildings and built environment are extremely vulnerable to climate change. Due to the increasing temperatures, extreme events and risk of floods or other phenomena, there might be an increase in the risk of collapse, declining state and significant loss of value. Buildings, indeed, can significantly be deteriorated by these factors and their lifespan reduced.
In particular, due to increasing temperature, the stadium cooling demand will enormously increase in order to guarantee comfortable temperatures to the users.
At urban scale, raising temperatures will affect the urban heat island effect in the area, causing comfort of people to decrease and risk of heat stress to increase.

2) ***How do users' comfort requirements vary according to the carried-out activity?***
Although temperatures will raise, users requirements still remain the same as today. In this research, two main activities were considered: football matches and concerts/events. For each activity there are different users and related needs.
In case of a football match, the users are the players and the spectators. Both users require cooling in case of hot temperatures to avoid health hazards. However, players must be able to perform in excellent conditions, whereas comfort requirements of visitors can vary and adapt to outdoor conditions, thus being more flexible. In any case, protection from sun, rain and uncomfortable wind is needed.
In case of a concert, the users are mainly the spectators. Here, as well, guaranteeing cooling and temperature control is one of the main requirement as there are many people likely to be performing heavy activities, such as dancing. Fresh air is also needed.
Not having control over the users' needs might lead to serious health risks due to heat stress.

As due to global warming temperatures will raise, these requirements will become more strict and hard to respect.

The third sub-question got an answer in the phase of design exploration.

3) ***Which are the parameters affecting the indoor comfort the most?***
In order to answer to this question, outcomes of calculations must be observed. According to them, the parameters having the highest influence on the comfort and temperature in the semi-outdoor area of the stadium are air change rate, so ventilation, and sun. In fact, when ventilation increases, temperature decreases, whereas when solar radiation decreases, temperature decreases as well.

The other sub-questions have been answered in the analysis and design phase and they were very important to get to the final design proposal.

4) ***How can the design allow for shading in such a way that daylight is still provided?***
According to calculations outcomes from chapter 4 "Case study: The new Feyenoord stadium", solar irradiance is one of those parameters affecting indoor temperature the most. Therefore, the design aimed at reducing it. In particular, the roof was designed to respond to the sun hitting it. The façade, instead, was not consider as it is in contact with the conditioned space and would not affect the semi-outdoor area. The design of the roof consists of PV solar-tracking panels, able two rotate on two axes. This allows to screen sun hitting the Souther, Northern, Eastern and Western sides of the roof. In addition, by rotation around the axes, the panels can let daylight reach the football pitch.

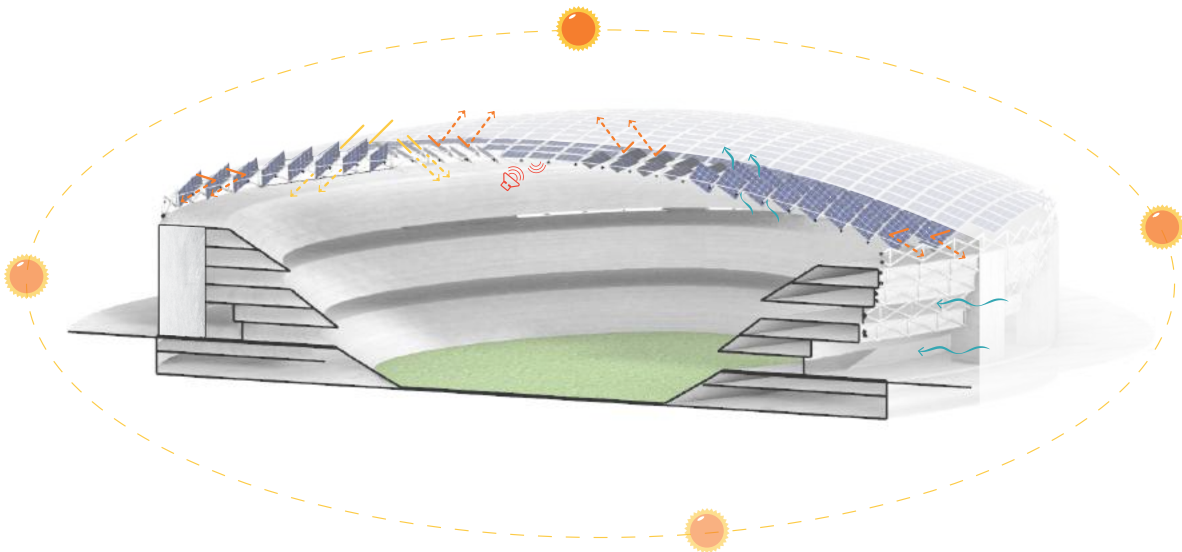


Figure 6.1: Roof concept overview

5) ***How can natural ventilation be implemented in the design? What would be the effectiveness of the measure?***
Calculations performed in chapter 4 analyzed the effect of different parameters on the temperature in the semi-outdoor area of the stadium. Outcomes shown that ventilation is actually very important to cool down the space, as it is the parameter having the biggest effect on the reduction of indoor temperature.
In order to integrate natural ventilation into the building design, a CFD analysis was done to check the wind flow around and inside the stadium. Results shown that wind is likely to be channeled into the stadium where the façade is open. In addition, when the air flow enter the stadium, it tends to go downwards on the tiers. All these aspect considered, some levels of the stadium are designed to be open to allow for ventilation. These are the concourses and the bottom part of the roof. Roof panels also help control natural ventilation by being operable.
Simulations in Design Builder were done to check what the indoor temperature would be on the areas the research focus on, namely the tiers and the field.
These simulations were performed taking as reference day the warmest day of the year, which from the modified weather file (with 3°C added to the monthly average) resulted to be the 3rd of August. Outcomes shown that when the outdoor temperature is too high, reaching up to 35°C, indoor temperature also increases and results to be uncomfortable for users.
Therefore, it can be said that natural ventilation can bring benefits to the comfort but it is necessary for it to be controlled. This can be done by means of sensors who allow for the façade to open only when outdoor temperature is favourable to cool down the space, or at night, when outdoor temperature is usually lower. In order to control it, special façade panels for the concourses have been designed.

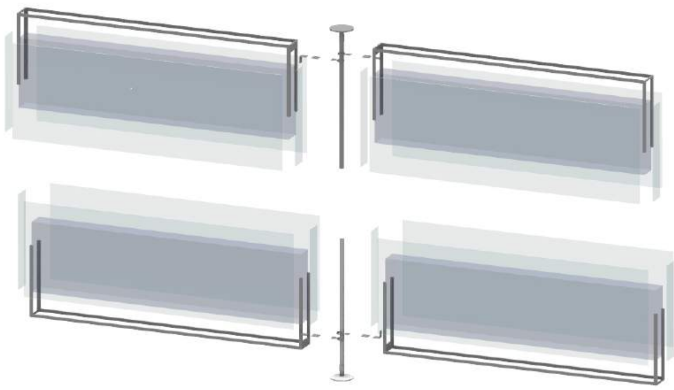


Figure 6.2: New façade panels components

6) ***How can cooling be provided to the space?***
This measure was discussed in chapter 4, when specific measures for the stadium were analyzed.
Although shading and natural ventilation already help control the indoor temperature, further measures were needed.
First, the thermal mass of the stadium itself can cool down the environment. Then, evaporative cooling can be integrated. In the design, evaporative

cooling is provided in the concourses and the bottom part of the roof, where particular panels are placed. This is a system made of CELdek panels, a material having properties similar to the one of a sponge when it comes to evaporative cooling. These panels are placed on the inner walls of the concourses and on the slab located at the bottom of the roof system.
According to the analysis, given the temperature and the relative humidity of the air entering through the concourses and roof, evaporative cooling results to be very effective. However, specific data of the product and inner walls dimensions were missing so the effect was estimated by using the psychrometric chart. Looking at the results obtained in chapter 5, in perfect conditions, if the air gets saturated, its temperature is likely to decrease by around 8°C.
However, in this scenario not the whole amount of air gets in contact with the panels, so the final mixing of air will be warmer than what was observed on the psychrometric chart. If as much surface as possible was covered with this evaporative cooling panels, temperature decreases and comfort of users is increased also during warmer days.
In addition, active cooling measures where defined in order to supply the stadium with cooling when passive measures are not enough. Cooling is here provided through an aquifer thermal energy storage system combind with the use of heat and cold from the river. ATES works at district scale. Next to it, a local cooling measure is proposed: a system of nozzles located on top of the tiers, in correspondence of the open levels of the stadium, to cool down the air that enters through natural ventilation.

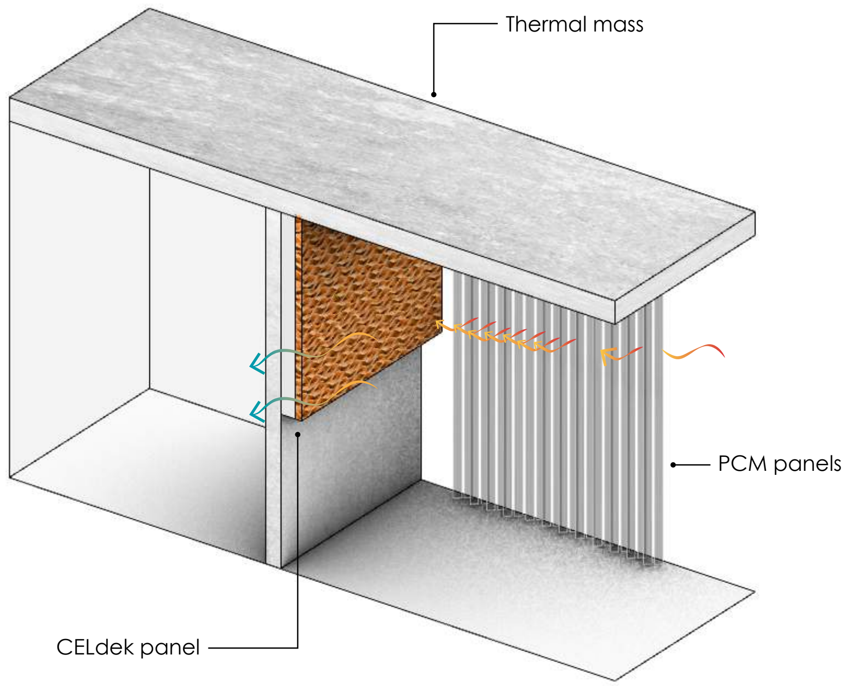


Figure 6.3: New façade panels system

6) ***Which materials can be used in the design of the envelope so that the indoor comfort is improved? How they help mitigate UHI in the surroundings?***
In order to reduce the UHI in the area, an analysis of the materials of the external façade was done. This is in contact with the areas that were considered as conditioned, and being the focus of the research on the semi-outdoor space of the stadium, it resulted that the external façade has no direct impact on the comfort of users in that space.
Therefore, materials were selected based on their effect on urban heat island. Simulations were performed with ENVI-met by changing the materials of the envelope. From the outcomes, the most effective in terms of reduction in UHI is aluminium. However, the effect is not very high and only in the immediate surroundings of the stadium. To further reduce it, it would be necessary also to change the paving material around the stadium and integrate green, which resulted to be the most effective in terms of temperature reduction in the immediate surroundings.

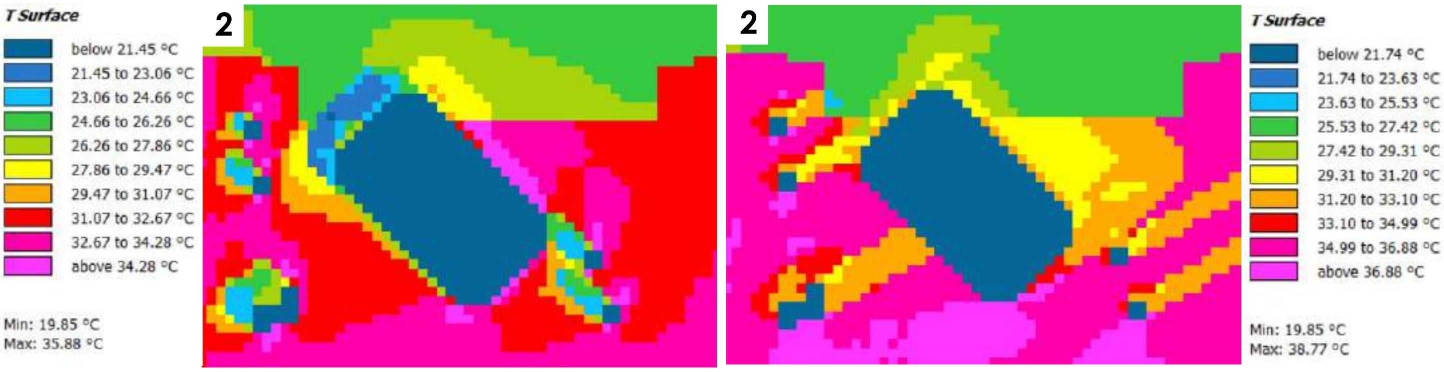


Figure 6.4: Surfaces temperatures at 12 and 18h - aluminium

Even though in general the façade does not directly enclose the semi-outdoor space of the stadium, the levels of the concourses are in contact with it, so design choices could help reduce the temperature. In particular, in the final concept, at concourses level, PCM panels were integrated, which help pre-cool the air entering the stadium, thus reducing the temperature when it reaches the concourses. This system does not affect the UHI but brings benefits at building scale.

Finally, the main research question is answered.

How can the envelope of a large-scale stadium be designed to integrate passive strategies to provide cooling in a future warmer scenario, thus guaranteeing a comfortable micro-climate to users, while reducing the UHI in the surroundings?
In order to integrate passive measures in the design of the stadium, a detailed analysis of the context is necessary. This helps create connections between the stadium and its surroundings and develop a coherent design which fits a bigger framework. Climate, sun, wind and local potentials were explored to understand how the design could exploit them as much as possible.

In addition, by analyzing several parameters, it was possible to set the focus of the design on those having the biggest effect on indoor temperature reduction. The design, therefore, focused on the two main components of the envelope: the roof and the façade.

Roof

The main goal in the design of the roof was to reduce the solar gains. From the calculations performed, indeed, it came out that if the solar irradiance is reduced, indoor temperature drastically decreases. As the external façade is not in contact with the semi-outdoor space, nothing could be done with it to reduce the temperature in the tiers and the field. Therefore, the roof is the element to be designed in such a way that shade is provided and temperature reduced.

In the design of the roof several factors were considered, among which sun and daylight. The former must be kept away not to increase indoor temperature, whereas the latter must be allowed to let the field grow and guarantee visual comfort to spectators.

To achieve the goal, the roof panels have been designed in such a way that they are solar-tracking modular system made of PVs.

Panels are operable and can rotate around two axes, with the rotation following solar radiation and wind direction.

Façade

The external façade was divided into two parts for the design: concourses levels and other levels. That was necessary as the concourses allow for wind to reach the semi-outdoor space, whereas other levels have no contact with that. Integration of passive measures, namely natural ventilation is possible at concourses levels.

Concourses façade has been designed in such a way that natural ventilation can occur. To check the feasibility of the design, a preliminary CFD analysis was performed to observe the air flow around and inside the building when the concourses are open.

The panels of the concourses are made of PCM, which allows for the air that passes through them to be pre-cooled (or pre-heated). This panels are movable by means of a pivoting system. In this way the façade is operable, so that in ca be closed when outdoor air temperature is too warm, and open when conditions are favourable.

In addition, once the air enter the concourses, it is further cooled down by the evaporative cooling panels and by the large amount of thermal mass that is exposed.

On the other hand, as previously mentioned, the design of the other levels' façade focuses on the choice of materials to reduce UHI. As previously mentioned, the most suitable material results to be aluminium.

The combined design of roof and façade allows therefore for shading to keep solar radiation away from the semi-outdoor space, but also for natural ventilation. By integrating these measures temperature control is possible in the semi-outdoor space, thus guaranteeing comfort to users. Next to it, measures are also integrated in some indoor areas, such as the concourses, where evaporative cooling occurs. Last, design choices allow for UHI reduction, even if small, so the design does not bring benefits only to the stadium itself but also to the surrounding environment.

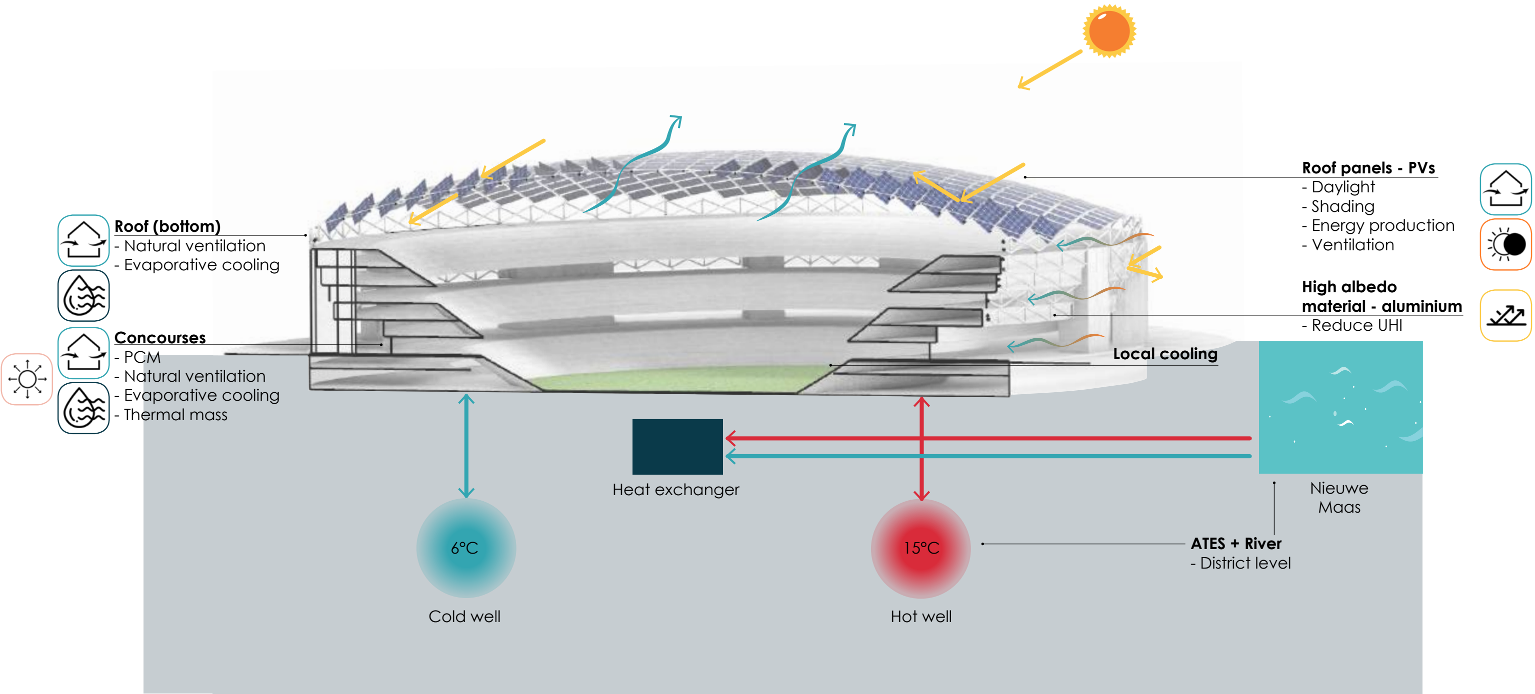


Figure 6.5: Final concept overview

Figure 6.6: Render - exterior

Figure 6.7: Render - exterior
OMA, 2018 (base model for render)

7 RECOMMENDATIONS

In this final chapter, recommendations for future research are provided, with the goal to help other climate designers with their research and design process.

The first aspect I would like to focus on is the quality and quantity of information about the project itself. In this case, in particular, I was provided with a full project report, giving a good amount of information. However, this report was produced on June 2018, therefore the design was outdated or not complete in several aspects: materials were not clearly specified, and the structure not detailed.
This made calculations and simulations outcomes accurate or reliable only to a certain extent. In some cases, digital simulations were not even possible to be carried out.
Better information quality should be accessible to the designer, which ideally should be provided with updates on the project when this is not finalized yet. This would help get more accurate results, which could be useful to verify the performance of the design proposal and apply changes when needed.

Also, the number of people, or companies, involved in the project could bring some limitations. Whereas on one hand having many advisors and experts working on different aspects could lead to a final optimal design, if the project is given to a student for research, this could bring issues. Indeed, it would necessary to speak to professionals from all the different companies to get a clear picture of the whole design proposal.
My recommendation, therefore, would be to find a way to get in touch with all the parties involved so that every aspect of the design can become clear enough to properly develop a personal design proposal, and improve the performance of the existing one.

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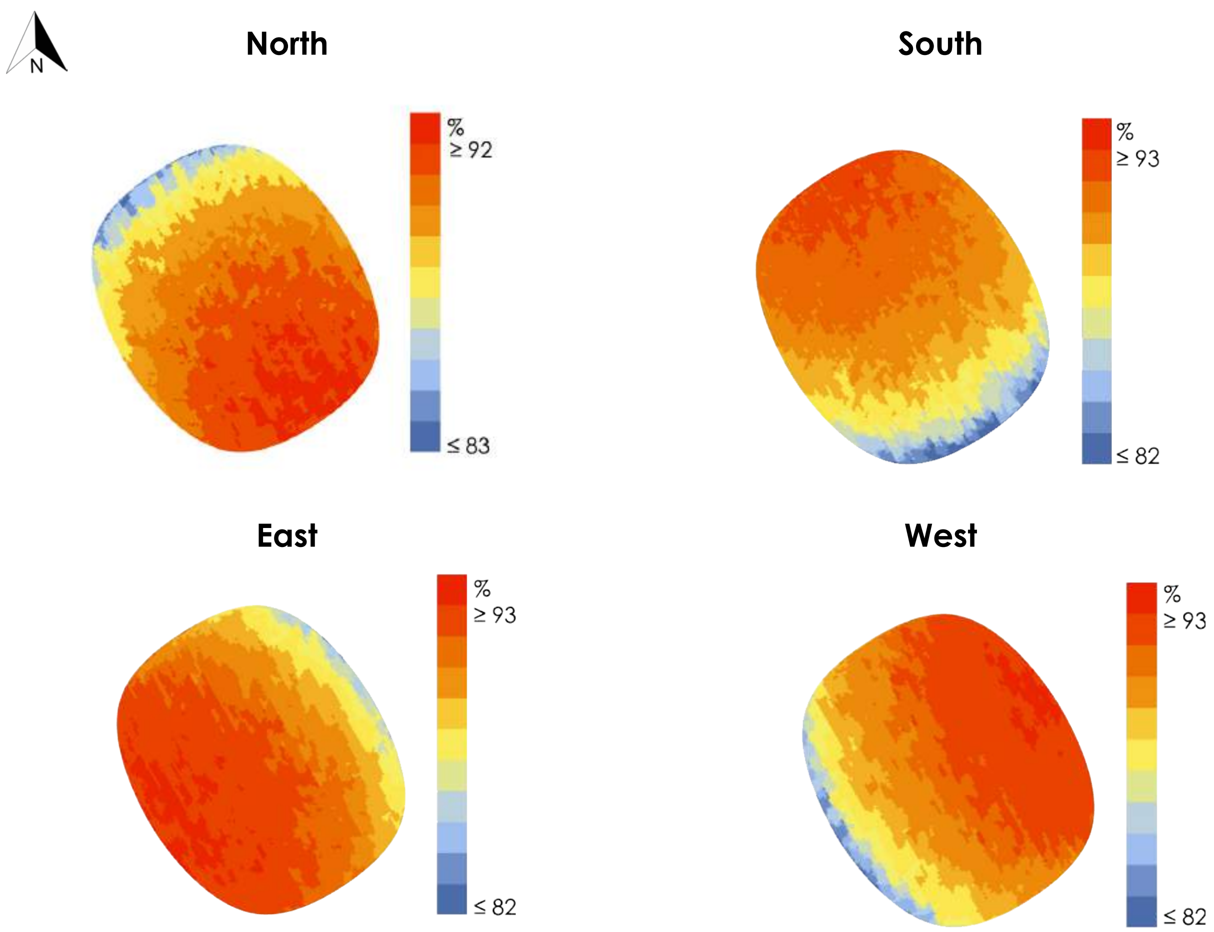
9 APPENDICES

A) ILLUMINANCE ON THE FIELD

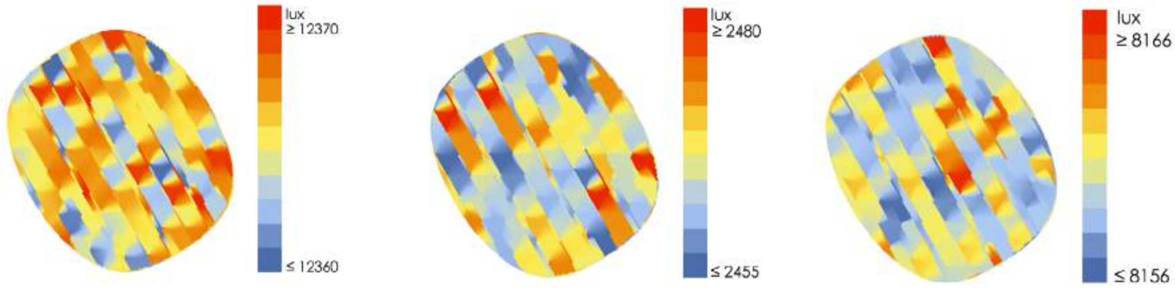
Annual



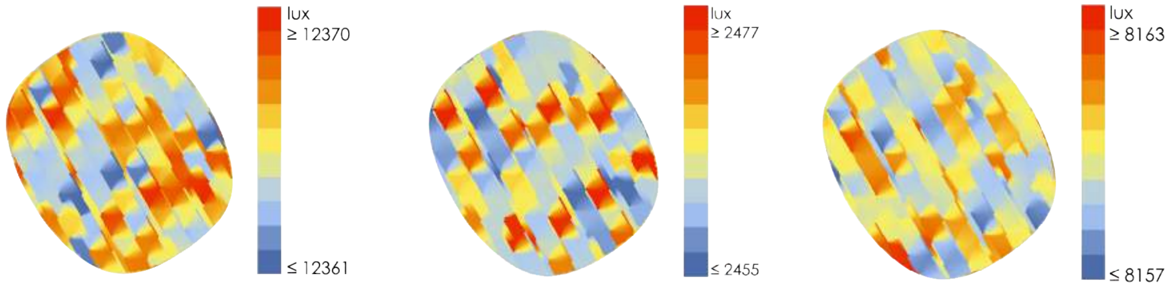
Hourly

21/06 maximum	21/12 minimum	21/03 average

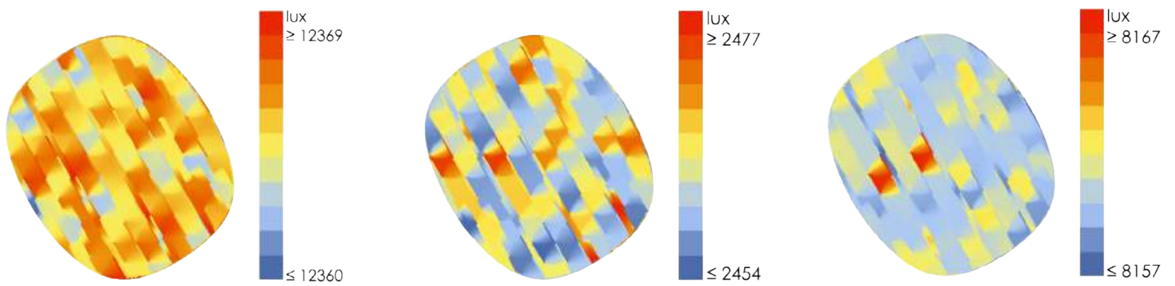
North



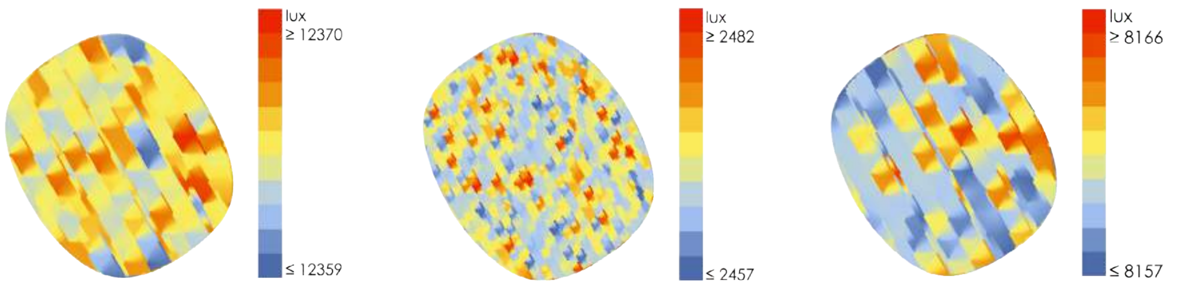
South



East



West



Data Sheet

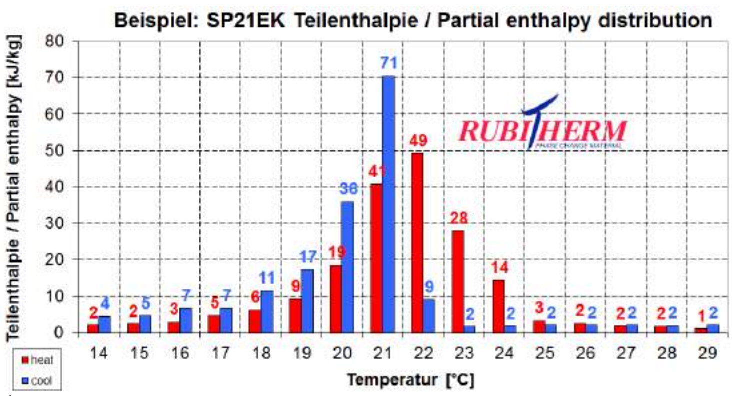
SP21EK

The creation of the latent heat blended material RUBITHERM® SP has led to a new and innovative class of low flammability PCM. RUBITHERM® SP consists of a unique composition of inorganic components.
RUBITHERM® SP is preferably used as macroencapsulated material. Densities of 1,0 kg/l and more can be achieved. This and all properties mentioned below make RUBITHERM® SP to the preferred PCM used in the construction industry. Both passive and active cooling can easily be realized e.g. in wall elements and air conditioners.
We look forward to discussing your particular questions, needs and interests with you.

Properties:
- stable performance throughout the phase change cycles
- high thermal storage capacity per volume
- limited supercooling (2-3K depenndig on volume and cooling rate),
- low flammability, non toxic
- different melting temperatures between -21°C und 70°C are available

The most important data:	**Typical Values**	
Melting area	**22-23** main peak: 22	**[°C]**
Congealing area	**21-19** main peak: 21	**[°C]**
Heat storage capacity ± 7,5% Combination of sensible and latent heat in a temperatur range of °C to 13 °C. 28	**170** **47**	**[kJ/kg]** **[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]***
Density solid at 15 °C	**1,5**	**[kg/l]**
Density liquid at 35 °C	**1,4**	**[kg/l]**
Volume expansion	**3-4**	**[%]**
Heat conductivity	**0,6**	**[W/(m·K)]**
Max. operation temperature	**45**	**[°C]**
Corrosion	**corrosive effect on metals**	

Note: The product must be initialized (melt, homogenize and cool to 0 ° C) once before use to achieve the specified properties.
Many SP-product are hygroscopic and may absorb moisture if stored improperly. This can result in a change of the physical properties given.



*Measured with 3-layer-calorimeter.

Rubitherm Technologies GmbH
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D-12277 Berlin
Tel: +49 30 720004-62
Fax: +49 30 720004-99
E-Mail: info@rubitherm.com
Internet: www.rubitherm.com

The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 30.09.2016

Munters

MATERIAL SAFETY DATA SHEET

Effective Date: 03/31/01

SECTION I - PRODUCT IDENTIFICATION AND PREPARATION INFORMATION

Product Name: CELdek, CELdek with Mi-T-edg, Mi-T-Cool, Mi-T-edg

Description: Cellulose paper impregnated with insoluble anti-rot salts and rigidifying saturants.

Manufacturer Name and Address:
The Munters Corporation
108 Sixth Street Southeast
Fort Myers, Florida 33907

MSDS Prepared by:
Dell Tech Laboratories Ltd.
UWO Research Park
100 Collip Circle
London, Ontario N6G 4X8
(519) 858-5021

Emergency Phone: (941) 936-1555

SECTION II - INFORMATION ON INGREDIENTS

Ingredients	CAS #	Wt%	ACGIH-TLV	OSHA-PEL	LC_{50}	LD_{50}
Copper, elemental	7440-50-8	<0.1	1 mg/m^3 TWA	1 mg/m^3 TWA	Not available	1.2 mg/kg oral, rat
Phenol	108-95-2	<0.1	5 ppm Skin	5 ppm Skin	316 mg/m^3 4 h, rat	317 mg/kg oral, rat
Formaldehyde	50-00-0	<0.1	0.3 ppm Ceiling	0.75 ppm TWA	590 ppm 4 h, rat	800 mg/kg oral, rat
Acrylic monomer	Not available	<0.1	Not available	Not available	Not available	Not available

SECTION III - PHYSICAL DATA

Boiling Point (deg C): Not applicable
Vapour Pressure (mm Hg): Not applicable
Vapour Density (Air = 1): Not applicable
Solubility in Water: Not applicable
Physical State: Solid
Appearance; Odour: Tan Kraft paper and rubber; odourless
Specific Gravity: >1.0
Percent Volatile (Wt %): Not applicable
Evaporation Rate (Water = 1): Not applicable
pH (as supplied): Not applicable
Viscosity: Not applicable
Odour Threshold (ppm): Not available

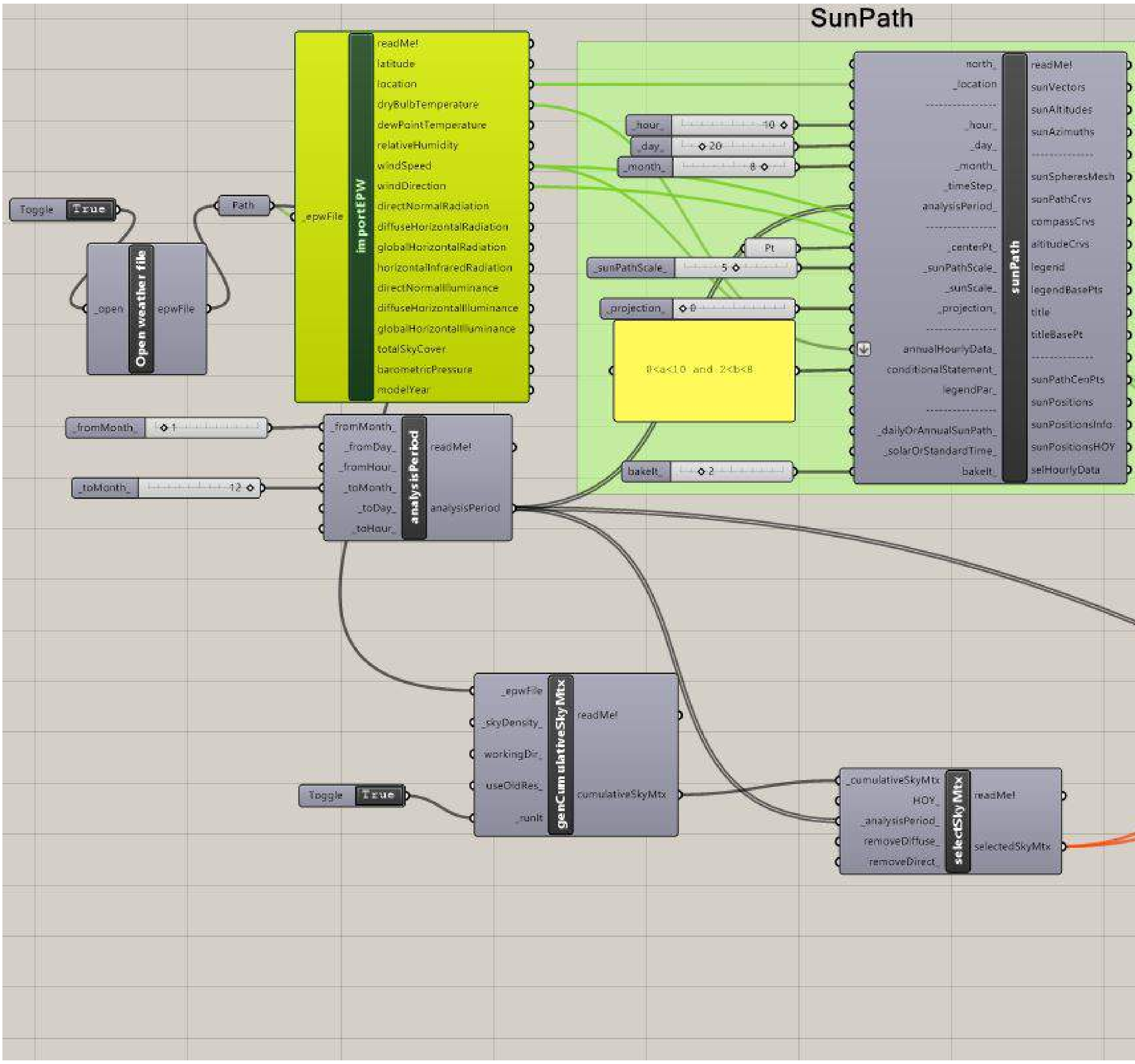
SECTION IV - FIRE AND EXPLOSION DATA

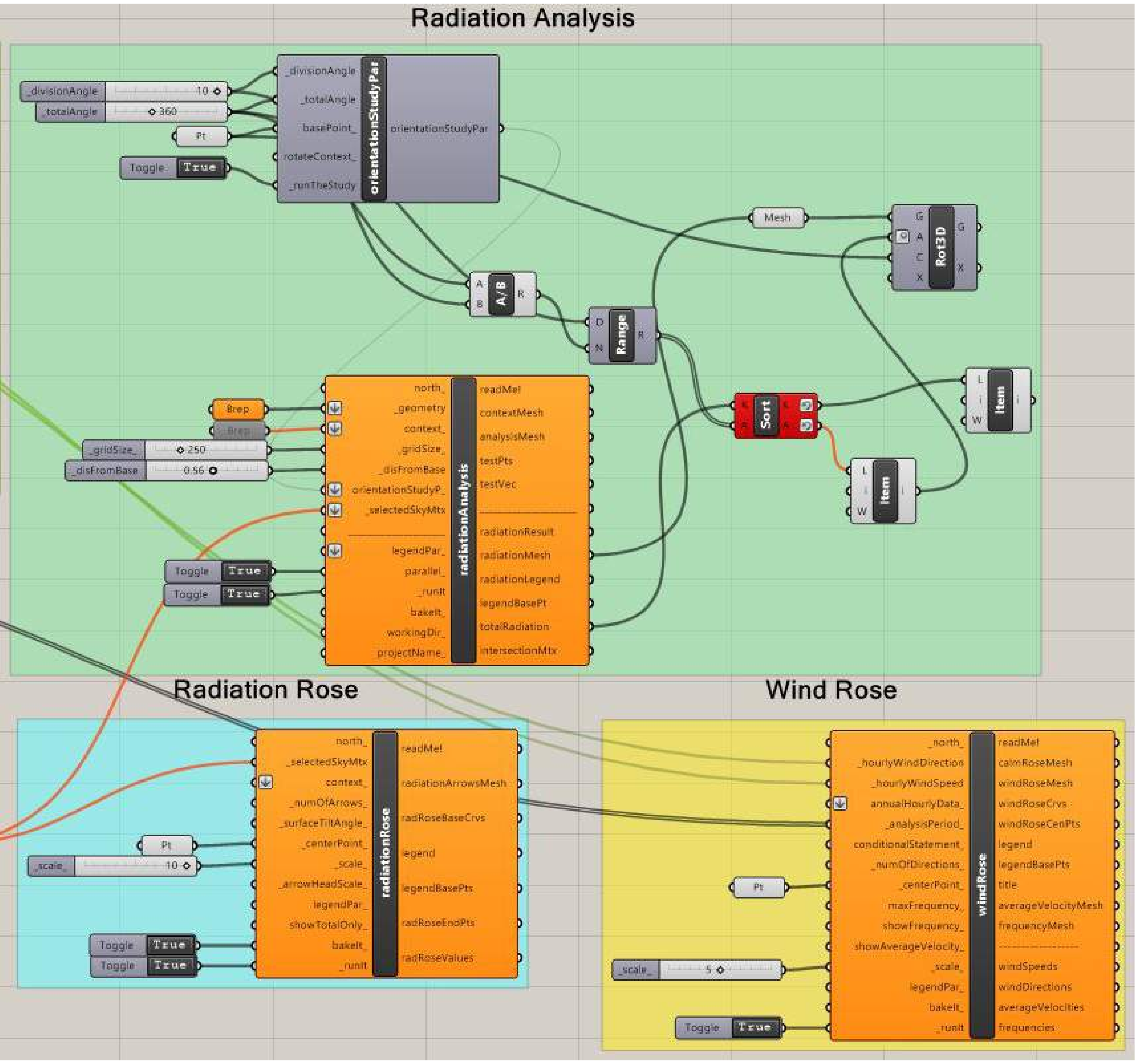
Flammability: Edge coating not flammable according to WHMIS criteria (no self-sustained flame). Corrugated paper not flammable according to WHMIS criteria (ignites at a rate of 0.13 cm/s under laboratory conditions). Will sustain combustion in the presence of an external source of ignition.
Flash Point of Liquid (^{0}C, TCC): None **LEL:** Not applicable **UEL:** Not applicable
Hazardous Combustion Products: May include and are not limited to oxides of carbon, oxides of nitrogen, organic acids, aldehydes, hydrogen chloride.
Means of Extinction: Water spray, carbon dioxide.
Special Fire Hazards: Firefighters should wear self-contained breathing apparatus. Avoid breathing smoke.

SECTION V - REACTIVITY DATA

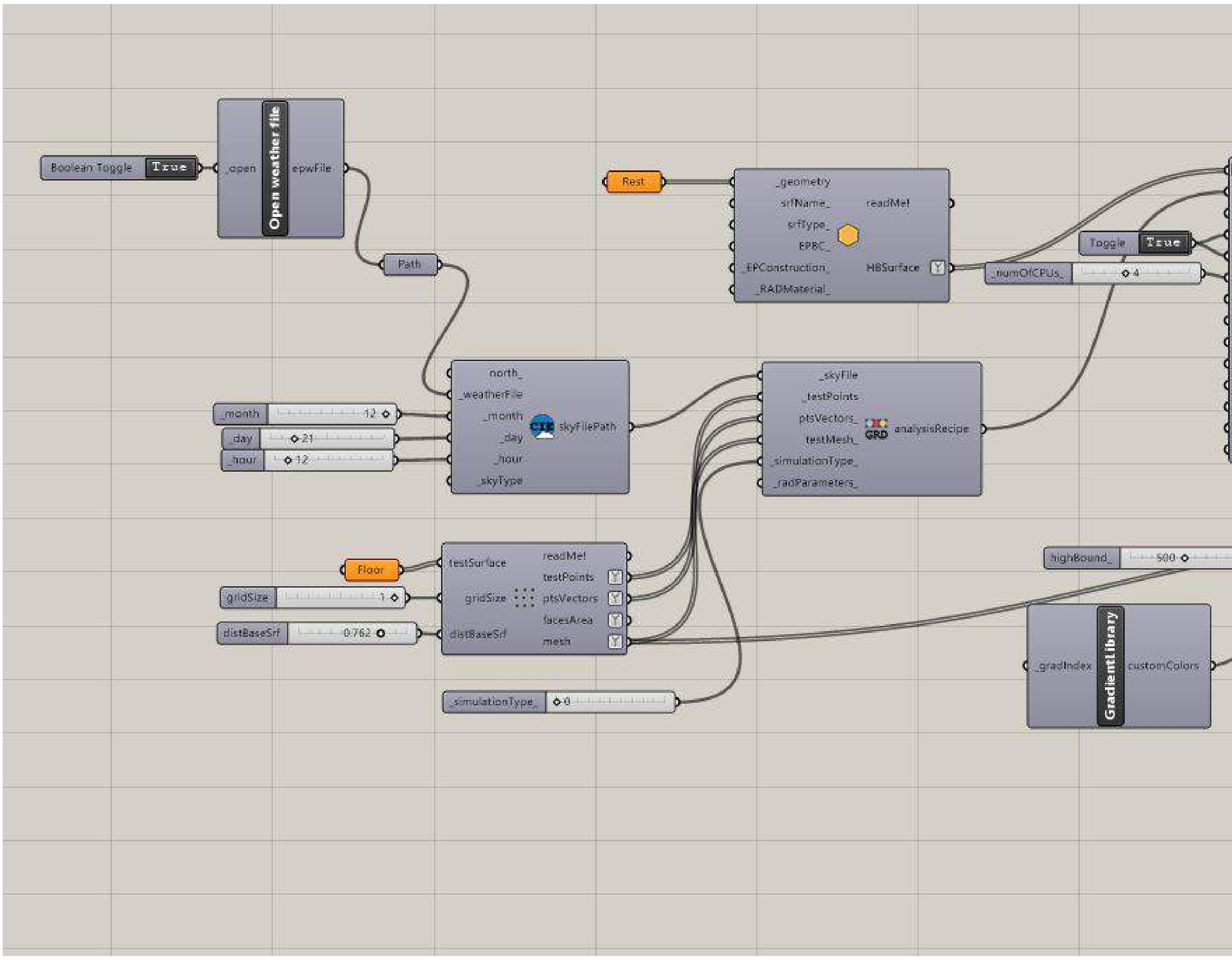
Conditions for Chemical Instability: Stable.
Incompatible Materials: None known to The Munters Corporation at this time.
Hazardous Decomposition Products: May include and are not limited to oxides of carbon, oxides of nitrogen, organic acids, aldehydes, hydrogen chloride when heated to decomposition.

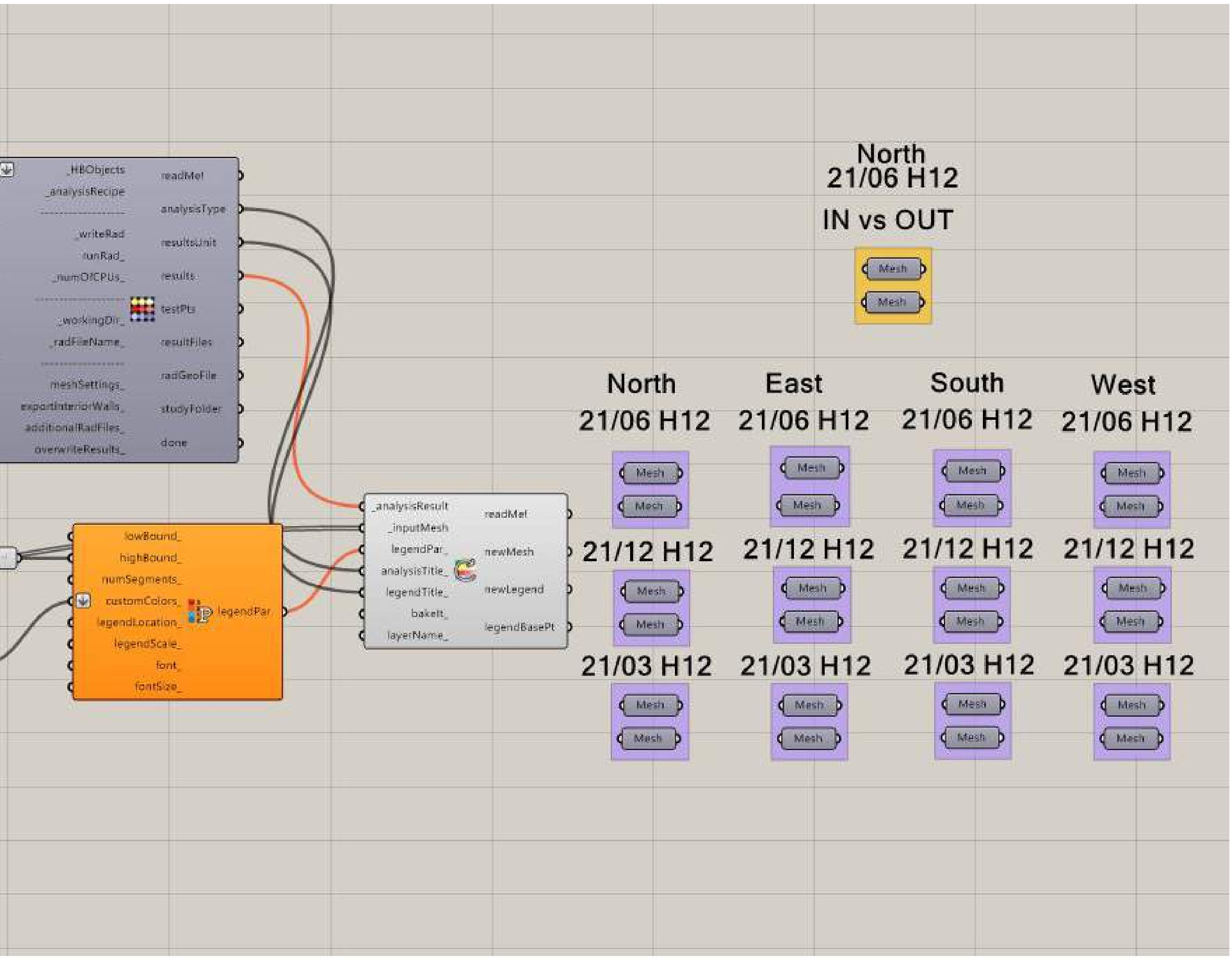
D) LADYBUG SCRIPT

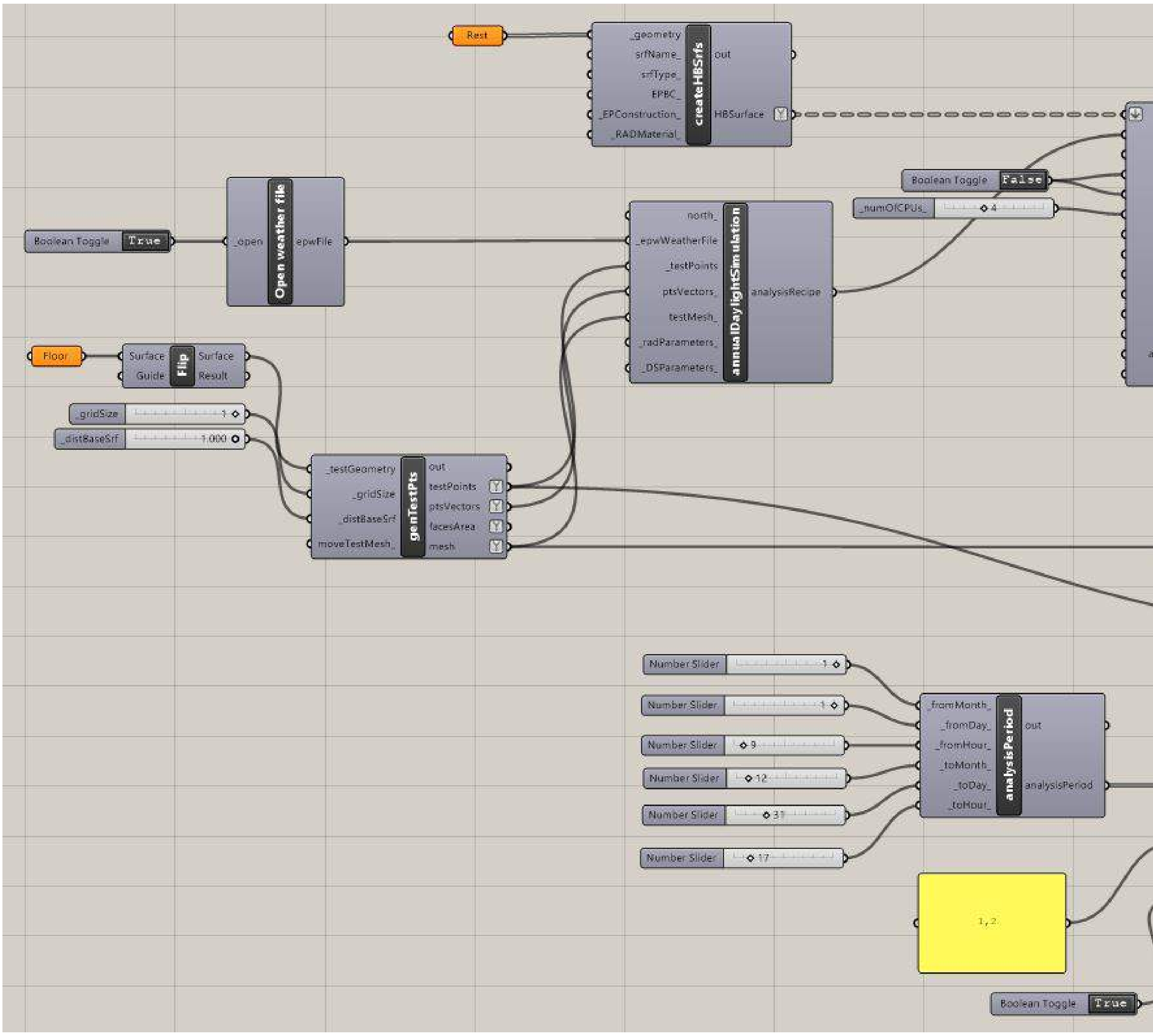



Radiation Analysis
Radiation Rose
Wind Rose
orientationStudyPar
radiationAnalysis
radiationRose
windRose
Rot3D
A/B
Range
Sort
Item
Mesh
Brep
Pt
Toggle
True

E) HONEYBEE SCRIPT




_HBObjects
_analysisRecipe
_writeRad
runRad_
numOfCPUs
workingDir
radFileName
meshSettings_
exportInteriorWalls_
additionalRadFiles_
overwriteResults_
readMe!
analysisType
resultsUnit
results
testPts
resultFiles
radGeoFile
studyFolder
done
lowBound_
highBound_
numSegments_
customColors_
legendLocation_
legendScale_
font_
fontSize_
legendPar
_analysisResult
_inputMesh
legendPar_
analysisTitle_
legendTitle_
bakeIt_
layerName_
readMe!
newMesh
newLegend
legendBasePt
North
21/06 H12
IN vs OUT
Mesh
North
East
South
West
21/06 H12
21/12 H12
21/03 H12


Rest
_geometry
srfName_
srfType_
EPBC_
EPConstruction
RADMaterial
createHBSrfs
out
HBSurface
Boolean Toggle
False
numOfCPUs
4
Boolean Toggle
True
_open
Open weather file
epwFile
north_
_epwWeatherFile
_testPoints
ptsVectors_
testMesh_
radParameters
DSParameters
annualDaylightSimulation
analysisRecipe
Floor
Surface
Guide
Flip
Surface
Result
_gridSize
1
_distBaseSrf
1.000
_testGeometry
_gridSize
_distBaseSrf
moveTestMesh_
genTestPts
out
testPoints
ptsVectors
facesArea
mesh
Number Slider
1
Number Slider
1
Number Slider
9
Number Slider
12
Number Slider
31
Number Slider
17
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fromDay
fromHour
toMonth
toDay
toHour
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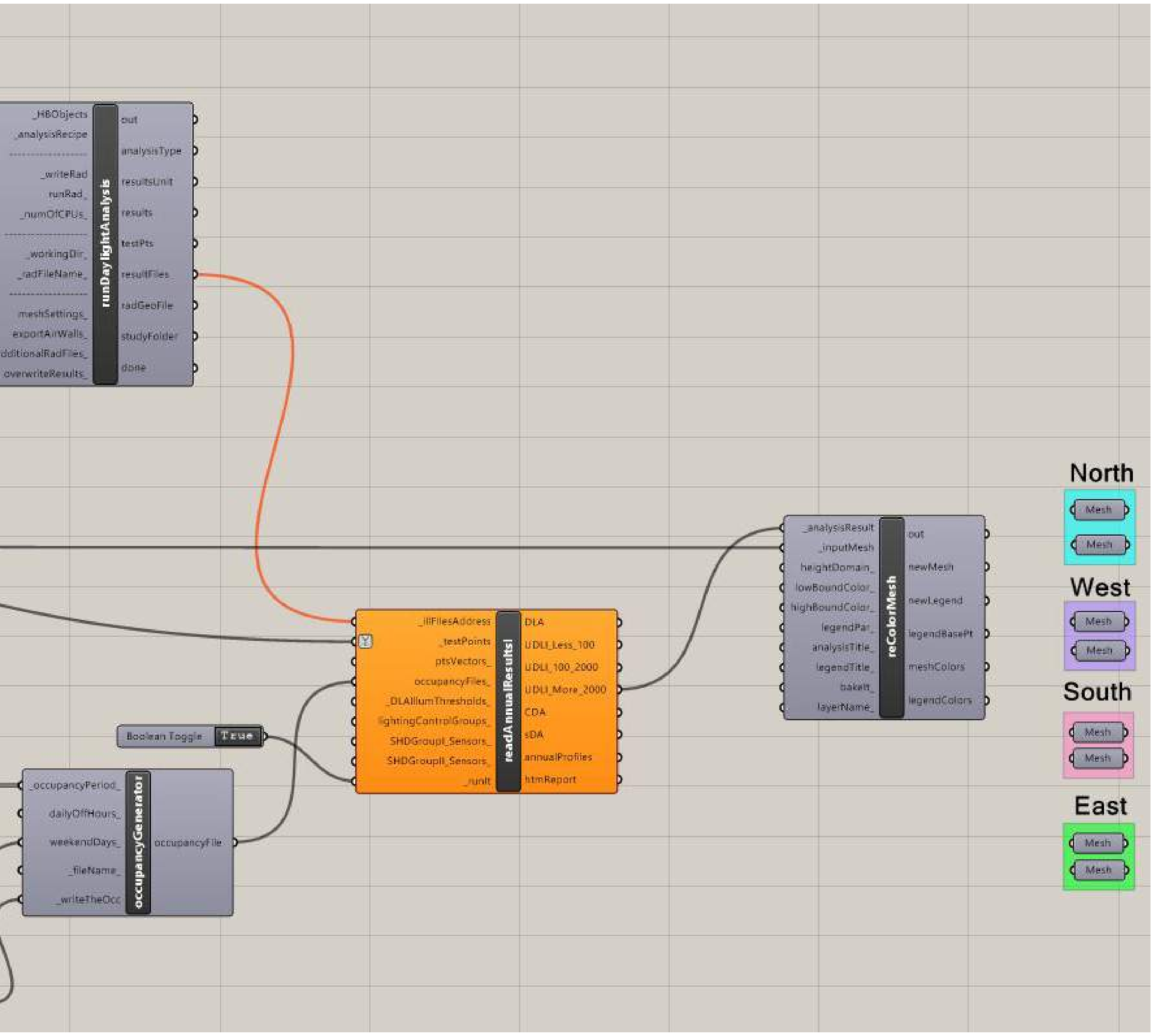
analysisPeriod
1,2
Boolean Toggle
True



_HBObjects
_analysisRecipe
_writeRad
runRad_
numOfCPUs
workingDir
radFileName
meshSettings_
exportAirWalls_
dditionalRadFiles_
overwriteResults_
runDaylightAnalysis
out
analysisType
resultsUnit
results
testPts
resultFiles
radGeoFile
studyFolder
done
_illFilesAddress
_testPoints
ptsVectors_
occupancyFiles_
DLAIllumThresholds
lightingControlGroups_
SHDGroupI_Sensors_
SHDGroupII_Sensors_
_runIt
readAnnualResults
DLA
UDLI_Less_100
UDLI_100_2000
UDLI_More_2000
CDA
sDA
annualProfiles
htmReport
Boolean Toggle
True
occupancyPeriod
dailyOffHours_
weekendDays_
fileName
_writeTheOcc
occupancyGenerator
occupancyFile
_analysisResult
_inputMesh
heightDomain_
lowBoundColor_
highBoundColor_
legendPar_
analysisTitle_
legendTitle_
bakeIt_
layerName_
reColorMesh
out
newMesh
newLegend
legendBasePt
meshColors
legendColors
North
Mesh
Mesh
West
Mesh
Mesh
South
Mesh
Mesh
East
Mesh
Mesh