Research Paper

Alternative Strategies for Theatres in Central European Climate

The potential of passive design strategies to lower the operational energy requirement for existing theatres in Berlin

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Abstract - This paper investigates the potential of passively lowering the operational energy requirement of performance buildings in the Central European Climate. The energy consumption of this typology is largely caused by mechanical ventilation to cool and ventilate the theatre during shows, necessary for the thermal comfort and ventilation requirements of the audience. Mechanical ventilation in theatres needs to significantly over-provide ventilation air in order to cool, and the exhaust air is not allowed to be mixed with incoming air, making them are inherently inefficient. Passive design strategies can lower the energy requirement of buildings during operation, by efficiently using ambient elements and simple laws of physics. Berlin, which perfectly embodies Central European's climate, experiences strong seasonal climate variations. In the hotter summer months, there is a low ambient cooling potential. However, the climatic conditions are sufficient for a direct connection between the theatre and the ambient air, which would result in no need for HVAC during operation. There is a high ambient cooling potential in autumn, winter and spring. This potential can be fulfilled by efficiently integrating thermal mass, indirect evaporative cooling in the roof of the theatre, radiative cooling in the ceiling of the theatre, natural ventilation through buoyan-cy stack effect or wind-driven cross ventilation. These methods are addressed on macro scale and deserve

micro scale validation of a site before implementation.

KEYWORDS: Passive Design Strategies, Passive Cooling, Energy Reduction, Metabolic Heat Production, Performance Building, Ventilation, Theatre, Concert Hall, Heat Sink, Heat Dissipation

1. INTRODUCTION

Back in the industrial revolution with the advent of steel, reinforced concrete, and elevators, we were able to build multi-storey buildings. With the rise of electric lighting less natural light was needed from windows so we created deeper floorplates. With the invention of mechanical ventila-tion systems, there was no need to open our windows anymore, so we could redevelop the skin of our buildings. Architecture has, for as long as we know, been closely intertwined with the world's inventions to develop its industry and methods. However, we did not only start to create buildings that made use of this development, but we also started creating buildings that are extremely reliant on these inventions. Our current building stock and modern way of building have gotten espe-cially reliant on the use of energy to operate and now, with global efforts towards less emitting societies to dim the effects of climate change, that reliance has become a massive problem in the footprint of the built environment today. It is therefore not surprising that the sector that houses every human on the planet is currently responsible for 36% of all global energy consumption and

39% of global energy related-CO2 emissions, of which 28% come from the operation of these buildings (Global Status Report 2017, 2017).
To lower the environmental harm of our built environment we could transition toward renewable energy generation to lower the environmental impact during operation, though, it would not make sense to over-supply energy to energy-inefficient buildings, as discussed by DeKay & Brown (2014), regardless of the energy source. The most effective way to work towards a more sustainable energy system is demonstrated in the classification of the Energy Hierarchy, see Appendix 1, as lowering the energy demand and being more efficient with the energy we use, before focusing on renewable energy generation. If it comes to new buildings we build now, already a great framework of knowledge has been developed to design buildings that use very little energy to operate, as demonstrated by the EU-wide regulation and pursuit to only create NZEB (Nearly Zero Energy Building) since 2018. The problem we are facing is the incredible amount of buildings in our current building stock that have been designed before focusing on the energy-efficiency of buildings, which can be characterized as 'climate-killers' (Connolly, 2022), a term used for buildings that are inherently inefficient when it comes to their energy usage during operation.

Berlin in Germany, which has the ambition to become one of the most sustainable cities in the world (Senate Department for the Environment, et al., n.d.), has a long way to go regarding climate protection through its existing building stock. Their first thermal insulation regulation took effect on the 1st of November 1978 and the first energy conservation regulation on the 1st of February 2002. As a comparison: a majority of roughly 58% of the non-residential buildings that operate today were built before 1978 (Government of the Federal Republic of Germany, 2013) when there was no regulation at all. In Berlin, buildings have the highest priority when it comes to future climate protection (Climate-Neutral Berlin 2050, 2016) and the municipality is now focusing on the energy-efficient renovation of their public buildings in an exemplary matter, to set the example for the public and private sectors to follow, and further aspire others outside of their borders. This has gained special attention since the government's recent statement that they are going to lower the average temperatures in their public buildings and turn off the external lights, as an alternative to save energy (Federal Cabinet, 2022). These measurements are temporary solutions adopted during the energy crisis of 2021 but stress the urge for the energy consumption problem of non-residential buildings. As Germany is extremely reliant on gas due to its policy to end coal and nuclear power generation in the last decades (L. Greer & Russell, 1982), it not only faces the consequences that its unsustainable public buildings are polluting, but they now also cost fortunes to operate.

To restore human symbiosis with our natural environment we should seek alternative ways to operate our buildings, to use less energy. The consideration of the available resources and climatic conditions on the site of a building can when used appropriately, significantly reduce the dependency on mechanical appliances, through passive-driven performance. Even though the most important design decisions surrounding the thermal and passive performance of buildings are realized during the early design phases of a building (Holm, 1993), this research paper will investigate how passive design strategies can play a role in the energy-efficient renovation of cultural buildings in the Central European climate of Berlin. The research is climate specific as passive design strategies are highly reliant on the climatic conditions of a site (Rodriguez-Ubinas et al., 2014). The focus is on cultural buildings, with the intent to aspire to a revision in their operational standard, to not prepare them for the near future, but for the decennia to come, so we can justifiably continue to enjoy cultural activities. The question this paper thereby tries to answer is: How can the integration of passive design strategies in cultural building renovation decrease the energy demand of operation while remaining acceptable building comfort?

The structure of this paper is as follows, there will be an exploration of the current method of operation and energy usage of cultural buildings in Berlin, which originate from 1945 to 2002. This will be followed by an evaluation of Berlin's local climate and its relation to thermal (building) comfort. Then possible design strategies will be discussed that have the potential to passively lower energy consumption during the operation of these types of buildings, within the local climate.

The results of the paper will be an overview of possibly applicable passive design strategies that lower the need for mechanical appliances to operate cultural buildings in Berlin's climate and implementation in existing cultural buildings through diagrammatic elaboration.

2. METHODOLOGY

The research is divided into two parts, the preliminary research and the research assignment. The preliminary research investigates which facets of the operation of public cultural buildings in the city of Berlin are predominantly accountable for energy consumption and suggest inefficiency. This is executed by field research through interviews with employees or operational managers of a selection of cultural buildings in Berlin, comprising theatres, concert halls, museums, libraries and opera houses. Also, the method of operation of a typical performance building is outlined by identifying mutual common features, observed during visits to these buildings, and the typical structure is defined.

The research assignment assesses the actual demand for ventilation and cooling in a typical theatre with calculations of the minimum required air change rate and temperature increase caused by metabolic heat production. With the assessment of Berlin's local weather data, done by using Climate Consultant 6.0, the research makes use of the Bioclimatic Chart and Climatic Cooling Potential (CCP) to identify the influence of the local climate on thermal comfort, and the cooling potential of the ambient environment. The Bioclimatic chart, seen in Figure 1, evaluates the influence the local weather might have on the comfort of a building. Placed on top of the Psychrometric Chart, a graphical representation to present the physical and thermal properties of moist air under standard atmospheric pressure (Fabian, 2016), Givoni defines the 'comfort area' (Figure 1: green), where 80% of the occupants feel thermally comfortable, assuming the occupants of the building are wearing normal indoor clothing. The thermal comfort zone is automatically defined by the software, for the given location. The model considers a non-residential building, with low- to medium thermal capacity. Besides the thermal comfort of occupants of a building, the chart also displays an indication of possible design strategies that passively enhance thermal comfort, and the numerical share of comfort hours that strategy can improve for the given period.

The CCP model shows when passive cooling would be most effective. It disregards the specific building parameters and places the temperature flux of the building (Tb) against that of the external air temperature (Te), in a cosine function seen as seen in Figure 2. Whenever the ambient temperature (Te) is lower than the temperature in the building (Tb), passive cooling becomes achievable. The larger the difference, the more significant the potential is.

Passive design strategies, according to the categorization by Geetha & Velrej (2012) based on the method of heat transfer known in physics, will be evaluated by their potential in cultural buildings, as concluded in the 3.1 Preliminary Research, 3.2.2 Local Climate, and conforming to the results of the 3.2.3 Building Bioclimatic Charts. At last, the integrative passive design strategies will be diagrammatically implemented in theatre buildings, by evaluation of the building elements they require to adjust.

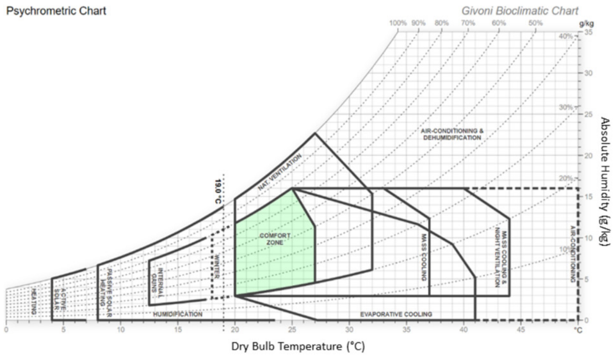


Figure 1. Bioclimatic Chart by Givoni (1994)

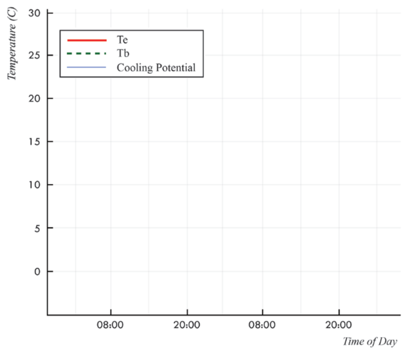


Figure 2. CCP Chart

3. RESEARCH

3.1 Preliminary Research

Cultural buildings are public buildings that concern the acquaintance of a community with cultural activities. The emphasis in the preliminary research was on cultural buildings with the intent to spread knowledge or entertainment, therefore; libraries, theatres, museums, concert halls, and opera houses. To investigate their current energy consumption, interviews with operational managers and employees of cultural buildings in Berlin were held, to identify their primary energy consumption and current method of operation. The preliminary research is summarized in Appendix 3. The form used in the

3.1.1 Main energy consumption

The preliminary field research contributed to an overview of the assumed main energy consumption per typology within the cultural building typology, see Appendix 2. Assumed because the energy consumption for these types of buildings has mostly not been digitalized yet. Within this overview, a noticeable distinction can be made with cultural buildings that host performances. Whereas most non-residential buildings in the climate of Northern Germany use almost three-fourths of their total energy for heating (Dena, 2018), 'performance buildings' use much of their energy for the cooling and ventilation of their main performance spaces. This could be regarded as an inefficient use of energy as cooling should not be a great problem in the climate of Berlin. From this point onward will the auditorium of a performance building be called a 'theatre', the hosted performances a 'show', and 'performance building' will cover the building in its entirety, for readability purposes. The reason this typology uses less energy for heating is due to its opening hours surrounding shows. The abundance of visitors entering over a short period, right before the performance will heat the space drastically due to emitting body heat, so-called metabolic heat production. Much pre-heating done before the opening hours would conflictingly result in extra cooling and ventilating after. The ventilation of a building can represent up to 30% to 60% of the total building's energy demand (Lui et al., 2010), which makes reducing ventilation requirements worthwhile. Especially in theatres, where heating, ventilation and air conditioning (HVAC) are inherently energy-inefficient because the return air is not allowed to be mixed with fresh air (Mohammad Ahmadzadehtalatapeh, 2014). Therefore heat recovery from exhaust heat is not directly possible.

The cooling and ventilating, the energy used for lighting and appliances, and some for heating, make up their estimated energy consumption. This is not unique to the location of Berlin; a vast majority of performance buildings around the world, regardless of their climate-related location, endure ventilation and cooling problems in their theatre (Chang, 2019). This research paper will therefore focus on the cooling and ventilation of theatres and will, for this paper, exclude the energy needed for lighting, appliances, or heating.

3.1.2 Main Method of Operation

During the observation of theatres, a generalized method of operation of a typical performance building has been developed, which can be found in appendix 3. Here is observed that predominantly these types of buildings are monofunctional and solely focus on hosting performances (together with corresponding functions such as a foyer, bar, and wardrobe). They deal with heavy peak loads, around two hours before and after performances. Their opening hours are situated around the schedule of shows, of which an average show starts between 19:00 and 20:00, and takes 90 minutes. Their urban placement is predominantly solo standing (when the initial design of the building was for the function it currently occupies). The show space is typified by its enclosed character without windows or apertures, with the main attention on acoustics and light. This research will disregard the effects of passive design strategies on acoustics and light, which should be regarded when implementing the strategies in a project specifically. The build-up of a regular performance building features three main elements and variable stage placement, as displayed in Figure 2, the front of house, back of house, and theatre. The front of house and back of house wrap around the auditorium in the plan. The front of house is occupied by visitors and the back of house is solely by the performers. The height of the back of the house exceeds the rest because that is needed for the technique of the stage. No value should be attached to the proportions of this figure, as this figure represents the diagrammatical layout. This standard will be used in the continuation of this research.

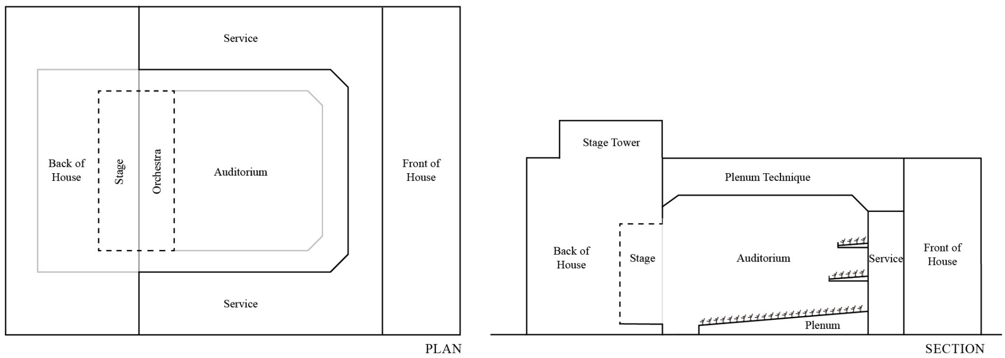


Figure 2. Typical layout of a performance building.

3.2 Research Assignment

There is a dichotomy in the way a method or system operates. Active systems use (paid) energy for their system to operate. Passive systems directly or indirectly use natural energy, like sunlight, temperature differences or wind to achieve a result without the use or conversion of or into electricity (Bradshaw, 2006). Active design strategies are not to be confused with systems that exclusively utilize energy to operate, as they can also retrieve energy from resources out of the natural environment, like solar panels or wind turbines, and convert those to energy, making them active systems.

Active Systems	Passive Systems
A system that uses and/or produces energy to achieve a certain result.	A system that uses natural energy such as sunlight, temperature differences and wind to achieve a certain result.

Active systems have proven their worth by converting ambient elements into electricity, significantly lowering the need for 'purchased' energy, which are still primarily generated by fossil fuels. This research will focus on passive systems, and how they can prevent the for requirement for mechanical alterations in the first place.

Hybrid systems

Passive design strategies might not always be fully capable of replacing active systems but may help decrease the requirement to use them (Rodriguez-Ubinas et al., 2014). When there is an incorporation of both active and passive systems working together, these are called hybrid systems. These types of systems have shown a great deal of success, where active systems can assist the shortcomings of passive systems, optimizing their operation, and minimizing the energy requirement.

3.2.1 Ventilation and Cooling demand

The specific need for cooling and ventilation in Central European climate is less common, as predominantly in this region there is a need for heating (Dena, 2018). The problem of overheating inside a theatre is not caused by ambient factors such as temperature or the sun, but by internal gains during performances due to heat produced by the audience and lighting. To get a better understanding of what the full occupancy of a theatre means for the ventilation and cooling of the space the ventilation and cooling requirements will be further elaborated. For this elaboration, a medium size concert hall or theatre is used as described by Guyer (2014), which has by standards a size of 1.400 people capacity, a square meter size of ~1350 m^2 (including the stage) and an average ceiling height of ~13.5 m. This means the volume of an average medium-size theatre, is 18.225 m^3. A visual representation of a regular theatre hall as laid out by Guyer (2014) is found in Appendix 4.

Ventilation Demand

The ventilation rates of mechanical ventilation in modern theatres, which have been built or refurbished in the last 10 years, are designed for 10 l/s/person (EMG & SAGE, 2020). For the ventilation alone, 10 l/s/person is equal to 10 dm3/s/person. The described typical theatre of 1400 capacity would result in 14 m3/s of air circulation necessary during a show, assuming full occupancy of the theatre, leaving out the performers. Therefore the air-change rate of the space is:

Air-change rate = [ventilation rate (l/s) * 3600 (s/hr)] * 0,001 (m3/s)]/[space volume (m3)]
= [14000 x 3600] * 0,001] / 18225
= 2,765

As this rate would result in enough ventilation to supply the audience with fresh air, mechanical ventilation also deals with keeping the internal temperature within reasonable limits. The air supply rate needed for cooling is much higher than the rate needed for the supply of fresh air (EMG & SAGE, 2020), and therefore the mechanical ventilation systems need to significantly oversupply ventilation air to keep the temperature moderate. Therefore the air-change rate needs to be increased by a substantial factor to cool, which is reliant on several variables including the volume of the space, the thermal mass, the temperature of the inserted air and the occupancy. If the cooling of the space would occur by other means, mechanical ventilation could drastically lower its performance. Also, often the even distribution of ventilated spaces is lacking, with the main focus on the audience, and occasionally overlooking the backstage and orchestra pits, creating undedicated environments for the performers (EMG & SAGE, 2020). These thermal conditions might affect the work of the performers.

Cooling Demand

An average human being in a 'quiet sitting'-mode produces 60W/m^2 of emitting body heat, and the average human is according to the DuBois method 1,8 m^2 (Ashrae, 1992), resulting in an average heat production of 108W per person during a show. With the full capacity of the audience, the heat production would result in 151.200 W. The total audience emits therefore respectively 544.320.000 J/h or 544 MJ/h. An average show of its kind takes accumulatively 90 minutes, see preliminary research, which would mean a total heat production of 816.5 MJ, during a show. The temperature increase by full capacity in a typical concert hall is derived by the following math equation:

Temperature increase (°C) = [metabolic heat production (W)] / [air volume (m3) * specific heat capacity air (J/kg/°C)]
= [151.200] / [18.225 x 1.005,00]
= 0,00826 °C per second.

This temperature rise would occur when there is an uninterrupted heat transmission from the human body to the air, therefore when the audience is not wearing any clothes- and not touching the seat. In that case, the temperature would rise by ~1°C every 2 minutes (121 seconds) under normal room temperature. In reality, this rise is reduced by the absorption of heat by elements such as the chair and clothing, leakage paths, limited by the relatively short time the audience is inside the space and maximized by the temperature of the human body. Because of that, the temperature is not likely to surpass or closely level 37 °C, but will still quickly create thermal conditions outside of the comfort zone of humans. When including the heat produced by lighting and appliances this temperature rise rate could only be increased. This sensible heat energy needs to be handled by mechanical ventilation, above the regular rates of fresh air supply.

3.2.2 Local Climatic Conditions: Central Europe – Berlin

This research takes into account the climate of Berlin, to analyse the possible effectiveness of passive design strategies, as their success is heavily correlated with the local climatic conditions (Al-Azri et al., 2013). Berlin perfectly embodies the climatic conditions of Central Europe (Koke et al., 2021), making this research appropriate to other locations within the same region, or locations with the same climate characteristics.

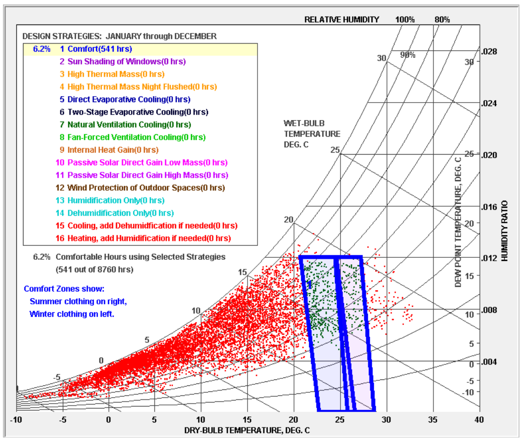
Berlin, positioned on latitude 52.47° N and longitude 13.40° E, is typically defined by its cool-humid climate type. There are strong seasonal differences ranging from cool winters between December and February with ranging temperatures between -2°C and 3°C and pleasantly warm summers from June to August between 15°C and 25°C, the full monthly temperature ranges are found in Appendix 5. The average humidity is between 63% and 86%. Wind speeds in Berlin have a maximum of 5 m/s and a minimum value of 3 m/s, and there is not a prominent direction, though westwind is most common, as seen in Appendix 6. Diurnal temperature variations and greater wind speeds throughout the winter and summer may appear stronger (Koke et al., 2021), though are also recorded in the other seasons. Berlin is densely populated and typed by its urban characteristics, with little undeveloped land. The location has few solar radiation resources, with in summer a solar height range between 0° at azimuth −133° to 133°, and 61° at azimuth 0°, for around 7 to 8 hours of sunshine hours a day and in winter the sun rarely shines due to the short solar time with a minimal of 0° at azimuth −53° to 53° and 14° being the highest at azimuth 0°, see Appendix 7.

3.2.3 Building Bioclimatic Charts

Building bioclimatic charts offer a convenient way to provide insight into the local climate in relation to thermal comfort in buildings and whether a passive design strategy will be able to improve this comfort. In this paper the Bioclimatic chart and the CCP-chart are used. The bioclimatic chart is synchronized with the coordinates of Berlin, as mentioned in section 3.2.2, by using Climate Consultant 6.0.

Bioclimatic Chart

In the Bioclimatic Chart of Berlin, as seen in Figure 3, the thermal comfort inside an unoccupied, unaltered building is defined by discomfort throughout the majority of the year (94%), for occupants wearing normal indoor clothing. When the chart considers design strategies for the respective location, as seen in Figure 4, the main suggested efforts of the design strategies should lie with the provision of heating and heat gain, to create thermally acceptable comfort inside the building. This outcome is in line with the predominant energy consumption of non-residential buildings in Central Europe caused by heating, as mentioned before. A limitation of this analysis is the lack of consideration of the specific building parameters, therefore it is not able to consider the stated heat gain inside a theatre by the audience and thus will not directly provide design strategies that can address this specific problem. What this method is able to present is the thermal building comfort throughout the year, without active or passive adjustments. As the charts below give a good general overview of the average climatic conditions of Berlin, a more accurate description will be given when assessed over a shorter timeframe, because of the large differences in climatic conditions per season as seen in section 3.2.2. Therefore the timeframe of seasons is analysed. As Climate Consultant 6.0 works with months, rather than seasons, the following months comprise the seasons: Dec-Feb (Winter), Mar-May (Spring), Jun-Aug (Summer), and Sep-Nov (Autumn).



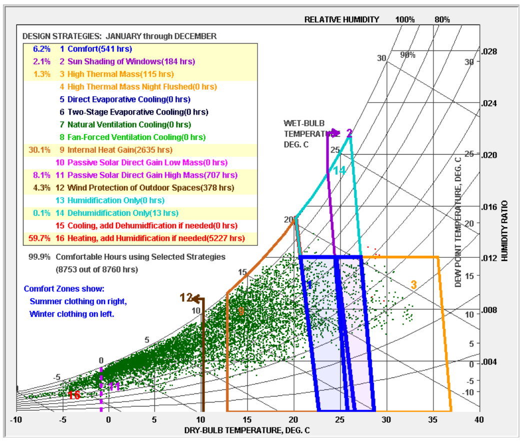


Figure 3. Bioclimatic Chart Berlin, no design strategies Figure 4. Bioclimatic Chart Berlin, design strategies

When plotting the data in seasons, it becomes possible to evaluate the climate more carefully. This is displayed in Appendix 8 and 9. Here, the seasonal Bioclimatic charts of the outside temperatures (8), as well as the thermal indoor comfort (9) are issued. Here it becomes clear that during most seasons; autumn, winter, and spring, the ambient conditions require significant thermal adjustment of the building, either passive or active, to achieve appropriate comfort for the users. Though in summer, Berlin's local conditions require very little to no adjustments in buildings, for the users to feel comfortable. Also, the ambient temperatures are sufficient for the thermal comfort of a considerable amount of people. According to the indoor comfort chart, a building would be 27,2% of the time comfortable in summer, without any other influence than outdoor climate. An extra 59,3% of the time would be considered comfortable by the effects of (some) internal heat gain. Internal heat gain is derived from occupants, light and appliances (Černý & Kočí, 2015), which in the case of theatres and their operation hours surrounding shows, always occur. Therefore, assuming that the internal heat gain in theatres would always be successfully manifested, 86,5% of its operational time will be comfortable. The last percentages would be derived from the solar gain on the low thermal mass of the building. In other words, in summer there could be no additional enhancement needed other than a theatre operating its function. Looking closer at the summer season, and plotting the data only around the main opening hours of performance buildings (7 PM - 9 PM), the chart in Appendix 10 shows an even more appropriate comfort model. When only relying on internal heat gain, 91% of the time during shows it is comfortable enough. Due to recorded climate change in the future, the

numbers be even pushed more towards the comfort zone.
The problem with theatres is that in an average show, the internal heat gain is so inordinate, as discussed in 3.2.1, the climate would quickly become too hot, and therefore uncomfortable. If the over-production of heat in the theatre would be able to dissipate, the theatre would not require any cooling or heating, for this period, though ventilation would still be mandatory. The external conditions in summer positively influence the conditions inside a building. Therefore, a direct connection between the theatre and the ambient sky in the summer months would provide appropriate climatic conditions inside the theatre, for the majority of the time, while the excess heat could be able to freely dissipate into the air. Also, no ventilation would be needed, due to the direct air refreshment of the sky. This would be predominantly possible in summer, although in adjacent months of summer, due to possible diurnal temperature variation, some days would also be suitable for this direct connection. The rest of the time would require other means.

CCP-chart

In summer, the external conditions are sufficient for the theatre to facilitate a direct connection with the outside, though, for the majority of the year, the weather would be not satisfactory. In the other months, alternative methods need to be considered to dissipate the heat out of the enclosed space of the theatre. To identify to which extent the local climate may contribute to the passive cooling of the theatre, the Climatic Cooling Potential (CCP) chart analysis is used. This method will be applied to a typical theatre. To assume the temperature rise of a theatre the following assumptions have been taken:

Only the operational hours of the theatre are taken into account, and as mentioned in the preliminary research, two hours before and two hours after shows, with an average of 90 minutes per show. Therefore between 17:00H and 22:30H, a base temperature of 19 degrees is considered, which is according to the Bioclimatic Chart of Givoni (1994) minimal thermal comfort where 80% of the occupants feel comfortable. The highest temperature is the maximum thermal comfort temperature by Givoni, 25 degrees, and will follow a parabolic course (even though presumably higher without passive or active cooling). The temperature decrease is assumed due to the departure of the audience and dissipation through leakage paths. The average day of each season is used for the external temperature variables. The average ambient temperatures of Berlin in Appendix 5 are used.

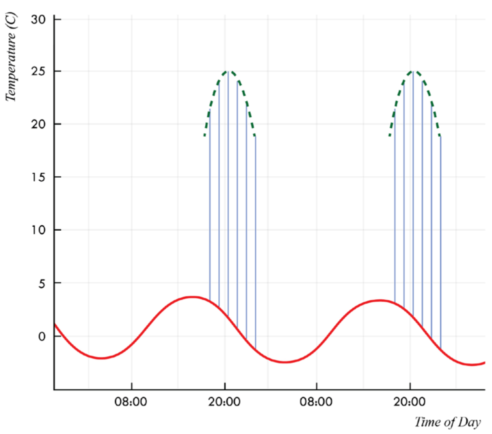


Figure 5: CCP Chart - Winter

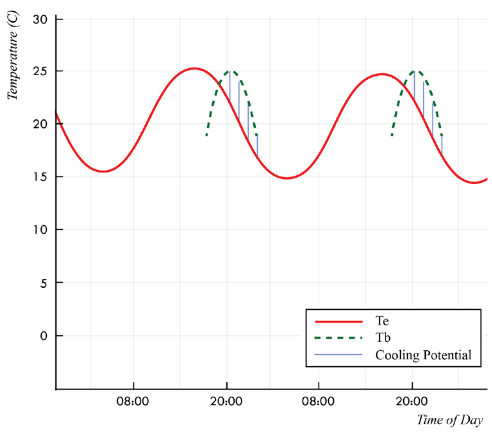


Figure 6: CCP Chart - Summer

It displays the potential of cooling in the colder seasons when the temperature difference between the ambient temperatures (Te) and the internal temperatures (Tb) is the highest. In summer, as seen in Figure 5, the temperature differences between the ambient temperatures and the inside temperatures are not significant, demonstrating very little cooling potential. In the winter, as seen in Figure 6, significant temperature differences are measured and therefore the cooling potential is very high. The colder the ambient temperature, the higher the cooling potential.

3.2.4 Passive Design Strategies

The design strategies should focus on passively cooling the theatre, to lower the need for mechanical ventilation systems. Passive cooling techniques cover all processes and methods that reduce the amount of cooling needed in buildings. Givoni (1994), identified passive cooling techniques as lowering the indoor temperatures of buildings with simple cooling techniques by using natural resources. Physicists Santamouris and Asimakopoulos (1996) assess passive cooling by the application of solar and heat control systems, dissipation of excess heat into low-temperature natural sinks and the amortization of the heat surplus through the use of an additional thermal mass of the building. These cooling techniques can be distinguished by their method of heat transfer, known in physics as convection, radiation, and perspiration and are categorised by Geetha & Velrej (2012), highlighted in the scheme, visible in Appendix 12:

- prevention of heat gains
- modification of heat gains (change of the impact available heat gains have)
- and heat dissipation (increasing heat loss)

This section will discuss the application of these techniques in overheating of existing theatres in Berlin's local climate.

Preventing Heat Gain

The passive cooling strategies lying with the prevention of heat gain mainly assume that the heat accumulated inside a building is derived from the sun or external temperatures. As the heat gain is caused by the metabolic heat production of the audience, and lighting, this will not be prevented, unless performance buildings will lower the amount of audience present. This would be in opposition to the principle of hosting shows and is not a feasible solution. For that reason, the prevention of heat gain will not be further discussed, in this paper.

Modification of Heat Gains

It will be difficult to stop the metabolic heat production of people as prevention of heat gain, but what deserves attention is how the impact of heat gain can be adjusted. According to Geetha & Velrej (2012), this can be achieved by thermal mass. Also, the heat increase is related to the amount of air that needs to be heated, therefore the air volume.

Thermal mass

The thermal mass of the building or building components can be used to absorb cold or heat and store it upon release (source, Xiaoyu Du, 2019). Effectively making use of this principle can reduce the peak load of cooling and regulate the size of indoor temperature swings. Thermal mass can either store cool or hot, which in the application of theatres can mean two things:

- Storing cool and releasing it during a show. This can occur when there are high-temperature swings between day and night. Thereby cold can be stored during the night and released when needed, this method goes hand in hand with night ventilation, see *Natural Ventilation* in the next section.
- Storing the heat transmitted by the audience during the show until releasing it after. This will be discussed in section *3. Heat dissipation*.

The effectiveness rate of thermal mass is dependent, according to Balaras (1996), on several parameters and conditions; building material properties, building operation, thermal insulation, ventilation, climatic conditions, use of auxiliary cooling systems and occupancy patterns. Within the properties of thermal mass, there is a distinction of two types which may be beneficial, either using the construction materials of the building or phase change materials (PCM) within the building. The effectiveness of cooling the space with construction materials is useful as you do not have to add additional elements to achieve a result. The consideration of passive cooling by construction materials is especially effective when applied during the initial design phase of the building (Balaras, 1996). Then the construction materials may be chosen and oriented beforehand, to have a viable effect. This might be less effective for building renovation when construction materials are already placed. What can be investigated is whether present construction materials can operate as thermal mass for night ventilation. Phase Change Materials on the other hand may be integrated with other building elements or finishes. They operate by changing phases when storing or releasing heat or cold. The benefit is that this can store a lot more heat than any other conventional sensible thermal storage method, and the heat released will occur at a constant temperature (Pasupathy et al., 2008). Phase change materials are easier to implement compared to construction materials once a building is constructed.

Air Volume

The pace of the temperature rise in theatres takes place is reliant on the amount of air that can be heated, the volume size of the space affects the pace of heat gain. When the volume of the space is increased, the heating occurs slower when the heat production stays the same, though the increase of volume to not overheat would be too big to consider.

Heat Dissipation

The last category dealing with passive cooling has to do with the disposal of excess heat. The transfer of heat goes naturally from a hot object to a cold object, according to the second law of thermodynamics. Therefore, the method of a building to dispose of excess heat is characterized by something with a lower temperature, such as the ambient air, ground, water, sky or materials (source, Xiaoyu Du, 2019), called a heat sink. According to Santamouris & Koloktsa (2013), there are two main preconditions for the effectiveness of heat dissipation in a building:

a) The availability of a proper environmental heat sink with a sufficient temperature difference for the transfer of heat

b) The efficient thermal coupling between a building and the sink.

There are four grounded techniques for heat dissipation, according to Geetha & Velraj (2012); evaporative cooling, ground cooling, radiative cooling and natural ventilation cooling. Each of these will be evaluated on whether a clear environmental heat sink may be provided in Berlin's local climate and whether an efficient thermal coupling is possible.

Evaporative Cooling

Evaporative cooling uses the effect of evaporation as a natural heat sink, by eliminating sensible heat through the evaporation of water. The amount of sensible heat which can be absorbed depends on the amount of water that can be evaporated (Geetha & Velraj, 2012). This is typically conceived in two forms, a direct and indirect system. With direct evaporative cooling hot air is drawn directly over an evaporative element which loses heat to evaporate the water. Thereby the heat is transferred to the water and the water is released in the evaporated form to humidify the air. This generally functions well in hot climates where the hot ambient air can be passively cooled and humidified by the evaporation of water, before entering and cooling the building. Thereby less energy is needed to cool the incoming air. In indirect evaporative coolers, suitable in more humid climate regions, the cooling is derived from evaporation but achieved indirectly, without humidifying the air (Givoni, 2011). When the air already has a high level of humidity, such as in Berlin, mentioned in *section 3.2.2*, it will not be able to absorb much moisture, so the direct cooling effect will be less effective. This can be enhanced by increasing the surface area of water to the air, or 'showering' incoming air. Also for the majority of the year, the ambient temperatures are already low enough to not need evaporative cooling to lower the incoming temperature. Direct evaporative cooling of the outside air does therefore not provide a proper heat sink.

What may be considered is indirect evaporative cooling of the inside air, which in theatres attains year-round significant temperatures, and no direct connection is necessary. To dissipate the ascending heat produced by the audience, water integrated into the ceiling of the theatre, or a roof pond functions as a heat sink as it absorbs indoor heat as well as the heat penetrating the building (Givoni, 2011). The water would in most seasons be naturally cooled by the ambient temperatures, especially at night. During the operation of the building in the daytime, the theatre could lose its heat to the cooled water. To keep the water cold and protected from sun rays, an isolation layer above the water can protect it from temperature rises.

Radiative Cooling

Radiative cooling operates by the transmission effects of high-wave radiation, corresponding to substances of higher temperatures, to lower wave radiation, thus substances with lower temperatures, which acts as a heat sink. In the application of buildings, the sky is predominantly used as a heatsink, as most objects on earth have a higher temperature than the temperature of the sky (Geetha & Velraj, 2012). Thermal mass, as discussed in *2. Modify heat gains*, are categorized under radiative cooling. The thermal mass successfully stores cool outside of operating hours, to modify the heat gain (*2. Modification of Heat Gains*), using night ventilation (*IV Natural Ventilation*), and can absorb heat during operation, lowering the need for cooling.

The heat storing application would incorporate a highly conductive material as a ceiling material with high insulation on top of that. Thereby the conductive material stays cool during peak sun hours and can work as a heat sink of the heat generated inside the building (Pacheco, Ordonez, & Martinez, 2012). Also walls can be considered as conductive material. After heating up by the operation inside of the building, the heat will be transmitted to the colder sky. Phase Change Materials may be a feasible solution due to their high conductive properties. The material would require abundant cooling by ambient temperatures in order to dissipate conducted heat, which would be limitedly possible in summer.

Ground Cooling

Ground cooling uses the temperature of the ground as a natural heat sink. Due to the higher thermal mass of the ground compared to the ambient air, occur temperature changes more slowly. The more the ground is exposed to the ambient temperature the more it is subject to temperature changes, which means at a certain depth the ground temperature remains relatively unaltered (Santamouris, 2007). The temperature difference between the ambient sky and the ground may be used to create a natural heat sink. The temperature of the ground is in general a little bit warmer than the average ambient temperature (Santamouris, 2012), though in summer ground cooling would be beneficial when the ambient temperature is much higher than the ground, so the highest difference exists. Due to the heat island effect many cities cope with, the cooling of the ground would in practice not always be a guarantee. The temperatures of the ground seen in Appendix 13, are therefore different in reality, as the system considers a grass field in the respective location. In the colder months of Central Europe, ground cooling would not be significant as the ambient temperatures are already low and the temperature difference compared to the ground is not as big. Due to the length, and depth, of the underground pipes necessary, this method would not possibly not be very feasible for implementation in urban settlements.

Natural Ventilation

Natural ventilation is achieved, as described by Santamouris & Asimakopoulos (1996) by the flow of outside air through a building, which may occur randomly through leakage paths or be directed through openings, windows and doors. When natural ventilation is allowed in, the airflow will follow its path due to a result of pressure differences caused by the wind or stack effect. There are two types of natural ventilation, described by Givoni (1994), comfort ventilation and night ventilation. Comfort ventilation directly cools the occupants of a building by allowing wind flow during the operation of the building. Night ventilation allows cold night air to cool the thermal mass of the building outside of operation hours, which will transmit its cold during the operation of the building, lowering the temperature of the building during daytime. There are two methods to get air to move, wind-driven and buoyancy:

o Wind-driven cross ventilation

This type of ventilation is driven by wind-induced pressure differences. It uses the principle that wind always flows from positive pressure to negative pressure. The main importance for its success is regular air velocity and building orientation. Either the wind blows onto the building directly or is caught and redirected by the use of a wind tower. It relies on the wind to blow, which cannot always be a guarantee. According to Givoni (1994), wind can come in at angles from 30 to 120 degrees to the proposed surface of the building and still be effective, though wind towers may catch wind from any direction. Nearby buildings may affect the anticipated wind direction and velocity. Building renovation studies should be undertaken to determine the wind velocity around the building and building extensions, top-ups and façade adjustments may influence the building orientation to benefit from wind-driven cross ventilation to ventilate and cool.

o Buoyancy-driven stack ventilation

This type of ventilation is caused by the stack effect. This occurs when there are temperature differences between one zone and the adjacent one. Warm air is lighter than colder air and will rise above as it gets heated. This creates a natural low pressure below, which can naturally draw ambient air inside, through leakage paths, windows, doors or directed by vents. The temperature difference between the theatre and outside is significant in the winter, spring and autumn and provides a proper heat sink. When the hot risen air is able to dissipate into the ambient sky through the roof, due to the negative pressure occurring below in the theatre, it would be able to draw cool ambient air in through the bottom.

Night-time ventilation

Night-time ventilation can be very effective in buildings with high thermal mass, this may store many cool temperatures during the night and release them during the operation in the day. With the optimization of building design for night ventilation to work effectively, a 20-25% reduction in air-conditioning may be achieved (Kolokotroni and Aronis, 1999). The limitation of night ventilation is the lack of moisture and condensation control. Also, when applied in cities, due to the heat island effect the cooling at night might not be as efficient (Santamouris, 2007), though, in Berlin, the heat island effect in winter is not as strong due to the marginal sun exposure during this period. In summer the night temperatures are not low enough, for proper nighttime cooling.

4. RESULTS

The seasonal differences in Berlin are very large, as discussed in *section 3.2.2*, as well as in *3.2.3*. Whereas in autumn, winter and spring the climatic conditions require significant adjustments to the indoor climate to be thermally acceptable for occupants, in summer barely any alternation is needed.

During the hotter months of summer and adjacent, the CCP model shows that the ambient temperatures would not facilitate a strong environmental heatsink for passive cooling. Rather none of the passive cooling strategies, as categorized by Geetha & Velrej (2012), except natural ventilation, would form a feasible solution in Berlin's summer as the ambient temperatures are too high, whereas in winter, autumn and spring it would be achievable. Because of these reasons will varying seasons require different approaches. It is acceptable that thermal comfort might not be reached for everyone, as it is rather a tool to predict the thermal comfort of the majority of the people involved. When a minority of people are not comfortable, they could increase or decrease their amount of clothing, to regulate their individual preferences.

Summer approach

Because the ambient temperature in summer is relatively high, it is more difficult to naturally dissipate the heat from inside the building to the environment. Therefore in summer the dissipation of heat gains may only be manifested passively by considering a direct connection to the ambient sky, to become completely non-reliant on active systems controlling HVAC, for this period. The theatre would therefore operate as a open air theatre. Heat would be able to freely dissipate and no airchange rate would be necessary as it is directly connected to the outside. The structure of a typical theatre gives space for either a retractable roof structure that can be opened during shows in summer and kept closed during winter (open theatre) or one that can allow a mutual connection to the sky (semi-open). Additionally, the integration of natural ventilation entry through the front of house and theatre would be beneficial for the flow of air through the theater. Otherwise the 'open' theatre would behave as a pit. Natural ventilation through the back of house may also increase thermal conditions for the performers, as concerned in *3.2.1 Ventilation Demand*. Attention should be given to acoustics and lighting, as well as respiration and diurnal temperature conditions. In Figure 7a diagrammatical integration into a typical theatre is displayed. In practice, it would possibly be more feasible to consider a hybrid system to boost the dissipation of excess heat into the environment, rather than a retractable roof and its corresponding consequences.

To cool the hot incoming air, ground cooling may be used as the ground temperature in summer is in general lower than the ambient temperature. Therefore has ground cooling the potential to naturally cool the incoming air before entering, which reduces the cooling load of the hot outside air. The size of the surface area of the ground to which the air needs to be exposed is relatively large for a typical size theatre. It can therefore be argued whether it this method is feasible in high urban places like Berlin. This does not diminish it's technical potential. Figure 7b.

Winter approach

The colder the ambient temperatures, as seen in the CCP-chart of *section 3.2.3*, the higher the passive cooling potential is. Multiple methods could be considered in winter to lower the need for mechanical ventilation and cooling in theatres. Preventing heat gain and increasing air volume would be not suitable solutions for the stated problem. Considering the categorisation by Geetha & Velrej (2012), the following possibilities are derived.

1. Thermal mass may be used in combination with night ventilation to passively cool the theatre. Thermal mass by construction materials may be used when already present. PCMs may be added to- or in walls, ceilings or floors, though not between the stage and back of house as this needs to be customizable for shows. Night cooling should be done through the roof, through the façade would negatively affect the temperatures of the front or back of house, which do not necessarily need to be cooled. Figure 7c.

2. Indirect evaporative cooling of the theatre by implementing water in the ceiling or as a roof pond, will dissipate heat from the audience while blocking solar heat from entering. Insulation on top of that could protect the water from the temperature increase of the sun. Figure 7d.

3. Radiative cooling works the same as indirect evaporative cooling, but then with a conductive material rather than water. It is placed on the ceiling and is protected by thick insulation on top. Figure 7e.

4. Natural ventilation due to the buoyancy-driven stack effect may be used for dissipating heat to the ambient sky. Therefore regulated shafts need to be integrated to and from the theatre hall, supplying from below and exhaust above, to support the stack effect. Also one-directional airflow regulators need to prevent reversed air movement. Figure 7f.

5. Natural ventilation due to wind-driven cross-ventilation may be implemented by extensions, top-ups and façade adjustments which have the potential to influence the building orientation to benefit from low and high-pressure zones to ventilate and cool. Figure 7g.

This research discusses passive design strategies based on the macroclimate of Berlin. When implementing these strategies in actual building renovation microclimate analysis is needed to further evaluate the strategy's feasibility, and discover the appropriate method of implementation. Incorporation of multiple passive design strategies might prove a success, though as some design strategies have interlacing elements of adjustment in theatre renovation, a holistic approach would be required. Further research should be done to investigate how passive design strategies could operate simultaneously, to achieve a common result. Also, further research could be done on how active system integration could enhance the performance of passive design strategy, making them hybrid.

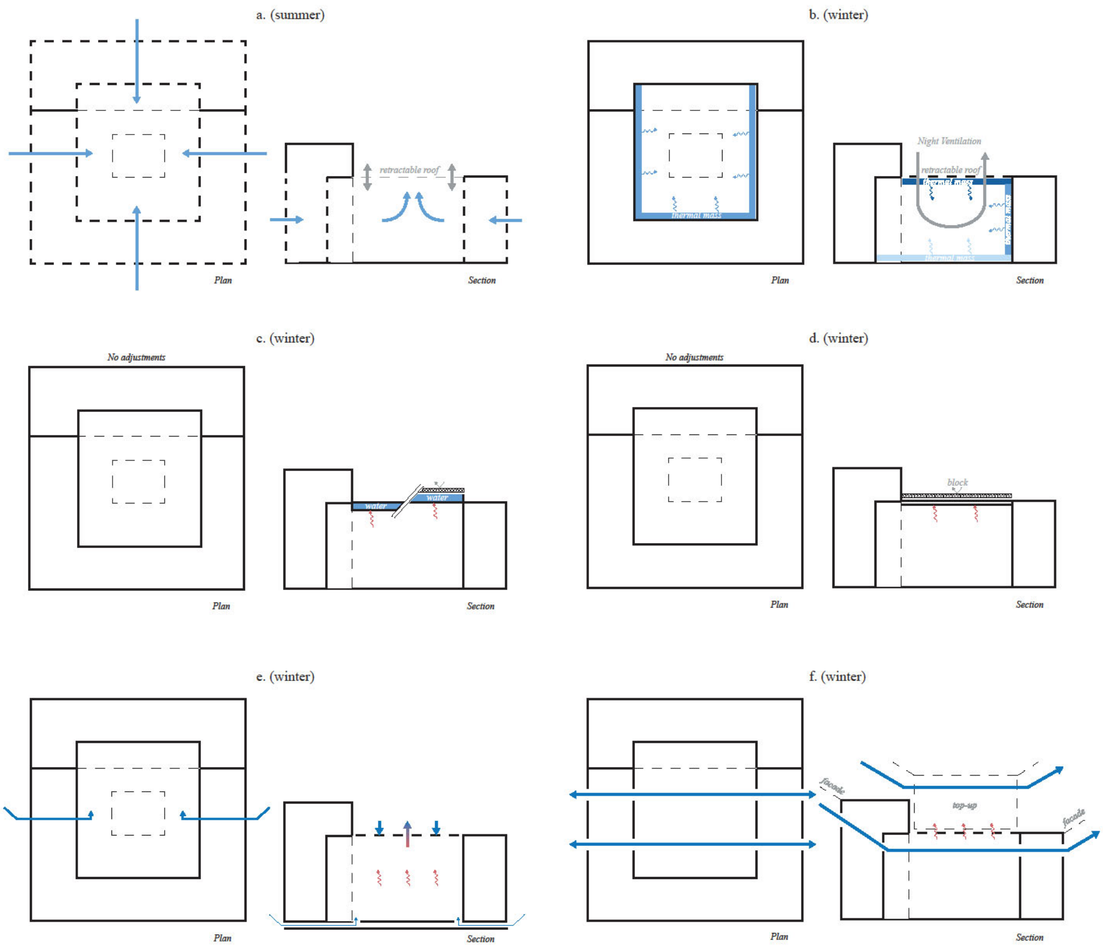


Figure 7. Implementation of passive cooling strategies in typical performance building typology. Direct connection theatre and ambient air (a), Thermal mass with night ventilation (b), Indirect evaporative cooling through the roof (c), Radiative cooling through the roof (d), Buoyancy effect (e), Wind-driven cross ventilation (f).

5. CONCLUSION

This paper set out to find an appropriate set of passive design tools which can be implemented in Berlin's local climate, that might lower the energy consumption of performance buildings, mainly focused on the mechanical ventilation and cooling of the theatre. Although passive design strategies can lower the energy consumption caused by active systems, they will not be able to fully replace them, when an ideal building comfort is at all times is desired. The high ventilation and cooling demands and complexity of peak loads in these type of spaces may require active systems as a back-up or support to ensure comfort at all moments in time, making them hybrid systems.

The modification of heat gains as well as heat dissipation can prove important tools to lower the operational energy of mechanical ventilation and cooling. In summer a direct connection to the ambient sky and the theatre will result in a beneficial effect on the thermal comfort inside the theatre, where the heat is able to freely dissipate, and ventilation will not be necessary. Integration of natural ventilation may improve airflow. In winter multiple passive design strategies may be integrated into theatres to lower the energy requirement. These include thermal mass, indirect evaporative cooling, radiative cooling, natural ventilation through the buoyancy effect or wind-driven cross ventilation. Figure 7 shows a diagrammatical representation of the implementation of these systems in a typical theatre structure.

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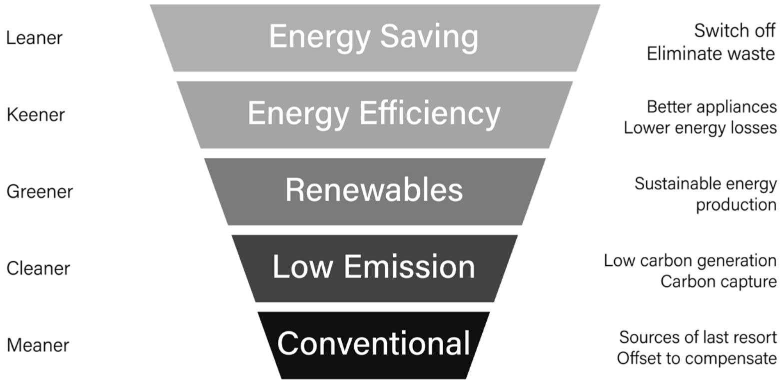
7. APPENDIX



APPENDIX 1
The energy hierarchy: own creation, based on the known model

Theatres	Heating	Cooling	Ventilating	Appliances	Lighting
A	X	X	X		
B		X	X		
C			X		X
D		X	X	X	X
E			X		X
Opera House/Concert Hall					
A		X	X		X
B		X	X		
C				X	X
D		X	X		X
E		X	X		
F		X	X		X
Library					
A				X	X
B	X			X	X
C	X			X	
D			X	X	
E	X				X
Museum					
A	X				X
B	X		X		X
C	X				
D	X		X		
E	X		X		

APPENDIX 2
The main energy consumption per program:
own creation, result of field research in Berlin

LEGEND

Theatres

A	Deutsches Theater/Kammerspiele
B	Berliner Ensemble
C	Volksbuhne am Rosa-Luxemburg-Platz
D	Friedrichstadt-Palast
E	Admiralspalast

Opera House/Concert Hall

A	Staatsoper unter den Linden
B	Deutsche Oper
C	Komische Oper
D	Berliner Philharmoniker - Grosser saal
E	Konzerthausorchester Berlin
F	Berliner Philharmoniker - Kammermusiksaal

Library

A	Amerika-Gedenkbibliothek
B	Zentral- und Landesbibliothek Berlin - Berliner Stadtbibliothek
C	Staatsbibliothek zu Berlin - Potsdammer plasse
D	Jacob-und-Wilhelm-Grimm-Zentrum
E	Universitatsbibliothek Humboldt

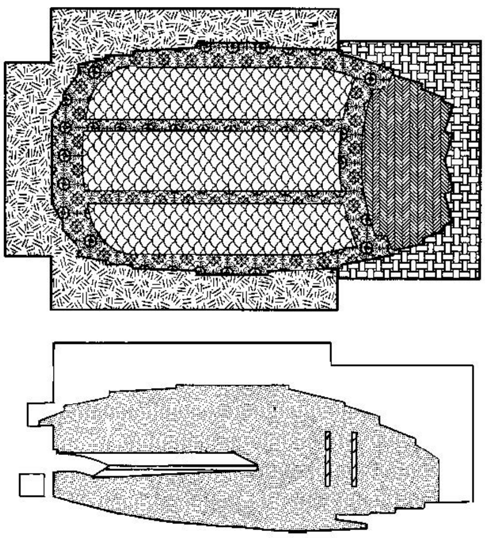
Museum

A	Hamburger Bahnhof
B	Neue Nationalgalerie
C	Pergamon Museum
D	Neues Museum
E	Kulturforum

Preliminary Research Summary	
What?	**Description**
Problem	Ventilation and the cooling problem of performance auditoriums due to metabolic heat production and ventilation rate requirements for the audience.
What type of building	Performance Building; Theatres, Concert Halls and Opera Houses
Function	Hosting Performances
Peak Load Usage	During Performances, either one or multiple a day.
Opening Hours	Two hours before shows, two hours after shows. The average show is 90 minutes. Predominantly evening shows start on average between 19:00 and 20:00.
Urban Placement	Performance Buildings are predominately solo standing, unattached to other buildings. Within urban areas.
Structure	Comprising of front of house, back of house and the theatre, *see Figure 2*

APPENDIX 3

Summary of preliminary research, source: own creation



APPENDIX 4

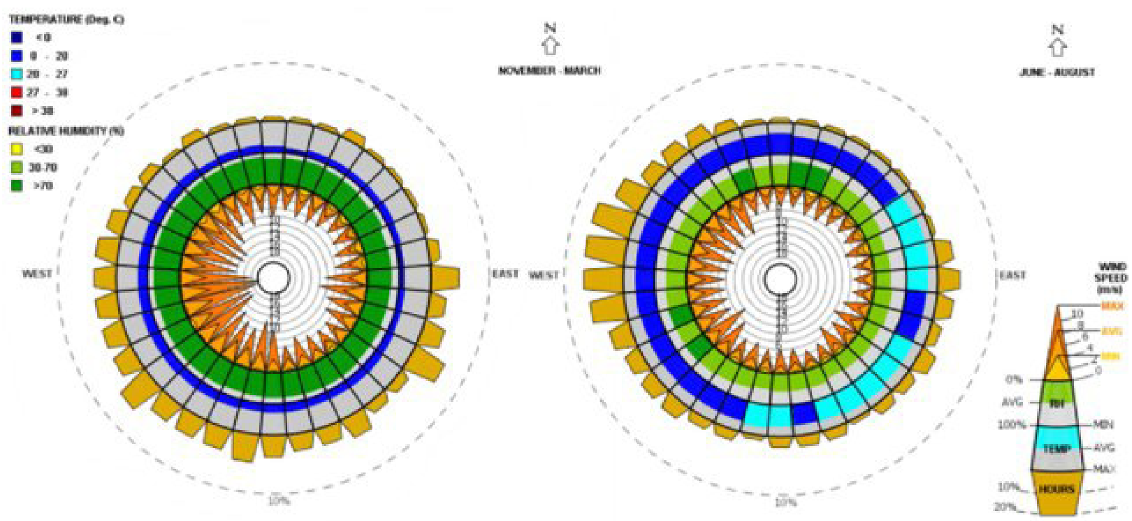
Standard medium size concert hall. Source: Guyer, P. J. (2014b). An Introduction to Architectural Design: Theatres and Concert Halls, Volume 1 (Theatre and Concert Hall Design) (1st ed., Vol. 1).

Hour	January	February	March	April	May	June	July	August	Sept	October	Nov	Dec
1	1,5	-0,5	4,2	6,3	10,7	15,2	16,8	16,2	13,1	9,2	3,8	2,0
2	1,4	-0,6	4,0	5,9	10,3	14,7	16,3	15,8	12,7	8,9	3,7	1,9
3	1,4	-0,7	3,8	5,4	10,0	14,3	15,9	15,3	12,4	8,7	3,6	1,9
4	1,1	-1,0	3,7	5,0	9,8	13,7	15,5	15,0	12,2	8,5	3,5	2,1
5	1,2	-1,1	3,5	4,7	9,5	13,7	15,1	14,7	12,0	8,2	3,2	2,1
6	1,1	-1,1	3,3	4,7	10,3	14,4	15,4	14,6	12,1	7,9	3,1	2,1
7	1,1	-1,2	3,1	5,2	11,5	15,3	16,3	15,3	12,2	7,9	3,0	2,0
8	1,2	-1,2	3,3	6,6	12,8	16,3	17,2	16,4	13,1	8,2	2,9	2,1
9	1,3	-0,7	4,0	7,8	14,0	17,2	18,2	17,6	14,2	9,0	3,2	2,1
10	1,5	-0,2	4,9	8,9	15,1	18,1	19,5	18,7	15,2	10,0	3,7	2,2
11	2,0	0,6	5,8	9,8	16,1	19,1	20,4	19,8	16,1	10,7	4,5	2,4
12	2,6	1,2	6,9	10,4	16,7	19,8	20,9	20,4	17,1	11,6	5,4	2,8
13	2,9	1,7	7,4	11,0	17,2	20,6	21,8	21,2	17,9	12,4	6,1	3,2
14	3,1	2,0	7,7	11,6	17,7	21,1	22,3	21,7	18,5	12,9	6,4	3,3
15	3,1	2,1	8,0	11,6	17,7	21,2	22,9	22,1	18,6	13,0	6,4	3,4
16	2,9	2,1	8,1	11,7	18,0	21,2	23,0	22,1	18,4	13,0	6,1	3,3
17	2,7	1,7	7,8	11,6	18,0	20,9	22,8	22,0	18,0	12,4	5,7	3,0
18	2,4	1,2	7,3	11,1	17,2	20,2	22,4	21,8	17,2	11,6	5,3	2,8
19	2,2	1,0	6,5	10,2	16,6	19,5	21,6	21,0	16,4	11,2	4,9	2,6
20	1,9	0,8	6,1	9,3	15,4	18,7	20,6	20,0	15,6	10,8	4,7	2,4
21	1,8	0,5	5,6	8,7	14,1	17,5	19,4	19,0	15,0	10,3	4,5	2,3
22	1,6	0,3	5,5	7,9	13,4	17,0	18,7	18,2	14,3	9,9	4,3	2,3
23	1,5	0,1	4,9	7,3	12,4	16,4	17,9	17,5	13,7	9,7	4,2	2,2
24	1,4	-0,1	4,6	6,8	11,9	15,7	17,4	17,0	13,3	9,4	3,9	2,1

Month	Min (°C)	Max (°C)	Mean (°C)
January	-2.2	3.2	0.5
February	-1.8	4.9	1.5
March	0.4	9	4.7
April	4	15.1	9.6
May	8.2	19.6	13.9
June	11.7	22.9	17.3
July	14	25	19.5
August	13.5	24.8	19.2
September	9.8	19.8	14.8
October	5.6	13.9	9.7
November	1.9	7.7	4.8
December	-0.9	4.1	1.6
Year	5.4	14.2	9.8

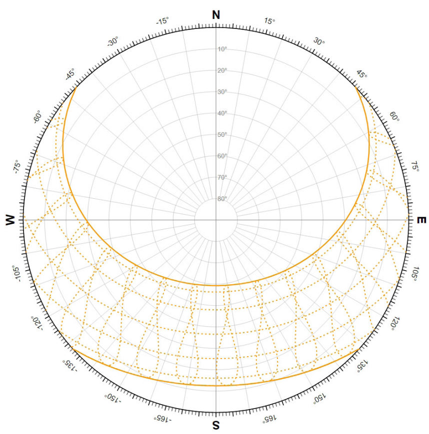
APPENDIX 5

Temperature variation throughout the year in Berlin. Source: https://www.climatestotravel.com/climate/germany/berlin



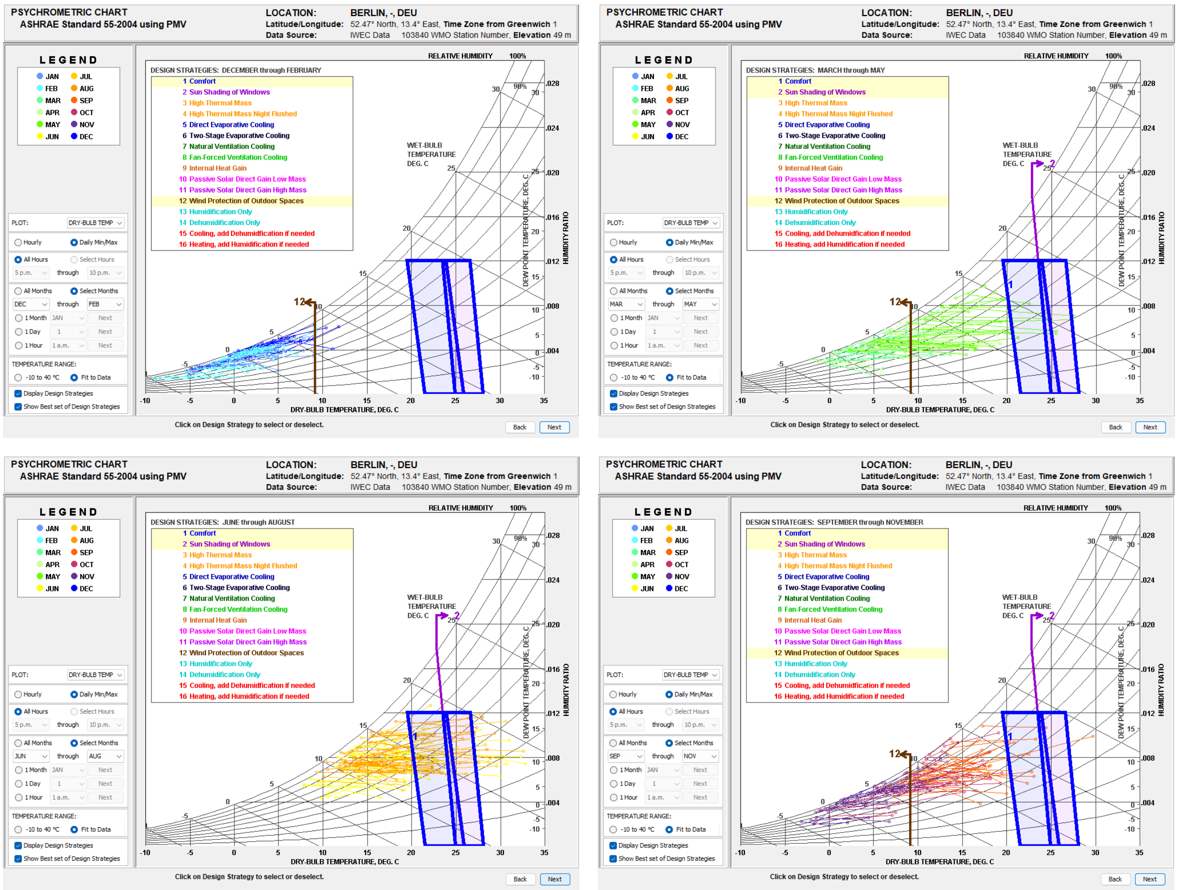
APPENDIX 6

Wind in Berlin. Source: Climate Consultant 6.0



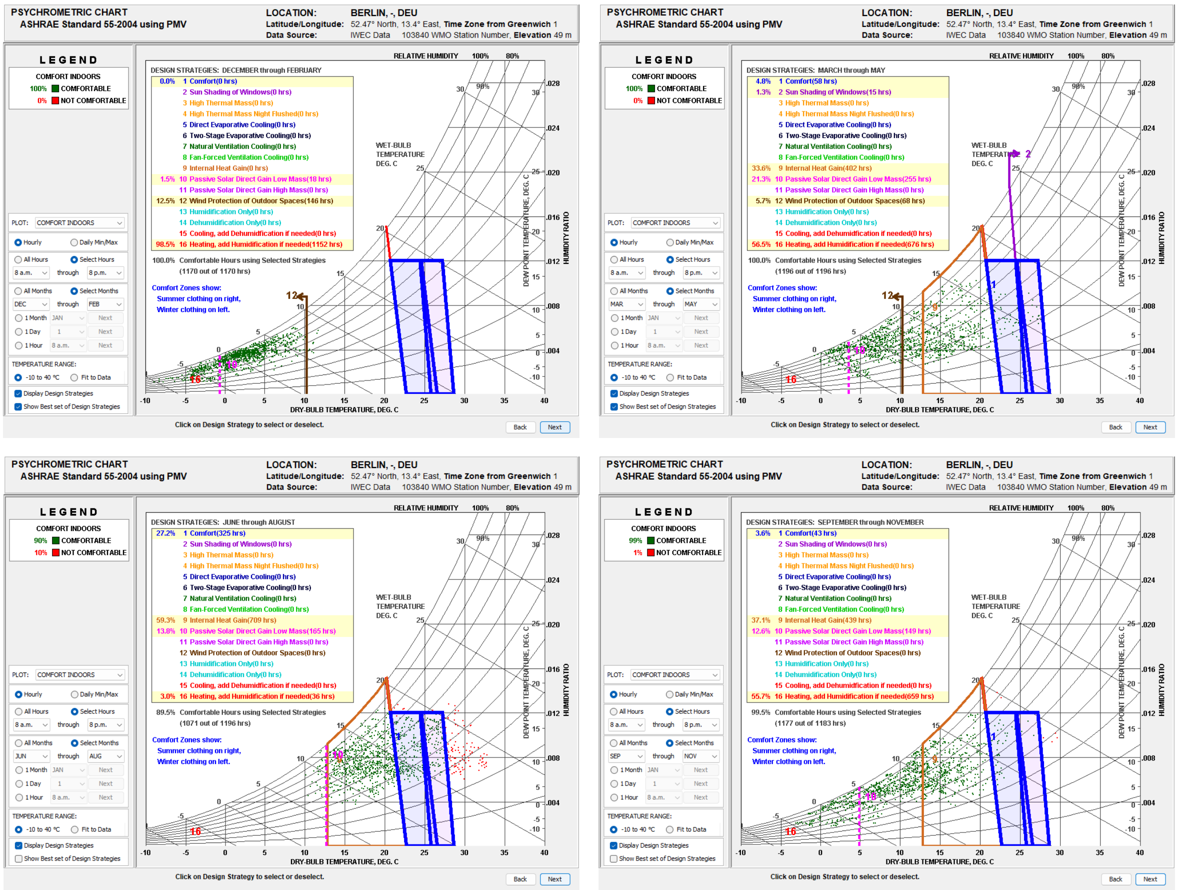
APPENDIX 7

Sunpath Berlin, Germany. Source: https://drajmarsh.bitbucket.io/sunpath-on-map.html



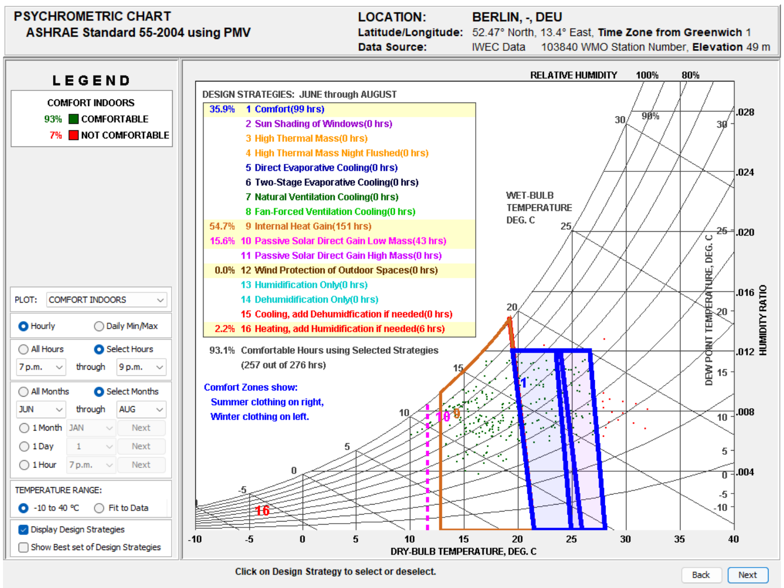
APPENDIX 8

Bioclimatic Charts of Berlin: Dry Bulb Temp. Upper left – winter, upper right – spring, lower left – summer, lower right – autumn. Source: Climate Consultant 6.0



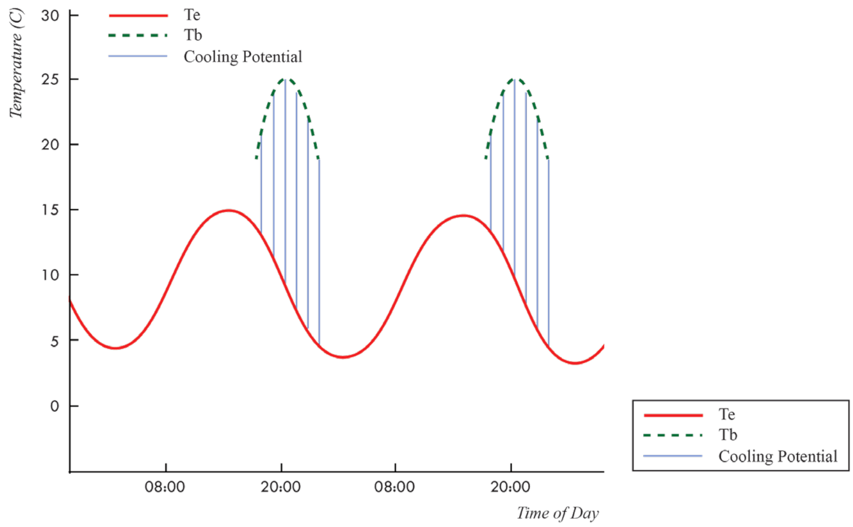
APPENDIX 9

Bioclimatic Charts of Berlin: Daytime Comfort Indoors. Upper left – winter, upper right – spring, lower left – summer, lower right – autumn. Source: Climate Consultant 6.0



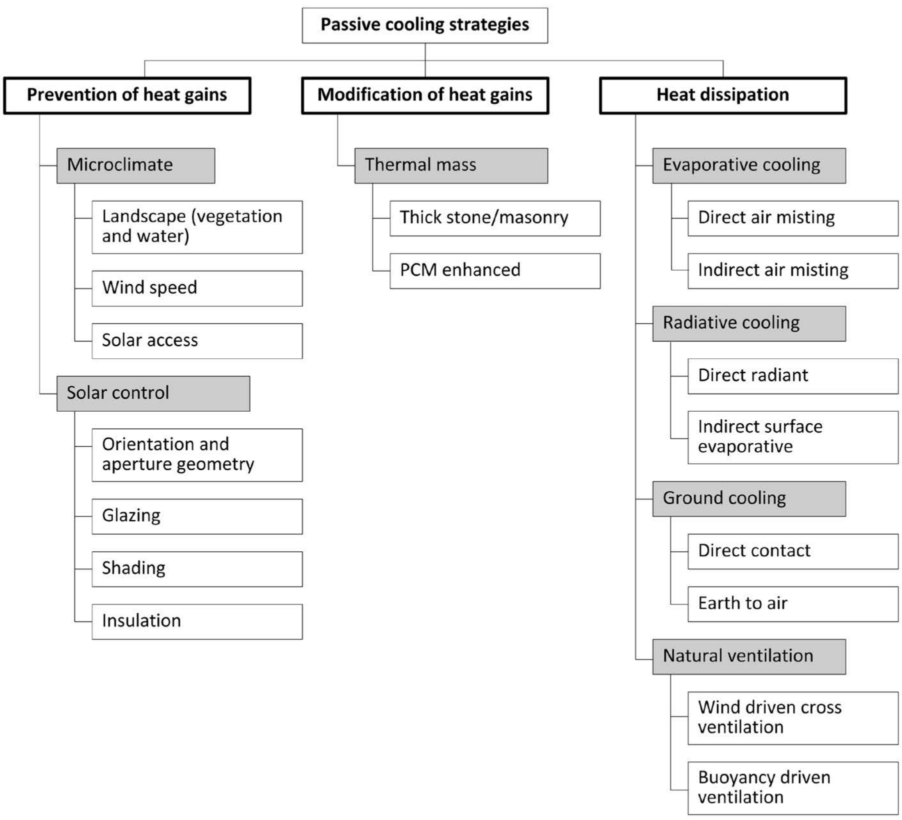
APPENDIX 10

Summer thermal comfort, Berlin, 7PM-9PM. Source: Climate Consultant 6.0



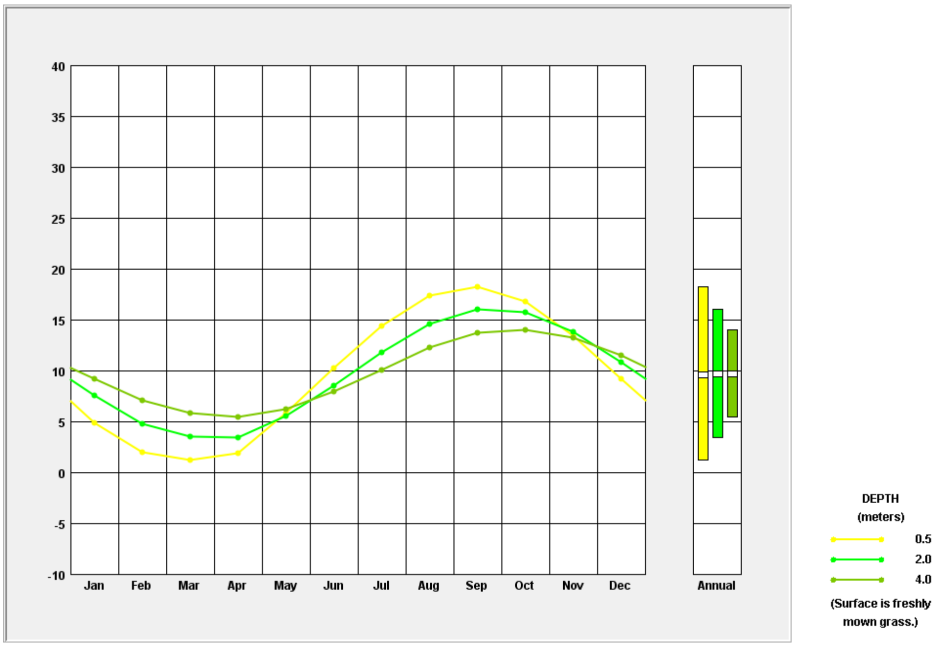
APPENDIX 11

CCP Chart Mid Seasons – Spring. Source: Own creation



APPENDIX 12

Overview of passive cooling strategies (Geetha & Velraj, 2012; Valladares-Rendón, Schmid, & Lo, 2017)



APPENDIX 13

Ground temperature Berlin, considered as a grass field. Source: Climate Consultant 6.0