DIPLOMARBEIT

URBAN GREEN SCHOOL

Approaches towards climate resilient school design to reduce the Urban Heat Island Effect

ausgeführt zum Zwecke der Erlangung des akademischen Grades einer Diplom-Ingenieurin unter der Leitung von

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E259/01 Digital Architecture and Planning

Institut für Architekturwissenschaften

eingereicht an der Technischen Universität Wien

Fakultät für Architektur und Raumplanung

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Matr. Nr.: 01325108

Wien, am 21. Mai 2021

KURZFASSUNG

Der begrünte Freiraum gewinnt an zunehmender Bedeutung für den Erhalt und die Steigerung der Lebensqualität in kontinuierlich wachsenden Städten. Der Urbane Hitzeinseleffekt stellt bereits eine große Herausforderung für Städte dar. Die großflächig bebaute Umwelt sowie die hohe Anzahl an versiegelten Oberflächen haben einen erheblichen Einfluss auf das Mikroklima und führen zu einer Zunahme von Hitzewellen in der warmen Jahreszeit. Um die Lebensqualität für die Bevölkerung in städtischen Gebieten zu erhalten und zu verbessern, sind Lösungen im Bereich der Architektur und Stadtplanung erforderlich. Als wertvolle Ressource ist die urbane grüne Infrastruktur ein wesentliches Mittel für die Verbesserung des Mikroklimas und die Abschwächung der negativen Folgen des Klimawandels in der Stadt. Die Kombination von Architektur und Vegetation stellt einen Lösungsansatz für klimaresiliente und zukunftsorientierte Städte dar. Der Schwerpunkt der Diplomarbeit liegt in der Entwicklung eines Begrünungskonzepts für Schulen, welches anhand des Entwurfs einer *Urbanen Grünen Schule* in Wien dargestellt wird. Die planerische Reaktion auf Herausforderungen des Klimawandels, wie die steigende Häufigkeit von Hitzetagen und starken Regenfällen, stehen im Fokus der Entwurfsaufgabe. Als Grundlage dient eine Literaturrecherche im Themenbereich urbaner Herausforderungen des Klimawandels, stadtklimatisch relevanter Indikatoren, Maßnahmen zur Klimawandelanpassung und Verbesserung des Mikroklimas sowie ausgewählte Fallstudien, die unterschiedliche Ansätze zur Einbindung von Begrünung an Schulen aufzeigen. Der Schulbau kann aufgrund des meist häufigen Vorkommens in den Städten, besonders in Zonen mit dichter Bebauung und hohem Anteil an versiegelten Flächen, zusätzlichen Grünraum schaffen. Extreme Temperaturen an Hitzetagen während der Schulzeit stellen für Kinder und Jugendliche eine große Belastung mit negativen Auswirkungen auf die Konzentration und Lernfähigkeit dar. Des Weiteren haben Schulen und deren Freiräume das Potenzial, zusätzliche begrünte Freiflächen mit hoher Aufenthaltsqualität für die lokale Bevölkerung in der umliegenden Nachbarschaft zu schaffen. Der Entwurf der *Urbanen Grünen Schule* dient als Modell, um den Einfluss von grüner Infrastruktur auf das Mikroklima an einem Hitzetag zu demonstrieren. In diesem Kontext wird eine auf ENVI-met® basierende Mikroklimasimulation in verschiedenen Szenarien durchgeführt. Die Ergebnisse werden anschließend durch das GREENPASS® Green Performance Assessment Tool ausgewertet, analysiert und bewertet.

ABSTRACT

Green spaces are becoming increasingly important in constantly growing cities. The Urban Heat Island (UHI) effect is already one of the major challenges for cities. Environmental effects of large constructed areas have a significant impact on microclimate and global warming. Population growth in cities demands solutions in the fields of architecture and urban design to maintain and improve the quality of life in urban areas. Urban green infrastructure is a valuable resource which has the potential to improve microclimate and reduce impacts of climate change in cities. The combination of architecture and vegetation is an approach towards more climate resilient cities. The aim of this master thesis is to develop a greening concept for schools, which is demonstrated by the design of an *Urban Green School* in Vienna. The design task focuses on the architectural response to challenges of climate change including the increasing frequency of heat days and severe rainfall. The development of the concept is based on a literature review in the fields of urban challenges of climate change, key performance indicators (KPIs) relevant to urban climate, design strategies for climate change adaptation and microclimate improvement. Selected case studies show different approaches for the inclusion of green spaces in schools. Since schools often are located all over the city, this type of use is suitable for creating additional green space especially in zones with dense construction and high areas of sealed surfaces. Children belong to one of the most vulnerable age groups regarding exposure to high temperatures. High indoor temperatures not only cause health concerns but also hinder children's concentration and learning at school. School buildings can also provide additional green open spaces with high quality of stay for residents in surrounding areas. The concept of the *Urban Green School* serves as a model to demonstrate the impacts of green infrastructure on microclimate on a heat day. In this context, a microclimate simulation based on ENVI-met® is conducted in different scenarios. The results of the microclimate simulation are analyzed and evaluated by the GREENPASS® environmental evaluation tool.

acknowledgments

I would like to express my appreciation to everyone who encouraged me during this time. In this context, I would like to thank my thesis supervisor Univ. Prof. Dipl.-Ing. Dr. Michael Hensel for his valuable advice, support and constructive suggestions.

I would like to thank GREENPASS GmbH and my colleagues for the opportunity and support to apply the simulation and evaluation tools.

Finally, I am extremely grateful to my parents and family for always being supportive and patient and to friends who made this time unforgettable.

CONTENT

TABLES

01 INTRODUCTION

1.1 Motivation

Green spaces are becoming increasingly important in constantly growing cities (Haaland and Bosch, 2015, Tzoulas et al., 2007) and the Urban Heat Island (UHI) effect is already one of the major challenges. Environmental effects of large constructed areas have a significant impact on microclimate and global warming. Population growth in cities demands solutions in the fields of architecture and urban design to maintain and improve the quality of life in urban areas. Therefore, the design of new construction projects needs to address greening measures by adding green spaces, a rare and valuable resource in cities, to improve microclimate and human health and well-being (Lee and Maheswaran, 2010, Ekkel and Vries, 2017).

The main focus of this project is the development of a concept for greening measures for designing schools. The concept is demonstrated by the design of an *Urban Green School* as a showcase in Vienna that responds to the challenges associated with climate change and considerations of the health and wellbeing benefits for children arising from close-by green spaces (Kabisch et al., 2017). Children belong to one of the most vulnerable age groups regarding exposure to high temperatures. High indoor temperatures not only cause health concerns but also hinder children's concentration and learning at school. By developing and implementing greening measures, the indoor air quality can be improved towards creating a more comfortable, focused and creative learning environment. Since schools are located all over the city, this type of use is suitable for creating additional green spaces especially in zones with dense construction and high areas of sealed surfaces. School buildings can also provide additional green open spaces for other sensitive population groups, including older adults or families with small children, within a walkable distance to their homes.

Integration of greening measures in school architecture allows for educational inclusion of related topics such as climate change, biodiversity, and the role of vegetation in cities. Furthermore, schools which focus on environmental education contribute to raise the awareness and interest of young generations and future decision makers to act as environmental conscious citizens. An additional focus of the project is the combination of building greening with urban farming and gardening. In contrast to rural areas, children and young people in the cities have less experience in proper food cultivation and the importance of biodiversity in cities. By inclusion of green spaces in school lessons, it is possible to expand the scope of theoretical and practical education while new learning methods and disciplines are adapted at different school levels. The combination of urban gardening with greening measures in school areas enables the local community involvement and expansion of the existing initiatives and projects that promote gardening in the city as a social leisure activity.

Local food production will become increasingly important for food security. Recent observations related to the COVID19 pandemic show that the capacity for growing food self-sufficiently can be a major relief in times of crisis (Pulighe and Lupia, 2020, Cutcher-Gershenfeld et al., 2021). Furthermore, by reducing food transport distances, levels of emitted air pollutants can be reduced as well. Cultivation land is a rare resource in cities. Vienna has a comparatively large number of green areas and areas for agriculture within the city limits. However, the need for construction entails a threat to these areas.

By including urban gardening and urban farming in greening measures, such as the greening of roofs, walls and open spaces, the ecological, economical and social value of the greenery will increase and such interventions can support the food supply chain. For schools this would enable local production of vegetables, herbs and fruits, for instance, which can be directly used for meal preparation in the school canteen and create a very short supply chain. In addition, the value of food and methods of eco-friendly agriculture can be taught to children.

1.2. Structure and contents

This project combines theoretical models with practical development approaches towards designing a showcase school with a green architecture in Vienna. The main chapters are research, case studies, a greening concept for schools, the *Urban Green School* design and results of the microclimate simulation and environmental assessment. The research will focus on urban challenges of climate change, urban green infrastructure and urban greening measures such as roof greening, facade greening, green open spaces, and urban gardening in cities. The chapter on urban climate will explain different indicators for environmental assessment including the Physiological Equivalent Temperature (PET), Albedo and Runoff Coefficient. The chapter on microclimate simulation will describe applied tools and data sources which are necessary to develop the simulation model of the *Urban Green School* showcase. The selected case studies represent different educational facilities with greening measures. They show the diversity of approaches towards the educational use of green space and the role of nature in each project.

The greening concept for schools is the basis for the implementation of greening measures in the *Urban Green School* design. The concept points out different demands and requirements for green infrastructure in schools and describes various possibilities for each functional category. The design demonstrates how greening measures can be part of the architectural concept while being incorporated into the school program and improving the microclimate and environment.

The aim of the building and open space design is to minimize the area of sealed surfaces through implementation of water-permeable surface materials and the Sponge-City concept which uses the water storage capacity of plants and soil by providing enough root space and substrate between sealed areas. The environmental impacts and thermal comfort of the design are calculated and analyzed through an environmental evaluation with the GREENPASS®[1] Green Performance Assessment tool, based on a microclimate simulation powered by ENVI-met®[2]. The results of the simulation and analysis visualize the impact of green infrastructure on reducing the Urban Heat Island effect.

1 https://greenpass.io/
2 https://www.envi-met.com/

2.1 Challenges of climate change: Urban Heat Island Effect

Climate aspects in urban areas and surrounding rural areas are different from one another in terms of precipitation, wind conditions and temperatures (Brandenburg et al., 2018). Urban areas usually have a lower humidity as a result of less vegetation compared to the surrounding countryside. Dark asphalt and concrete surfaces lead to an increased absorption of solar energy. Therefore, city centers often have higher temperatures than the surroundings (EU-Kommission, 2014). This phenomenon, also known as the Urban Heat Island (UHI) effect, is defined as a temperature difference of 12 °C to 15 °C between an urban area and its surroundings. The high areas of sealed and dark surfaces in cities lead to a higher absorption rate of heat, which prevents nighttime cooling on hot days. Furthermore, there are fewer trees and green spaces in cities which leads to less natural cooling through evapotranspiration (Environmental-Encyclopedia, 2003, p. 1442). Natural open spaces are mainly covered with vegetation and consist of moisture absorbing soils whereas impermeable materials cause a quick surface runoff of rainwater, which results in less water retention for evapotranspiration (Brandenburg et al., 2018).

The UHI effect is generated by heat waves and can have damaging impacts on the population. Children, older adults and people with chronic diseases are particularly vulnerable. Although humidity could be artificially reproduced by electrically generated water vapor in urban areas to reduce heat, the economic and energy cost would be much higher compared to the humidification by natural vegetation. The amount of energy used for air conditioning will increase significantly, if measures and strategies are not developed to increase the volume of greenery and thus natural cooling in cities (EU-Kommission, 2014). Reduction and fragmentation of urban green spaces also amplify the UHI effect. In addition, waste heat from industrial processes, air-conditioning and motor vehicles adds anthropogenic heat to the environment. A thermal image of the city of Vienna (Figure 1) clearly shows the outlines of the UHI effect in the evening on a summer day and the differences in surface radiation temperature between densely developed urban areas including impermeable parking lots and industrial areas, and cooler areas such as parks, farms and water bodies. Due to the generally high thermal mass of construction materials, heat is stored and radiated to the surroundings after sunset until the next morning which reduces nighttime cooling (Brandenburg et al., 2018).

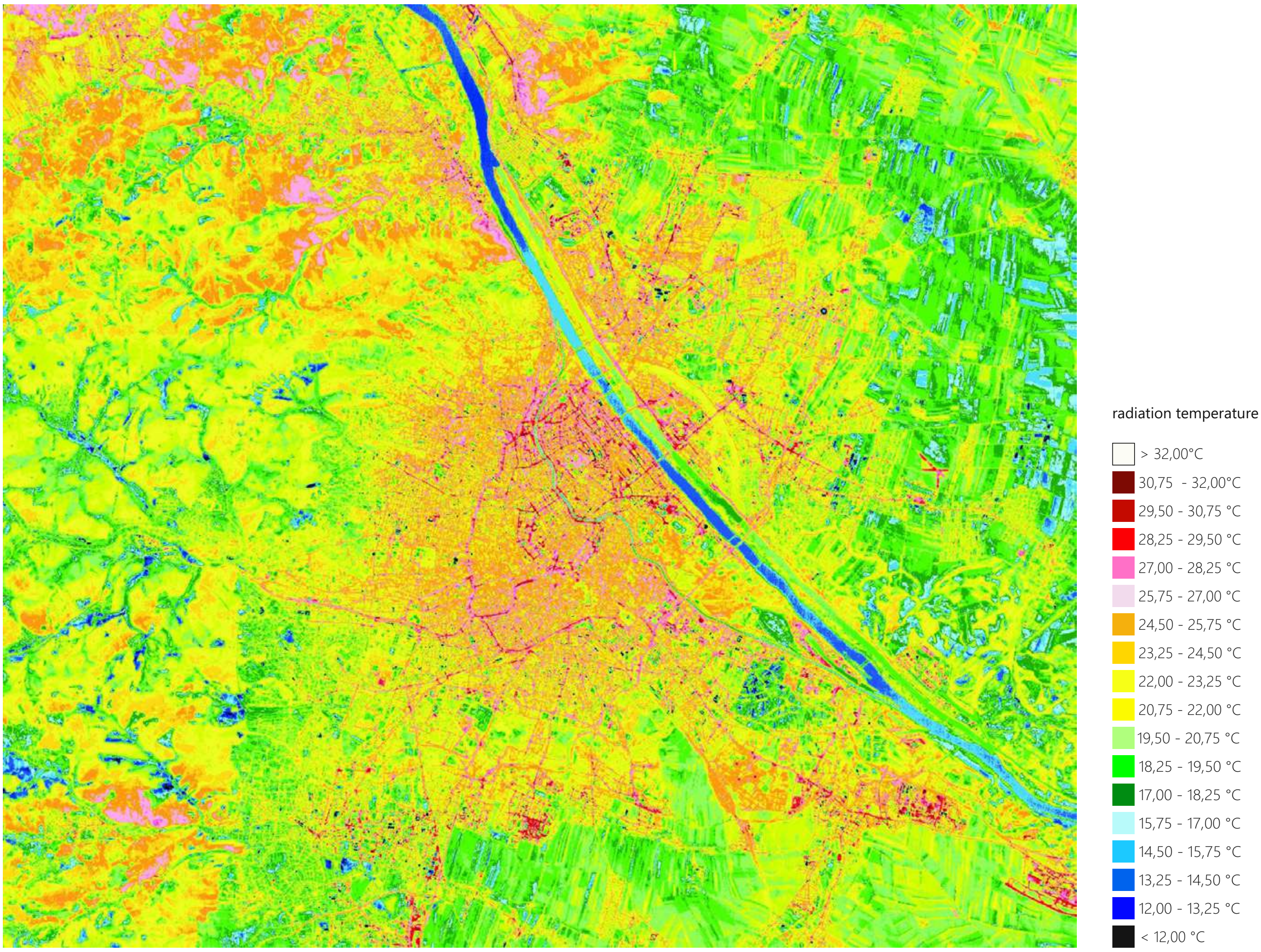


Figure 1 thermal image of the city of Vienna and surrounding countryside on a summer day evening, MA22

2.1.1. Urban Heat Vulnerability Map of Vienna

High temperatures due to the UHI effect can negatively affect the health of citizens. The size of areas with low thermal comfort will increase not only inside of the buildings but also outside at sealed open spaces. The increasing frequency of hot days is a growing stress factor that reduces citizens' quality of sleep as well as wellbeing and productivity. While the majority of citizens are able to overcome heatwaves without suffering permanent damage, highly vulnerable individuals including children, older adults, and people with chronic diseases, particularly with lower socio-economic status, suffer from extreme heat to such a degree that it can be life threatening (Brandenburg et al., 2018).

The urban heat vulnerability map of Vienna (Figure 2) shows areas where people are most affected by high temperatures. It was developed by the environmental engineering company ECOTEN for the municipality of Vienna and shows districts, where the city planning should react and implement strategies to protect the health and wellbeing of residents. Susceptibility to extreme heat depends on different individual characteristics such as age and existing health problems and is related to the strength of human response to high temperatures (Bhattacharjee, 2019).

The concept of vulnerability incorporates on different factors and is defined by the Intergovernmental Panel on Climate Change (IPCC) in the third assessment report *"TAR Climate Change 2001: Impacts, Adaption and Vulnerability"* as a function of exposure, sensitivity and adaptive capacity.

"Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity" (IPCC, 2001, p. 6).

In development of the urban heat vulnerability map of Vienna, the *Urban Heat Vulnerability Index* (UHVI), the difference between adaptive capacity and the product of exposure and sensitivity was used. Areas with a higher UHVI have a higher degree of vulnerability. The sensitivity factor is defined through calculation of the *Vulnerable Population Density Index* (VPDI) which is based on the *Sensitivity Index* (SI). SI is defined as the density of the population belonging to the most vulnerable age groups of 0 to 14 and above 65 in any given district. The adaptive capacity factor is described by the *Enhanced Vegetation Index* (EVI) and the *Normalized Difference Water Index* (NDWI), which represent natural cooling contributed by greenery and water bodies. The addition and normalization of EVI and NDWI lead to the *Adaptive Capacity Index* (AVI). The data for the monitoring of vegetation and water bodies was taken from the Sentinel 2A EO Satellite, which is part of a mission by the European Space Agency for land monitoring. The exposure factor, which represents overheating, was calculated as the weighted average of annual maximum atmosphere satellite brightness (ASB) temperatures. The data was taken from the years 2015 to 2019 with the number of heat days over 30 °C in each year in Vienna as the weighting factor. The normalized temperatures between 19 °C and 40°C were used to measure the *Exposure Index* (EI). The UHVI map of Vienna is the result of the equation: UHVI = (EI x SI) – AVI (Bhattacharjee, 2019).

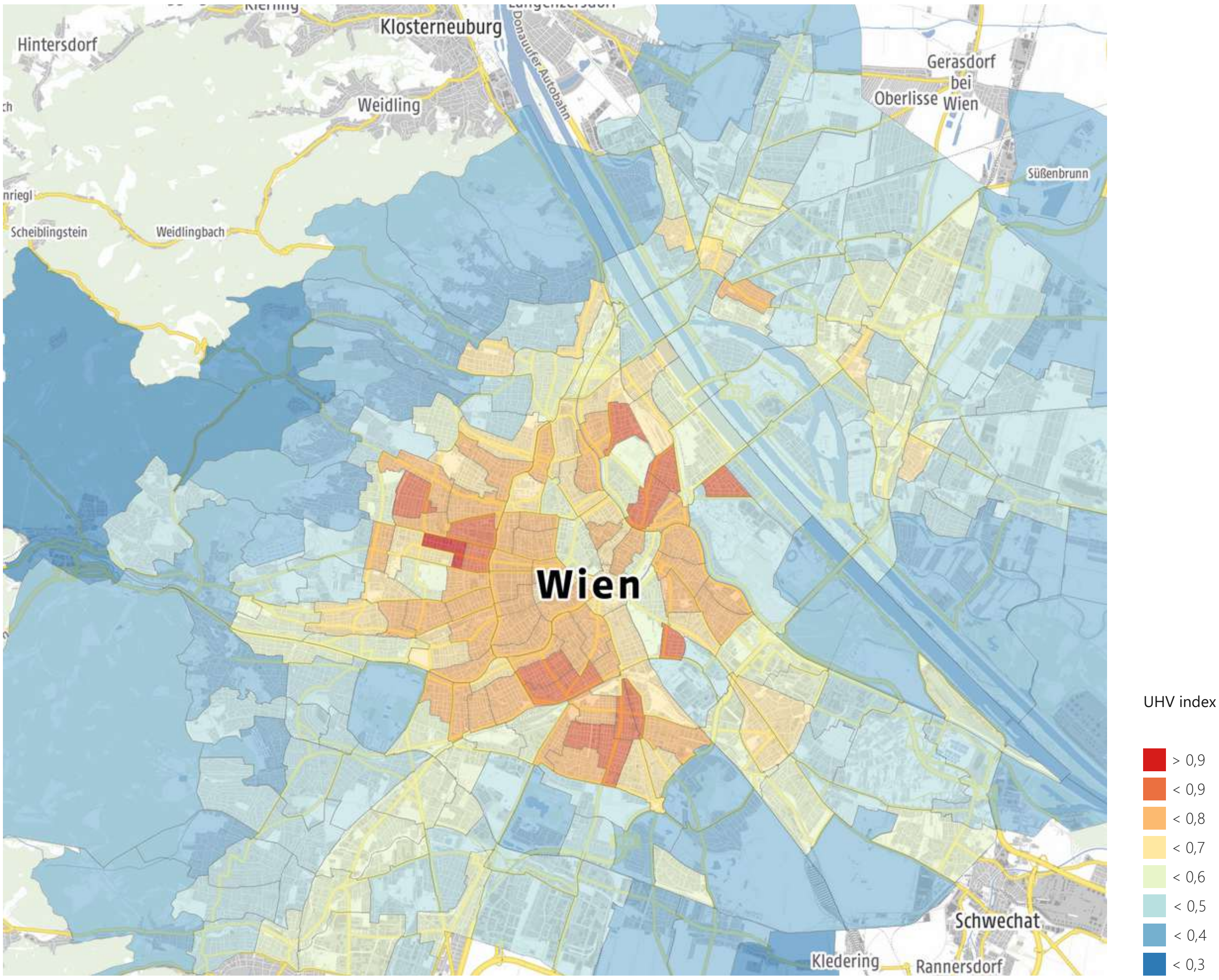


Figure 2 Urban Heat Vulnerability Index Map for Vienna, Stadt Wien, OpenStreetMap ECOTEN (2019)

2.1.2. Urban Heat Island (UHI) and Park Cool Island (PCI)

In order to observe UHIs, the difference of air temperature or relative temperature of ground surfaces between a city and its suburban and rural areas needs to be measured. UHIs are typically identified by a peak in temperatures which is locally detected at the dense urban core of a city in comparison to its rural surroundings. The UHI effect is especially recognizable during nighttime and under calm and cloudless weather conditions. UHI effect intensity depends on many factors, such as the geographical location of the city, size, population, urban structure, land use distribution, and the relative number of trees and vegetated green spaces in comparison to the sealed areas. It is typical for the surrounding areas of an UHI to have higher temperatures compared to the rural areas outside of the city. The increase in the sensible heating of the environment is caused by the modification of land surface by buildings and paved areas, which leads to the absorption of the incoming solar radiation. The heat is then retained by dense surface materials and cannot escape the city, because the reflection rate of solar and emitted thermal radiation is very low as a result of the three-dimensional geometrical dense structure of buildings and urban street canyons. In addition, waste heat from air conditioning, heating, industrial processes, motorized traffic, and other urban activities causes a further intensification of the UHI effect. The thermal comfort experienced by pedestrians is in particular influenced by heat islands within the urban canopy layer (UCL) and in the layer of extended air volume from street level to the average height of surrounding buildings and trees. In this air layer the measured urban-rural temperature difference can vary from 1 to 3 °C, which is the typical range. However, the temperature difference can increase to 12 °C in large cities during nights with stable, calm and cloudless weather conditions. A Park Cool Island (PCI) is described as a greened area, such as a park, which has locally lower air temperatures than its constructed surroundings. Thus, the cooling effect of urban parks can be measured by the air and ground surface temperature difference between vegetated and sealed urban areas. The type of vegetation, size of the park, tree species and coverage together with seasons and weather conditions are factors on which the varying intensities of PCIs depend (Hiemstra et al., 2017).

Figure 3 shows, how the air temperature changes from UCIs to PCIs and the rural area outside of the city.

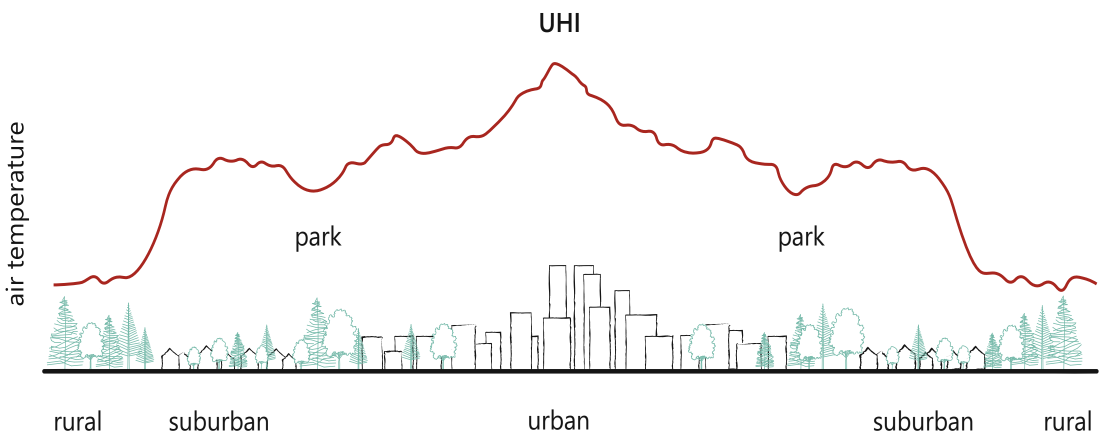


Figure 3 schematic illustration of increased temperature in the urban area, own illustration based on Oke (1987) and Zafrir-Reuven (2017)

2.1.3. Health benefits of urban green spaces

The relation between urban green spaces and their benefits on wellbeing, physical and mental health were investigated in the review *"The health benefits of urban green spaces: a review of the evidence"* by Lee and Maheswaran (2010). Green spaces provide opportunities in urban areas for exercise in a natural environment. It is documented that physical activity has a variety of health benefits including among others the decrease in the risk and severity of cardiovascular diseases, osteoporosis, and diabetes. Furthermore, improvement of mental health and wellbeing, and long-lasting psychological benefits can be referred to higher physical activity levels. The access to green space can also have an influence on emotional and mental health, behavior, stress balance, and quality of life. The social benefits of green spaces can be described through common spaces which allow social interaction and the development of social ties in a neighborhood (Lee and Maheswaran, 2010).

Studies of available evidence show, that there is a positive association between green spaces and improvement of health and wellbeing. However, there is a high complexity in the correlation of green space and urban health. It is likely that there are many factors besides the presence of green space itself that influence the suggested public health benefits. Accessibility, perception of safety, and quality of space for example are significant factors that have an influence on the decision of people whether to use a green space or not (Lee and Maheswaran, 2010).

The review by Lee and Maheswaran (2010) summarizes studies on the relationship between green space and health. The following table shows an excerpt of their findings.

study	study design	findings
Kweon et al., 1998	Qualitative interviews of 91 residential home residents	Exposure to green common spaces associated with better social integration of elderly persons.
Maas et al., 2006	Self-administered survey of 250 782 persons of their perceived general health and the characteristics of their living environment.	Reported that the amount of green space present in the respondents' living environments was positively associated with their perceived general health. This association was stronger for lower socioeconomic groups, youth and the elderly.
Sugiyama et al., 2008	Cross-sectional mail questionnaire survey of 1895 adults. Used spatially-based sampling.	Perception of neighborhood greenness associated with better physical and mental health as well as recreational walking.
van den Berg et al., 2010	Questionnaire survey of 96 parents of children with attention deficit disorder. Convenience sampling used.	Children with attention deficit disorder function better after activities in green setting.
Taylor et al., 2001	Survey of 4529 respondents.	Respondents with higher levels of green space reported being less affected by stressful life events, and better perceived mental health.

Table 1 studies on the relationship between green space and health (Lee and Maheswaran, 2010, p. 214f.)

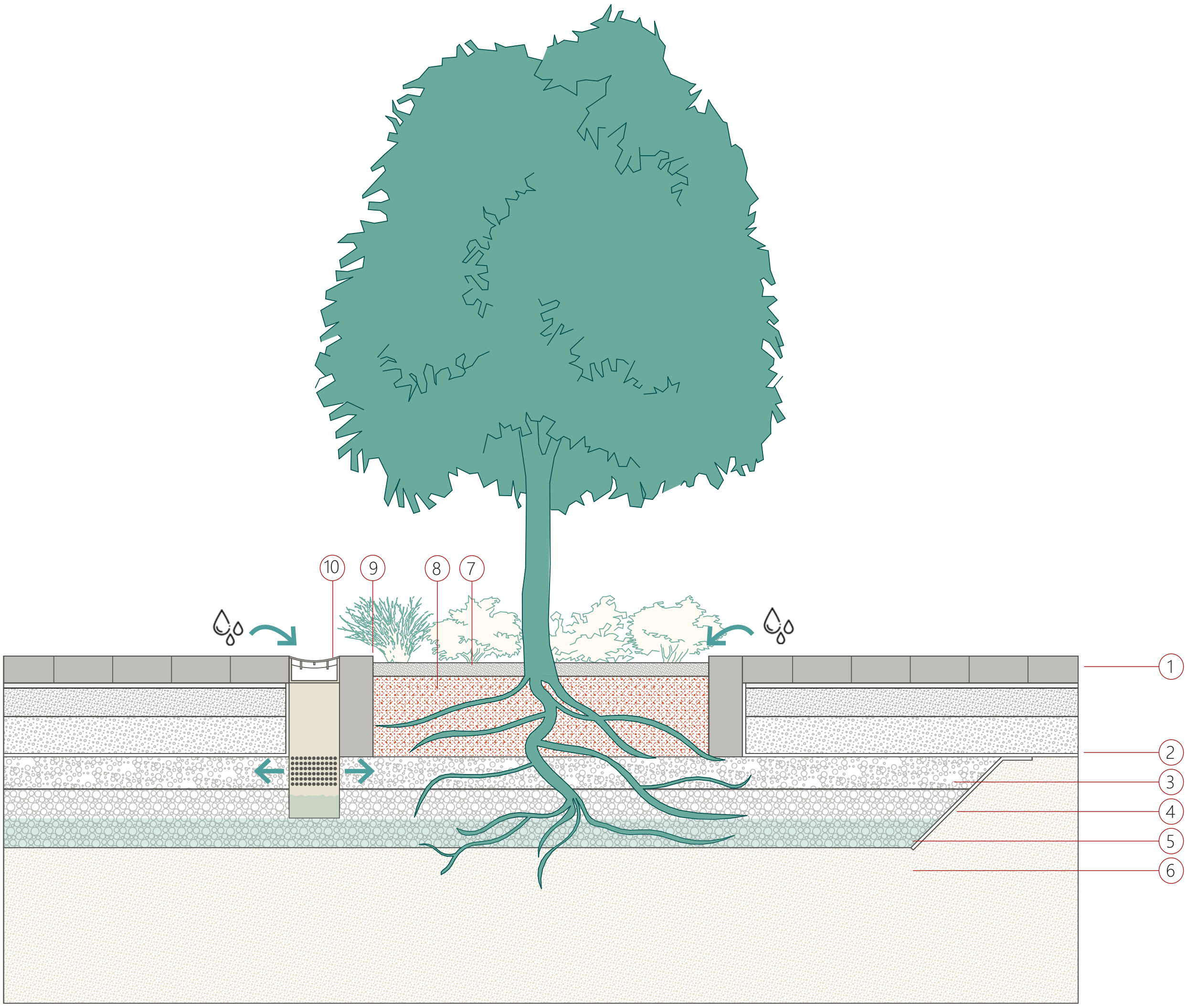
2.2. Challenges of climate change: extreme precipitation

Urban drainage, flood risk and water resources are affected by climate change. On one hand, hot and dry summers result in a higher water demand, reduced soil moisture, and decline of the groundwater level. On the other hand, long-term observations have shown a correlation between the global warming and increase in frequency and intensity of sudden heavy rainfall resulting in local flooding in many regions during the last century with a trend of further increase over the coming decades. In cold regions, riverine flooding can also be caused by rapid snow melt accelerated by climate change. Because of the high percentage of sealed surfaces in urban areas, overloading of the surface water drainage system occurs during extreme precipitation or snow melt. An increase in permeable surfaces in urban areas would allow rainwater to get absorbed and offload the urban drainage system. In order to reduce damages due to floods as a consequence of climate change, a more stringent control of urban development can minimize constructions and ground sealing in high-risk areas and increase the amount of green and permeable spaces for urban cooling and flood control (Wilby, 2007).

2.2.1. Sponge City Principle

The sponge city principle (Figure 4) is an innovative ground preparation system which uses the space below and around the trees as a temporary water storage and allows rainwater to remain in the local water cycle. This solution addresses two main problems which are a) peak water levels overloading the urban drainage system during extreme precipitation and b) shortage of rainwater supply for plants at the same time. Functioning as a smart rainwater management system, the sponge city principle also improves the health and appearance of city trees by providing sufficient root space and enhancing their stability and enabling them to grow larger crowns (Drlik and ÖGLA, 2019). The sponge city principle specifies the substrate in the tree root area which is a mixture of rough crushed rock and stones, compost and biochar. The micropores retain the rainwater in the ground, which functions as a water reservoir for plants during dry periods. The potential of the sponge city principle to manage rainwater as a valuable resource is remarkable, considering its capability to store a high percentage of 93 to 97 % of rainwater that would otherwise run off into the sewage system and not be part of the natural water cycle in densely built and sealed urban areas (Zimmermann and Marboe, 2021).

The locally stored water also has a cooling effect because of evaporation and transpiration by the plants. In general, the integration of blue and green infrastructure in urban planning is an effective strategy regarding resiliency to climate change in cities (Drlik and ÖGLA, 2019). Blue infrastructure refers to landscape elements linked to water. They can consist of natural elements including rivers, canals, natural ponds, wetlands and floodplains as well as semi-natural elements such as pools, pond systems and artificial buffer basins (GREEN4GREY, Root-Bernstein, 2020).



1 - pavement and sub-layers 2 - separating fleece 3 - ventilation and distribution layer 4 - protective layer in facade area

5 - rough crushed rock, compost and biochar 6 - subsoil/ground 7 - vegetated gravel bed 8 - tree substrate 9 - tree grid frame 10 - rainwater inlet

Figure 4 sponge city principle, own illustration based on 3:0 Landschaftsarchitektur

2.3. Urban open space

Urban open spaces are generally described as undeveloped public and private areas in a city allocated for functions and usage. They include unsealed green spaces and blue infrastructure such as rivers, lakes and other water surfaces but also sealed squares, courtyards and traffic areas. In the broader spatial context, open spaces of buildings also have to be counted among the urban open space, since buildings create horizontally and vertically a large part of the city surface. Vertical areas as potential open spaces are particularly relevant under ecological and urban climatic aspects (Hagen, 2011).

The variety of functions of the urban open space can be divided into three main categories. The environmental and ecological functions include improvement of climate and thermal comfort, noise and dust filtration, water cycle impact, surface water management as well as preservation and improvement of biodiversity. Green and blue urban open spaces are essential for the mitigation of global warming and can function as an instrument for the city's adaptation to the changing climatic conditions. Furthermore, urban open spaces have a social and community function as they provide areas for leisure activities, recreation, and sports and encourage social interaction and communication in the city. Therefore, urban open spaces are crucial for the wellbeing of citizens and quality of life in the city. As a third category, urban open spaces also have a structural and symbolic function as they shape the urban structure, create different local characteristics and can improve orientation and readability in the city (Hagen, 2011).

2.4. Green and Blue Infrastructure

Green infrastructure (GI) can be described as a strategically planned network of valuable natural, semi-natural, and artificial areas that create and provide a wide range of ecosystem services in urban and rural areas to increase resiliency to climate change and protect biodiversity. Networks of green (land) and blue (water) spaces, known as green and blue infrastructure (GBI) combine ecosystem services provided by water bodies and vegetation. GBI improves air and water quality by absorbing pollutants and increasing water storage capacity by retaining rainwater, which prevents flooding and ground erosion by improving soil quality. The (re-) connection of natural environments by ecological corridors supports biodiversity and enlarges habitats. One of the main advantages of GBI is its ability to provide multiple functions within the same area, unlike most "grey" infrastructures, which usually have a single purpose. A social value of GBI is the improvement of health and wellbeing of the population, among other things by reducing the UHI effect. In order to provide valuable ecosystems and have their benefits, including carbon sequestration, reduction of rainwater runoff, and natural cooling, GBI networks should be given more space for their development (EU-Kommission, 2014).

By integrating GBI in urban and architectural design it can function as an effective tool to increase cities' resiliency to climate change. There are different implementation strategies with mitigating and/or adaptive effects. The use of vegetation for microclimate regulation through evaporation and shading is an adaptive strategy against a warming and drying trend caused by extreme high temperatures. At the same time, CO_2 is sequestrated by the plants photosynthesis process which reduces greenhouse gas emissions and contributes to the mitigation of climate change as well (Perini, 2017).There are several environmental elements that can be part of GBI, from small elements such as hedges and trees, buildings with green roofs and facades, ponds and urban rivers to whole functional ecosystems including intact riverside forests, wetlands, moors or free flowing streams. Each element of GBI can provide ecosystem services in urban, periphery and rural areas, however not every green area, water body or environmental structure is automatically qualified and part of a GBI network. To be an integral part of a biotope network, the elements must be suitable for biodiversity and serve more functions than being just a “green space”. Monotonous landscapes such as lawn areas without any other environmental element or intensively farmed agricultural fields are hardly considered as green infrastructure, unless they have multifunctional benefits and are not harmful to the local biodiversity. There is a wide range of vegetation types and structures that are considered as urban green infrastructure (UGI), for example in the form of parks with high biodiversity, public and private green spaces, roadside vegetation, building greenery and fresh air corridors (EU-Kommission, 2014).

According to Carlos Bartesaghi Koc, Paul Osmond and Alan Peters classification of GI typologies is necessary to compare the thermal benefits and impacts of different GI elements and support climate studies. Figure 5 shows the approach towards a standardized and specific classification scheme that evaluates the existing GI elements and divides them into main categories and sub-classes of vegetation layers as well as the greened structure including ground surfaces and building structures (Bartesaghi Koc et al., 2016).

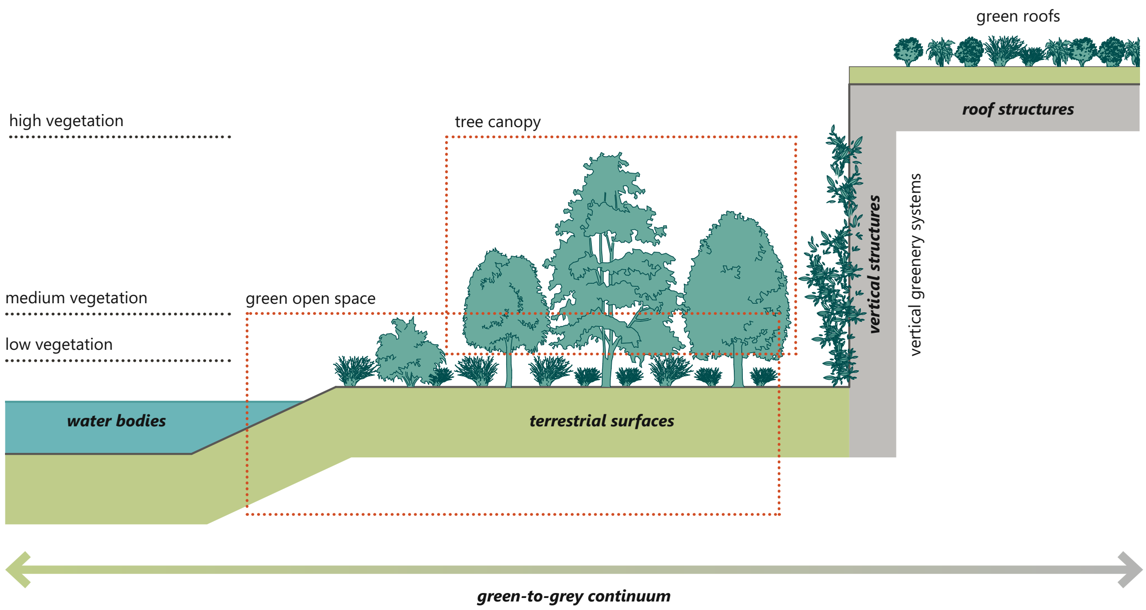


Figure 5 main GI typologies as a combination of different vegetation layers, ground surfaces and building structures, own illustration based on Bartesaghi Koc et al. (2016)

Table 2 and 3 on the following pages describe the *Green Infrastructure Typology Matrix*. It is suggested that functional, structural (morphological) and configurational (spatial) aspects are used as criteria for the GI classification. In their proposed double-entry matrix, the axis with vegetation layers differentiates ground vegetation from climbing vegetation. Their sub-classes are the result of classification according to vegetation height (low, medium, high) and growing length of climbing plants (short, tall). The second axis describes different types of surfaces. Ground surfaces are divided into terrestrial surfaces and water bodies, and building surfaces into roof and vertical structures (Bartesaghi Koc et al., 2016).

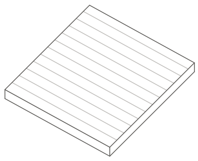
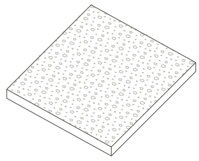
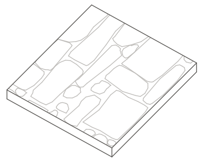
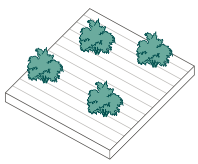
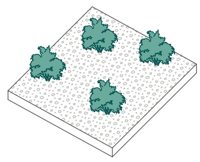
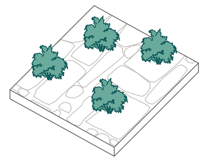
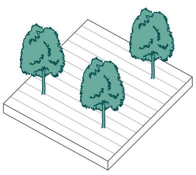
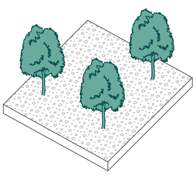
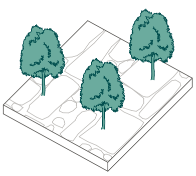
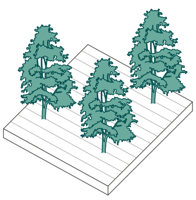
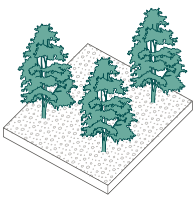
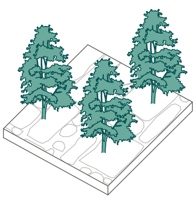
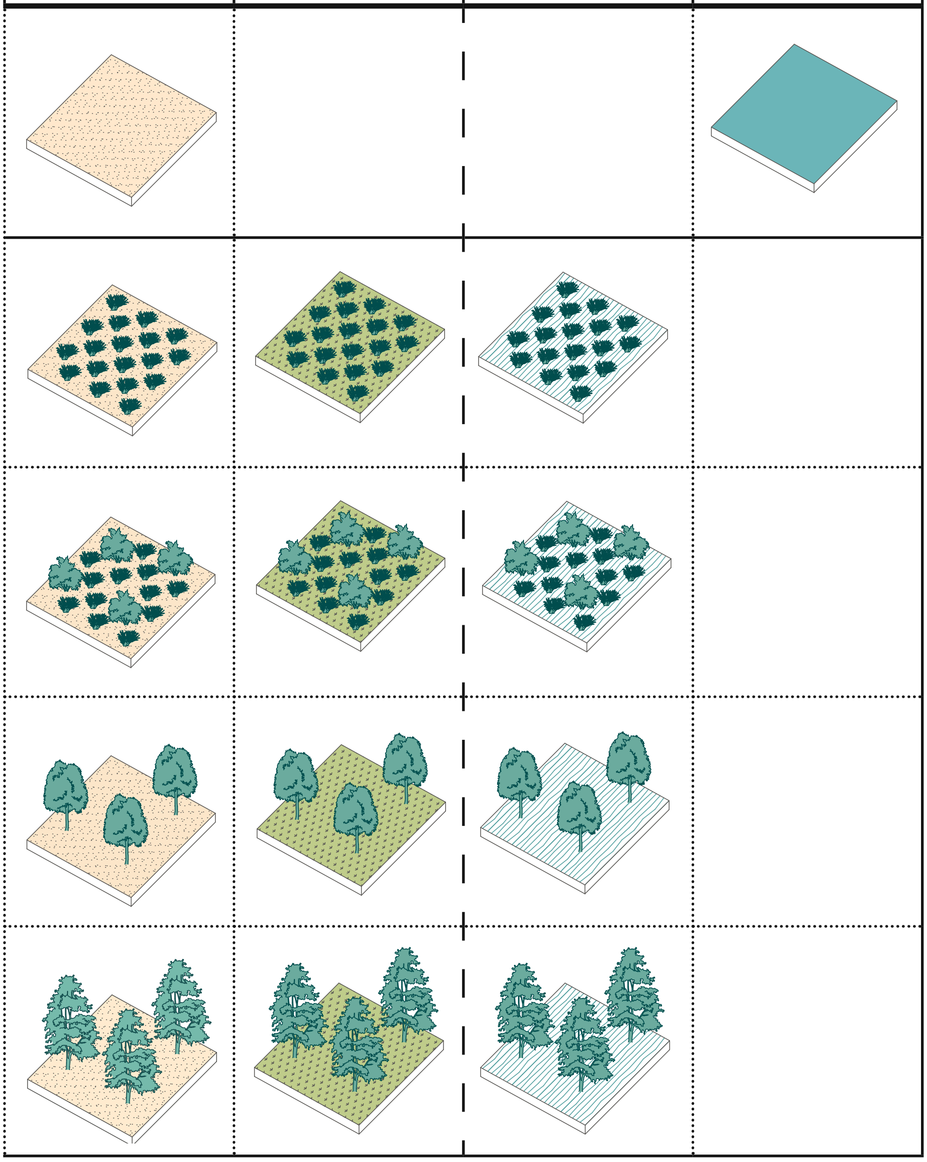
green infrastructure typology (GIT)				ground surfaces (GS)		
				terrestrial surfaces (TS)		
				impermeable surfaces		permeable
				artificial (hard surfaces & pavements)	natural (bare rock)	porous pavements
no vegetation						
vegetation layers (VL)	ground vegetation (GV)	(L) low vegetation	turf/lawn, grasslands/ prairies & herbaceous ground cover (< 1 m)			
		(M) medium vegetation	shrubs, hedges & small trees (1-2 m)			
		(H) high vegetation	trees (2-10 m)			
			trees (> 10 m)			

Table 2 Green Infrastructure Typology Matrix – ground surfaces, own illustration, based on Bartesaghi Koc et al. (2016)

		water bodies (WB)	
surfaces		vegetated	non-vegetated
bare soils, sands & perennial snow	vegetated surfaces	wetland (marsh, swamps, mangroves)	open water (lakes, rivers, oceans)



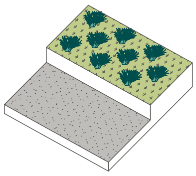
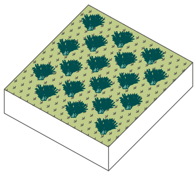
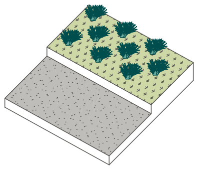
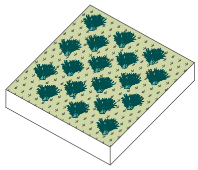
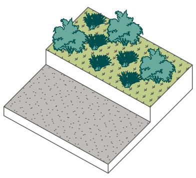
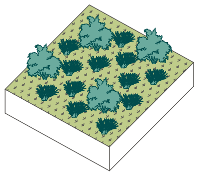
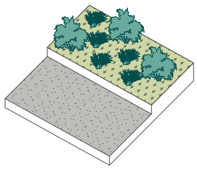
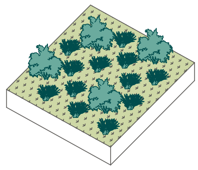
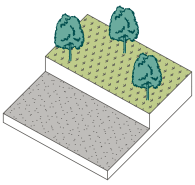
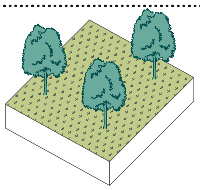
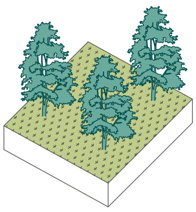
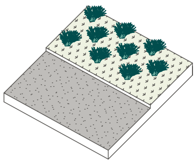
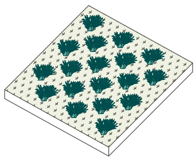
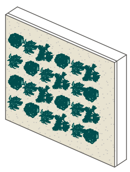
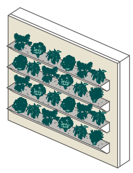
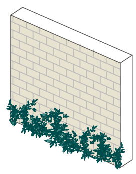
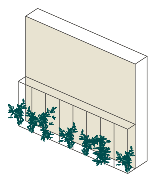
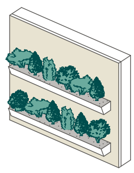
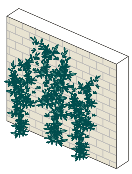
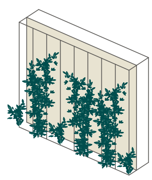
green infrastructure typology (GIT)				building structures (BS)			
				roof structures (RS)			
				intensive		semi-intensive	
				intensive semi-vegetated	intensive vegetated	semi-intensive semi-vegetated	semi-intensive vegetated
vegetation layers (VL)	ground vegetation (GV)	(L) low vegetation	turf/lawn, grasslands/ prairies & herbaceous ground cover (< 1 m)				
		(M) medium vegetation	shrubs, hedges & small trees (1-2 m)				
		(H) high vegetation	trees (2-10 m)				
			trees (> 10 m)				
	vertical vegetation (VV)	short plants	(climber) species (< 5 m)				
		tall plants	(climber) species (> 5 m)				

Table 3 Green Infrastructure Typology Matrix – building structures, own illustration, based on Bartesaghi Koc et al. (2016)

		vertical structures (VS)			
extensive		living walls (rooted on wall)		green facades (rooted on ground)	
extensive semi-vegetated	extensive vegetated	modular panel & geo textiles	elevated substrate (tray, box, pot, bag)	self-climbers	guided climbers
					
					
					

2.4.1. Green infrastructure typology (GIT)

Table 4 shows an overview of GI associated elements according to their typology, and classified based on their functional and structural aspects.

GI typology	classification	associated elements
tree canopy	*functional*	street trees / vegetated street verges
		urban tree canopy / urban forests / woodlands / park trees / shrubs / hedges
	structural	*configuration:* grouped, isolated, scattered linear
		leaf type: evergreen and deciduous
green open space	*functional*	parks, gardens, courtyards and public green spaces
		cycle/pedestrian trails, vegetated roads and power lines
		institutional and civic spaces: squares, plazas, school gardens
		natural & semi-natural green spaces: woodlands, forests, grassland, meadow, greenways, green corridors, green buffers
		agricultural land, urban farming, urban gardening
		regenerated brownfield land: quarries, landfills and derelict land
		recreational area, sport fields, golf courses, play-grounds
		churchyards and cemeteries
	structural & functional	*permeable surfaces:* irrigated, non-irrigated, vegetated, sand, perennial snow, bare soils, rain-gardens, biofilters, bioswales
		impermeable surfaces: pavements, hard surfaces, bare rocks
		water bodies: lakes, rivers, ocean, vegetated wetlands and vegetated
green roofs	*structural & functional*	*green roofs / living roofs:* extensive, semi-intensive, intensive
		cool roofs: blue roofs, semi-vegetated roofs
vertical greenery systems	*structural & functional*	green facades (rooted on ground/base)
		indoor and outdoor green walls / living walls (rooted on wall)
		climber green walls
		herb-shrub green walls

Table 4 associated elements of GI typologies, based on Bartesaghi Koc et al. (2016)

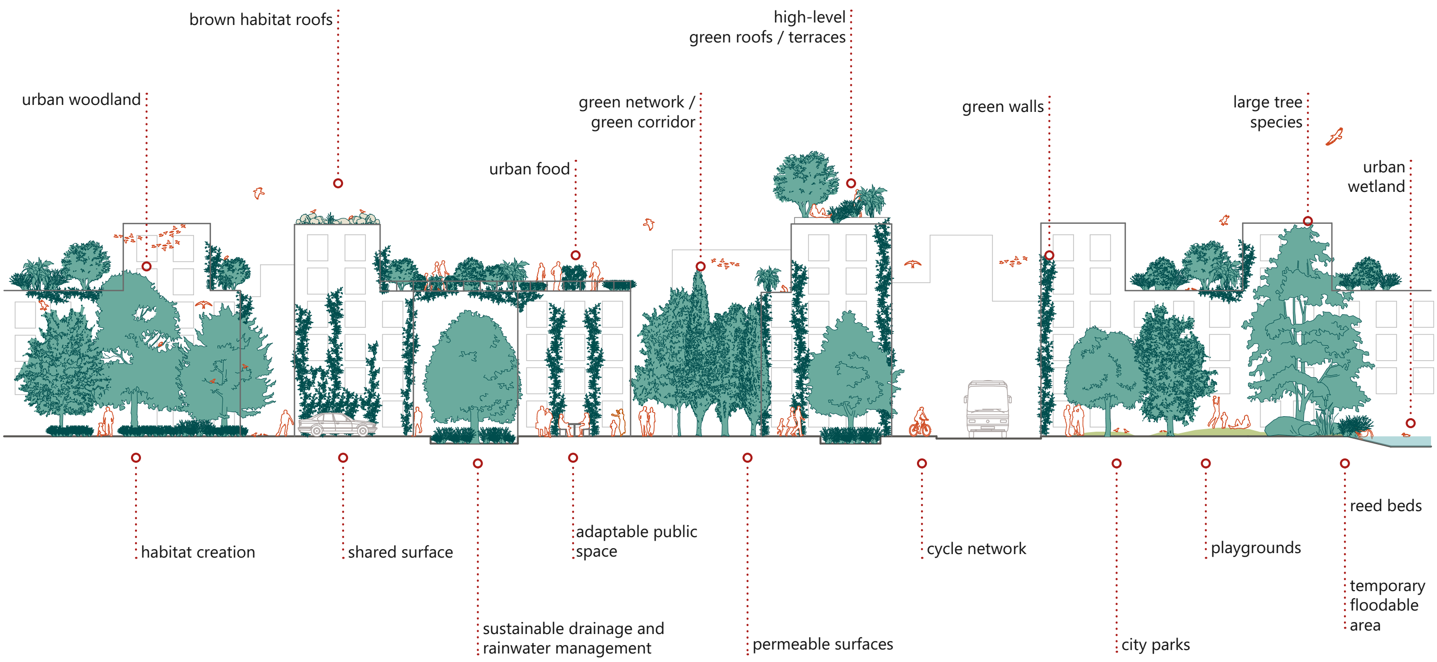


Figure 6 examples of Green Infrastructure integrated into an urban landscape, own illustration based on UK Green Building Council (2015) and Arup (2014)

2.5. Urban Green Infrastructure (UGI)

Urban green infrastructure can be described as the collection of different natural elements in a city including the remains of agricultural and forestry areas, which can usually be found in the periphery, and nature designed for cities including parks as well as public and private gardens. Wetlands and forests in the cities are often relicts of "ancient wildlands" which were not developed or designed according to anthropological principles. The self-regeneration of fallow land after their use as a construction site creates successively self-preserving new wildernesses in urban areas. From forests and gardens to solitary trees, parks, wildlands and landscape art; urban nature in its various appearances is an essential element for livable cities. By the usage, preservation, and further development of urban nature in a conscious and targeted way, the quality of urban life can even be improved. Disciplines related to urban nature are very diverse and include ecology, urbanism, architecture and city planning, sociology, and psychology. There are many different interest groups when it comes to land use designation due to a high competition for land in the cities, and urban nature often gives way to other uses because of its conceived lower importance. Therefore, preservation and protection of urban nature has to start with the recognition and acceptance of all urban nature types by all stake holders with the aim to raise the awareness that urban nature is both of great value and essential for a livable city (Breuste, 2019). The concept that nature and construction can be integrated and planned or preserved with the same priority at a site allows for both benefiting from this integration. The demand for new constructions such as housings, offices, educational, and health facilities increases with the growth of the population in expanding cities. If new construction and renovation projects also include expansion of urban nature, interests of all stakeholders will be addressed.

2.5.1. Trees and green spaces

Urban trees can be considered as the most essential components of urban ecosystem and urban landscape. Beside their environmental benefits, such as the moderation of microclimate and thermal stress, sequestration of CO_2, reduction of air pollution and enhancement of soil quality, citizens often feel a strong emotional connection to trees, especially to those in their neighborhood, place of work or school. Because of their size, which can be massive, and their shades providing thermal comfort, trees are a characterizing element in the city structure ranging from an individual tree, rows of trees along streets and highways to assemblages in parks to large-scale planting of trees in the city and its surroundings, also known as "urban forestation" (Samson, 2017).

Green spaces with mature trees are very effective in generating the Park Cool Island (PCI) effect by their shading and evapotranspiration. Evapotranspiration is described as the combination of evaporation from water bodies and moist ground surfaces and the transpiration of water from plants. While evapotranspiration plays a significant role in the cooling effect of urban green spaces by reducing the sensible heating of air, the shading effect particularly leads to improvement of thermal comfort for pedestrians by blocking and reducing the exposure to short-wave radiation directly from the sun and long-wave radiation from ground surfaces caused by the lower surface temperatures of the shaded terrain. The cooling by transpiration from leaves of the tree canopy is limited by their volume and biomass and therefore, large dense crowns are more effective in reducing the air temperature than smaller trees. Ground covering vegetation can also reduce the air temperature by evapotranspiration, however, their effectiveness largely depends on the soil moisture and water availability (Hiemstra et al., 2017).

2.5.2. Roof greening

Green roofs consist of several layers with different functions, where the substrate has the function of both water storage and drainage level. With anti-slip and anti-shear protection, not only flat but also sloping roofs can be greened. Other important parts of the roof are the gravel strip at the edges of the roof and drainage facilities. A root-proof sealing is mandatory to avoid damages of the roof construction. There are different types of green roofs, which are distinguished on the basis of structure height, necessary maintenance and usability (GRÜNSTATTGRAU, 2019).

Semi-extensive

Semi-extensive roof greenings have a reduced level of vegetation and biodiversity. The minimum thickness of structure is 8 cm and the roof is only walkable on maintenance paths. Due to the thin layer of substrate the vegetation consists of stress-resistant, undemanding ground-covering succulent plants such as sedum and moss. Semi-extensive roof greenings belong to the least expensive solution because they require little maintenance and therefore no additional watering or fertilization of substrate, however a certain number of species and a suitable substrate structure are necessary to achieve a successful vegetation. In order to remove unwanted wild growth, one inspection per year is required (VfB, 2018).

Extensive

Extensive roof greenings similar to semi-extensive greenings have a thin structural layer of 8 to 15 cm with a substrate with low content of organic materials. Vegetation for extensive roof greening consists of low-growing plant species, with a high regenerative capacity and ability to adapt to difficult environmental conditions, for instance long dry periods, heat, wind, and severe frost. Plants like aromatic perennials, bulbous plants, grasses, herbs, and ground covering plants such as sedum are suitable for this environment. Due to the light weight of the construction, which is 90 to 200 kg/m^2 in the water saturated state, extensive greenings are also suitable for existing buildings that are greened after construction. Extensive roofs are only walkable for maintenance, which should occur once a year (VfB, 2018).

Semi-intensive

The structure of semi-intensive roof greenings consists of several layers with a minimum thickness of 15 cm. Some maintenance and additional irrigation are necessary in order to achieve a successful vegetation, which can consist of ground covering plants, grasses, robust flowering perennials and small shrubs. Semi-intensive roof greenings are mostly suitable for use with some limitations in their design. Semi-intensive roofs have a higher water storage capacity than extensive roof greenings which allows for growing a variety of species and increasing biodiversity (VfB, 2018).

Intensive

Intensive roof greenings have a thick layer construction from 20 up to 100 cm. Due to their heavy weight from 180 to 1000 kg/m^2 in the water saturated state, intensive roof greenings are usually implemented within the new construction projects, where the greening load can be incorporated into the design planning. The multilayer structure consists of separate vegetation, filter, and drainage layers with an irrigation system. High maintenance such as regular watering, fertilization of substrate and gardening care is necessary. The vegetation can consist of all common garden plants such as herbs, grasses, perennials, vegetable crops, shrubs, wooded plants and trees which need at least 80 cm substrate thickness and protection against wind loads. Intensive roof greenings are suitable for permanent usage and provide various design possibilities (VfB, 2018).

2.5.3. Facade greening

Vertical greenings can be implemented in different systems, either facade-based, as tray systems or with ground-connected climbing plants. The greening systems have different suitable vegetation types. Living walls are planted with perennials, grasses and herbs. Climbing plants can be self-climbing, for instance Virginia creeper, or frame climbing, in which case the plants depend on a supporting structure to climb (GRÜNSTATTGRAU, 2019).

Facade-based

Facade-based greenings can be implemented over a wider area, linearly or selectively. This system provides a large variety of greening possibilities, such as the greening of targeted areas, facades without ground connection and higher parts of the wall. Furthermore, a rapid greening with many plant species is possible. However, facade-based systems require higher maintenance than ground-based systems (Green4Cities et al., 2019).

Planter-based

Planter-based facade greenings have similar requirements as roof greenings regarding the durability and structural stability of the substrate. Therefore, planters are constructed in different layers with water retention, which helps to save water. There are over 20 different climbing plants, which can be used for planter-based facade greenings and some of them can grow up to 30m in height (GRÜNSTATTGRAU, 2019). The planters can be connected either to the ground or to the facade and they can be installed linearly or at selected spots. In order to achieve greening of a larger area, the planters should have a vertical distance of less than 50cm to one another (Green4Cities et al., 2019).

Ground-connected

Ground-connected facade greenings are either spreading and self-climbing direct vegetation or guided/aided climbing plants. In both cases, the vegetation roots are planted in the ground. Climbing aids can be installed as rigid or flexible systems. Rigid systems are used for vegetation with high growth thickness to withstand the forces. The greening of a large area can be achieved by using a grid structure, whereas a linear growth requires single rods. Flexible systems are suitable for plants with low thickness growth. For a linear growth of vegetation, the climbing aids can consist of steel cables. Net-like constructions allow the greening of a wide area which also provide light and visual block. In all cases it needs to be considered that the greening of a wide area takes a longer period of time (Green4Cities et al., 2019).

2.5.4. Urban Gardening

Urban gardening is a type of green infrastructure which is actively used and has recently gained popularity as a recreational activity in many cities. The variety of possibilities for gardening in cities has emerged in the recent years. Allotment gardens have a historical background, especially in Vienna, where they were established in the beginning of the 20th century for the purpose of improving the city residents' health and education. Located in the periphery of the city, allotment gardens consist of large private parcels maintained by an individual or a family. The garden plots include a residential unit for temporary (seasonal) or permanent use under strict restrictions regarding their size, height, and shape. In the past, there were also strict guidelines on the garden design and arrangement, not only by legal regulations (Kleingartengesetz) but also by private bodies under the aspect of self-organization. Nowadays, the allotment gardens appearance can be quite heterogenous. However, the majority consist of large lawn areas, fruit trees, flower beds and vegetable beds as a rarity. Beside the private plots, allotment gardens usually have common use spaces including semi-public paths between the plots that are mainly used by the members themselves and residents from the surrounding areas. And there is often a communal parcel with a building for festivities (Exner and Schützenberger, 2018).

Gardening as a creative and social activity in the city is increasingly gaining interest, in particular in the inner districts. Moreover, self-cultivated organic food is an important step towards a more ecological, sustainable and self-sufficient lifestyle. Since most of the population in a city do not own a private green space, the concept of community gardens has emerged in the last decade, while the idea of shared garden plots in a city has been there for quite some time. In Vienna, the first community gardens were established in the 1990s, however their popularity and number have risen only since they were formally supported by the government starting in 2010. Community gardens are located throughout the city as well as in the inner districts and are managed by a group of people either working together informally or in a formal organization arrangement. In contrast to allotment gardens, individual plots are not fenced, and some garden beds are shared collectively. Allowing for group participation in the design of public space is an important activity of the semi-public bodies such as Urban Renewal Offices (Gebietsbetreuung Stadterneuerung) and the Local Agenda 21 groups. Many existing community gardens are the outcomes of initiatives and municipal projects (Exner and Schützenberger, 2018).

Some creative initiatives also show that gardening in the inner districts does not necessarily need a large space, if the existing green infrastructure is used effectively. The initiative "gardening around the corner" allows and promotes the greening of micro areas and the tree grids in between the parking lots by local residents. The grids are necessary to protect the trees from damage caused by vehicles. Through this initiative the micro areas are transformed into creative flower beds, which not only beautify the street area but also protect biodiversity as a food source for bees, butterflies and other insects and animals. The tree grids are maintained by interested residents, who register for a particular grid, usually close to their homes. The care for the tree grids is provided through a design agreement with the Urban Renewal Office in-charge. Some gardening equipment including soil compost is provided by district offices, the seeds and plants are arranged by the hobby gardeners themselves at no charge to the city (Gebietsbetreuung Stadterneuerung Stadt Wien, 2020).

2.6. Urban Climate

Urban Climate describes a climate, which is modified by anthropogenic changes in land use. Because of the large local density of population and the high local energy consumption, urban climate is of particular concern in the context of climate change (Matzarakis, 2013).

The following section describes different indicators for environmental assessment. They are related to temperature, climate, physiological perception or materials and surfaces.

2.6.1. Physiological Equivalent Temperature (PET)

There are different factors besides air temperature that have an influence on the physiological perception of heat, such as solar radiation depending on day and season, shadowing, humidity, wind speed and especially in urban areas long-wave heat radiation of buildings and sealed surfaces. Depending on the situation, the influences of radiation and wind conditions can dominate air temperature. For the observation of urban heat islands, thermal loads and heat stress are characteristics of urban climate. To evaluate thermal comfort, different thermal indices such as Predicted Mean Vote (PEV), Standard Effective Temperature (SET), Perceived Temperature (PT) and Physiological Equivalent Temperature (PET) are commonly used. PET is an indicator for evaluation of the thermal comfort of a person based on the energy balance. Defined in Celsius degrees, PET is easily understandable and is often a major component of microclimate simulations (Matzarakis, 2013).

PET describes the thermal environment conditions by a human-biometeorological measure and transfers the actual thermal outdoor conditions to an equivalent calculated indoor environment with the same expected thermal sensation. The calculation of PET considers the same human energy balance (mean skin temperature and sweat rate) for the assumed indoor conditions as for the actual outdoor conditions. Table 5 shows the classification and evaluation scale of PET for the corresponding human sensation and thermal stress level for human beings with an internal heat production of 80 Watt and a heat transfer resistance of clothing of 0,9 clo (Mayer and Matzarakis, 1998). Clo is a unit for measuring the thermal insulation of clothing and 1 clo equals 0,155 m^2K/W (Engineering ToolBox, 2004).

PET values around 20 °C can be perceived as comfortable in regions with temperate climate conditions (Mayer and Matzarakis, 1998). PET values can be modified according to the wind speed and radiation fluxes. Up to a certain level, an increase of wind speed can reduce hot conditions in complex structures. However, the influence of changes in radiation fluxes on PET are much higher. Such modifications can be arranged by plantation of specific vegetation types that produce shading in summer, but also allow short-wave radiation to reach surfaces and areas in winter in order to increase thermal comfort in cold and heat periods (Matzarakis and Endler, 2009).

PET	human sensation	thermal stress level
< 4 °C	very cold	extreme cold stress
4 – 8 °C	cold	strong cold stess
8 – 13 °C	cool	moderate cold stress
13 – 18 °C	slightly cool	slight cold stress
18 – 23 °C	comfortable	no thermal stress
23 – 29 °C	slightly warm	slight heat stress
29 – 35 °C	warm	moderate heat stress
35 – 41 °C	hot	strong heat stress
> 41 °C	very hot	extreme heat stress

Table 5 PET, human sensation of thermal environment and thermal stress level in temperate climate regions, according to Mayer and Matzarakis (1998, p. 156)

2.6.2. Albedo

Albedo is the reflection coefficient of the surface of a material and is calculated as the ratio of incoming to outgoing shortwave solar irradiance. A completely reflective white surface has an albedo value of one, whereas a value of zero describes a totally black surface without any reflection of light rays. The color and structure of a surface and the angle of solar radiation affect the albedo value. The highest albedo of natural surfaces is fresh, dry snow with a reflection coefficient of 0.80 to 0.95, which means that up to 95% of the incoming light is reflected. Oceans have a very low albedo value of 0.07 to 0.23, which means that maximum 23 % of the light rays are reflected and the rest is absorbed. Clouds can have an albedo of 0.70 to 0.80 if they are dense or a value of 0.25 to 0.50 if there is a thin overcast. The reflection of the light by the clouds in the atmosphere is very important to life on Earth, because an extreme absorption of solar radiation would make the planet unlivable. The planetary albedo, which describes the mean albedo for Earth is about 0.30 to 0.35 (Seeley, 2003). The urban surface albedo is a factor that is used to define the urban heat balance, which is influenced by the building structure and the surface material of street and open space. The decrease of urban surface albedo can be considered as one of the primary causes of urban warming, because large percentage of the solar radiation is absorbed by the material surfaces. Typical construction materials in urban areas for building roads, pavements and courtyards are asphalt with a very low albedo of 0.12 and fresh concrete with a value of 0.2, which becomes darker in time. In addition to the building and roadway structures, vegetation is a key factor that has a strong influence on the urban albedo. Due to the brighter surface of plants, vegetation generally has a larger albedo than dark artificial urban materials. Therefore, the urban albedo can be affected by the amount of vegetation (Sugawara and Takamura, 2014).

2.6.3. Degree of soil sealing and surface runoff coefficient

The sealing of surfaces influences the urban ecosystem in many different ways including urban climate, infiltration of rainwater and groundwater regeneration. The functions of soil as a) being a basis of life and habitat and b) a part of the natural balance with water and nutrient cycle, filter, buffer, substance converter, and groundwater protector are severely hindered by anthropogenic land use that limits soil preservation in highly sealed grounds. The degree of infiltration is particularly affected by the area of sealed surfaces and the type of ground covering. As an indicator, the runoff coefficient is defined as the percentage of rainwater which directly runs off into the sewage system and is not soaked into the ground. The German Sustainable Building Council (DGNB) determines and evaluates the degree of soil sealing by the building structure and land use in relation to orthophotos as shown in Table 6 (DGNB, 2012).

degree of sealing	description	examples
80 – 100 %	areawide covered with buildings	city center, partly industrial area
60 – 79 %	mainly covered with buildings	dense block development, commercial and industrial area
40 – 59 %	built area outweighs vegetation	block perimeter development, ribbon development/row houses
20 – 39 %	mainly covered with vegetation	single-family and duplex houses
0 – 19 %	covered with vegetation	woods, parks, cemeteries, garden plots, farmland

Table 6 degree of soil sealing in relation to building structure and land use (DGNB, 2012)

Calculation of the drainage area is necessary for the implementation and dimensioning of rainwater management measures. The runoff coefficient is a non-dimensional factor with a value between 0.0 and 1.0 that corresponds to the degree of sealing for a specific material. It is calculated as a ratio of the of the amount of direct runoff to the total amount of precipitation, which depends on the geographical location. A value of 1.0 means that 100% of the precipitation runs off while a value of 0.0 means that 100% of the precipitation is soaked into the ground. Therefore, the runoff coefficient of a developed site should be as low as possible in order to avoid flooding due to extreme rainfall and to enable rainwater to be returned to the water cycle (Reschl, 2019). Since the surface of a developed site usually consists of different structures and materials, for each subarea the runoff has to be calculated separately by multiplying the area with the corresponding runoff coefficient. The individual results are then added to determine the runoff coefficient of the whole site. Table 7 shows the runoff coefficients of different types of surfaces based on ÖNORM B 2506-1 (ÖNORM-B2506-1, 2013).

	type of surface	runoff
roof	solid covered roofs	1.0
	extensive roof greenings	0.5
	intensive roof greenings	0.3
ground	paved courtyards and paths	0.8 – 1.0
	covered with vegetation	0.6 – 0.8
	green spaces, lawn grid stone (depending on slope and permeability)	< 0.5

Table 7 runoff coefficients of surface types (ÖNORM-B2506-1, 2013)

2.7. Environmental performance assessment

There are many variable factors changing over time which must be taken under consideration when planning a building. Demographic, financial, and technological changes can lead to new requirements and conditions to which a building has to be adapted, for example through reconstruction or alternate usage. However, adaption might not be possible in each case, which often results in vacancy or demolition. In the past few decades global climate change has become an additional challenge particularly in urban areas, where the adaption of already existing buildings and open spaces to the increase of heat stress in spring and summer and more frequent extreme weather events is not a simple task. Therefore, it is important to consider climate change and the urban heat island effect while planning a new construction at an early stage of design. Microclimate simulations can help to gain a better understanding of a design's thermal performance and its effects on the local environment. In addition, it can be evaluated how a design would perform in a future scenario and how it should be optimized to fulfill the required qualities as long as possible with the aim to improve its microclimate and to reduce the UHI effect.

Microclimate simulation tools are used to calculate and predict the impact of building structures and open spaces on microclimate in a simplified reality. The analyzed results of a microclimate simulation can be used to optimize a design by identifying problematic spots of an existing structure to improve microclimate and environmental performance through interventions. Incorporating microclimate simulations at an early stage of design also allows to visualize the effect of greening measures in different scenarios and variations and could be a basis for deciding on a particular design. Since there are many different environmental parameters that must be considered in the process of designing, microclimate simulations should be a part of a holistic environmental assessment. Other essential parameters which affect the quality of use and sustainability such as natural light exposure, materials, adaptivity of use, and barrier-free accessibility also have to be considered in the design and evaluation phase. The balance, inter- and counteraction of different parameters can be significant for the environmental performance of a design.

In relation to climate change and the UHI effect, the implementation and analysis of microclimate simulations during the planning process aims to increase thermal comfort and natural cooling and decrease overheating and surface temperatures of an architectural and landscape design. Normally this involves simulating a heat day or a sequence of days in the summer season with corresponding climate conditions such as temperature range, humidity, and wind speed. Climate data of the project's location is a main input for microclimate simulation. Since weather conditions can be different in each year, average values based on data from previous years or decade are usually used. The accuracy of the project's location and weather measuring station and currency of climate data are therefore of high importance. The following section addresses the question of how data driven modeling, microclimate simulations and environmental performance assessment tools can help designing more climate resiliently and which kind of software, tools and data is needed in order to plan a sustainable building greening.

2.7.1. Geographic Information System (GIS)

GIS software are a useful tool for preparation of data for microclimate simulation and implementation of terrain analysis. To perform a microclimate simulation, the project and its surrounding area have to be georeferenced in a specific coordinate system. Many cities provide a digital city map with access to GIS data. The municipal department for city mapping in Vienna (MA41) provides different types of geo-data including 2D vector information of city surfaces, digital surface model (DSM), digital terrain model (DTM) and 3D building models in different levels of detail. This data can be accessed through the ViennaGIS® geo-data viewer application and map sections can be downloaded as Shapefiles (.shp) or Drawing Interchange Format (.dxf). As an important data source, the download is free of charge facilitated by the Open Government Data (OGD) initiative.

Shapefiles can be imported into *QGIS*[1] which is a free and open-source GIS tool for georeferencing, creating, editing, visualizing, analyzing and modifying geo-data. *SAGA*[2] (System for Automated Geoscientific Analyses) is another open-source GIS software with a large number of different analysis tools. The basis input for terrain analysis is a digital elevation model (DEM). Additional input data such as geographic location, weather and climate data enable advanced analysis and modeling of the environment.

2.7.2. Microclimate Simulation Tool - ENVI_MET®

ENVI_MET®[3] is a microclimate modeling tool, which was initially developed in 1994. The holistic approach allows so incorporate a variety of areas of application including solar analysis, wind flow and turbulences, pollutant dispersion, building physics, microclimate, and thermal comfort. The simulation results can be displayed as different representational maps, such as wind patterns, air temperature and thermal comfort maps. The interaction between different elements in an urban setting is calculated based on a high-resolution numerical simulation (ENVI_MET, 2017). The urban context and structure of a design has a high impact on the environmental performance, regarding wind flow. Therefore, the simulation model also must contain the surrounding area to a certain extent. Surface materials, which are assigned to buildings and ground surfaces as well, are main input parameters, particularly for building physics and surface radiation calculations. Vegetation types can be either ground covering materials, such as lawn and shrubs, or inserted as three-dimensional tree elements in different sizes and with different leaf densities.

1 https://www.qgis.org/de/site/
2 http://www.saga-gis.org/en/index.html
3 https://www.envi-met.com/

2.7.3. Green Performance Assessment Tool - GREENPASS®

GREENPASS® is an evaluation, optimization and certification tool which enables climate resilient and resource efficient urban development. The technology has been developed over the last decade in the context of the international research project *Green4Cities* with participation of universities and enterprises in the green sector, sustainability research, architecture, and urban planning.[1] With *GREENPASS®* the effects of green infrastructure are assessable in a standardized way and can be visualized and communicated as a decision basis to stakeholders including planning experts, authorities and citizens. This allows to evaluate and optimize climate change adaptation measures for architectural and urban development projects. The evaluation refers to the urban challenges which are climate, water, air, biodiversity, energy, and costs with up to 28 indicators. *GREENPASS®* has developed different tools for various project types and planning stages. They distinguish themselves in terms of evaluation scope and level of detail (GREENPASS, 2020).

Assessment

The *Assessment* tool is suitable for a basic analysis and initial assessment of designs in an early project phase. The climate resiliency of building structures and open spaces is analyzed through a multi-parametric machine learning database check and calculation of five indicators. The data basis consists of Urban Standard Typologies (USTs), which are typically recurring, abstracted and standardized urban structures. To consider different climatic conditions, the typologies were developed in cooperation with international case study cities of Vienna, London, Hong Kong, Cairo, and Santiago de Chile (GREENPASS,2021).

Pre-Certification

The *Pre-Certification* tool is recommendable for the preliminary design draft phase and is based on a simplified microclimate simulation powered by *ENVI_MET®*. The multi-parametric analysis includes a preliminary check of 12 indicators, which allows to optimize thermal comfort and climate resiliency during the design process. In addition to the planning, further scenarios such as the status quo or different design options can be analyzed and compared with each other. This allows to make the impact of climate change adaptation measures visible, which serves as an effective basis for decision (GREENPASS, 2021).

Certification

The *Certification* tool is implemented in the detailed design phase based on a more detailed simulation model and full analysis of 28 indicators. The evaluation of each indicator leads to a total degree of fulfillment and according certification level which is certified, silver, gold, or platinum. The performance of the design is evaluated in relation to standardized reference scenarios, which represent a best, moderate, and worst case version of the design. The optimization recommendations can help to achieve a higher certification level by improving climate resiliency of the design. In addition, the fulfillment of bonus indicators in the fields of biodiversity, resources, and social aspects can lead to a better result (GREENPASS, 2021).

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1 Green4Cities project partner: Institute of Soil Bioengineering and Landscape Construction (BOKU Vienna), Environmental Modeling Group (Johannes Gutenberg-University Mainz), Department of Environmental Meteorology (University of Kassel), WSGreenTechnologies GmbH, Institute of Crop Science and Resource Conservation (University of Bonn), Sekem Energy GmbH, Institute of Architecture and Landscape (TU Graz)

03 CASE STUDIES OF SCHOOLS

The following chapter describes case studies from open air schools to education for sustainable development. The aim is to show different approaches and backgrounds for the connection of educational facilities with nature and environment.

3.1. Open Air Schools - a historic overview

The establishment of open-air school movement started in the late 19th century and the first open-air schools were built in the early 20th century because of the awareness, that a high proportion of school children in urban areas suffered from malnutrition and underfeeding. Berlin, London, Paris, New York, and Chicago were among the cities with many reports about weakened school children and widespread child hunger in urban schools. This had a significant impact on children's physical and mental condition and development and lead to a high vulnerability to diseases. The concept of open-air schools was developed to reduce the vulnerability to chronic and epidemic diseases and to support the physical, mental, and educational development of malnourished, anemic or sickly schoolchildren, who had also been exposed to or considered at risk to suffer from tuberculosis. The open-air schools implemented fresh-air prophylaxis, feeding and vitalization therapies, that had been developed in tuberculosis sanitariums. Some city schools started open-air school classrooms as an experiment on the top floor of an existing school by replacing brick walls with windows that could be opened and lifted against the ceiling with ropes and rollers. The windows were held wide open most of the time, except for extreme snow or rainfall. The subject matter, which was taught at open-air schools was very similar to the regular classes, but with a reduction of workload and more frequent resting periods (Meckel, 2013).

The idea of open-air schools created a shift in the design of schools and an multidisciplinary approach towards progressive pedagogy, medical expertise combined with a high modernist architectural and design ideal (Alegre, 2018). One of the early open-air schools was the *Waldschule Charlottenburg* (Figure 7) built in 1904 in the suburban area of Berlin as a collaboration of the teacher and education councilor Hermann Neufert and the school physician Dr. Bernhard Bendix. The school was located in the middle of a pine forest and therefore named Waldschule (forest school). The design of the school was made by Walter Spickendorff, who was the city architect, with the approach to preserve all of the tall pine trees and the irregularity of the existing terrain while providing a maximum of sun exposure at the same time. The school building was constructed as a wooden cabin

Figure 7 Waldschule Charlottenburg, Germany, classroom and dining sheds (1908)

with two six-by-eight meters classrooms and two small offices for the school's principal and teachers, with solar exposure from the east side. During cold weather or rainfall, the classrooms were used as playrooms and school's canteen and thus were furnished with lightweight and easily movable tables and chairs out of birch wood. Further cabins were used as the kitchen, storage, medical room, washrooms and changing rooms. The green space in between the cabins was used as an open-air dining area with long tables, air and sunbathing area, resting area and for practical lessons such as singing, gymnastics and gardening lessons, in which plots were cultivated by the children while learning about local species. The school was opened during the summer until November and as the number of pupils grew with each year, a cabin with three classrooms was added after a few years. In the first years, between 95 and 120 children were admitting the school, as they were selected by the school physicians of local schools in Charlottenburg because of their weak health conditioned after suffering from tuberculosis. To monitor their improvement and progress, the children were examined at the beginning and at the end of their stay. The school included a cure gallery, which consisted of a wooden structure with solar exposure from the south and windows to the north. The geographical orientation was a key element of the design by the architect, as he emphasized, that he chose "the most appropriate solar exposure" for the different buildings. The concept of the school also contained innovative teaching methods, which respected children's living pattern, adapted to their behavior, and used encouragement rather than sarcasm and irony as a teaching tone. The new educational concept of the Waldschule was spread in Europe by international conferences on school hygiene encouraging educational leaders of municipal authorities to create similar schools. In 1907 the first open-air schools were founded in Lyon, Padua and near London, the following year in Barcelona,1912 in Den Haag and 1914 in Stockholm. The first open-air school in the USA is assumed to be founded in 1908 in Providence, Rhode Island. While the german term *Waldschule* was simply translated in some languages, such as *"escuela del bosque"* in Spanish, within the years it changed into *"école de plein air"* in French speaking countries and *"open-air school"* in English speaking countries, which are still the most common descriptions (Châtelet, 2008).

Between 1908 and 1914 the *escuela del bosque* in Barcelona (Figure 8 and 9) was established as one of the first municipal schools in the city. A summer mansion located on the Montjuïc hill had been re-purposed for the public school because of its large outdoor area with forested surroundings (Dovel, 2014).

Figure 8 escuela del bosque, Barcelona, indoor classroom (1918)

Figure 9 escuela del bosque, Barcelona, outdoor classroom (1918)

3.1.1 École de plein air de Suresnes - Open Air School Suresnes

The open-air school in Suresnes, designed by the architects Beaudouin and Lods in Paris, was built from 1932 to 1935 for the children in the district, who were not able to attend the common primary school because of their week health conditions. The aim was to achieve high educational and medical requirements at the same time, while providing proper meals and a natural environment. The classrooms were built in a pavilion system which offered air and natural light by ceiling-high foldable windows on three sides of the classroom, while the fourth wall was solid to install the blackboard. The natural outdoor environment became part of the classroom and the gardens and greened open spaces between the pavilions were used for outdoor lessons. As this required flexible furnishing, which could be rearranged easily, Beaudouin and Lods designed school furniture made from aluminum and plywood in order to be lightweight and easy to move by the children and to fulfill the hygienic and safety requirements (Alegre, 2018).

Within the two acres of school property the main entrance, pavilion classrooms, a medical center, separated wards for girls and boys, and outdoor pools for showers and baths were arranged. The school had space for 350 children in two day care groups and eight elementary school classrooms. The roof terraces and greened open spaces with groups of trees between the pavilions were used for outdoor classes and during breaks (Beaudouin and Lods, 1943).

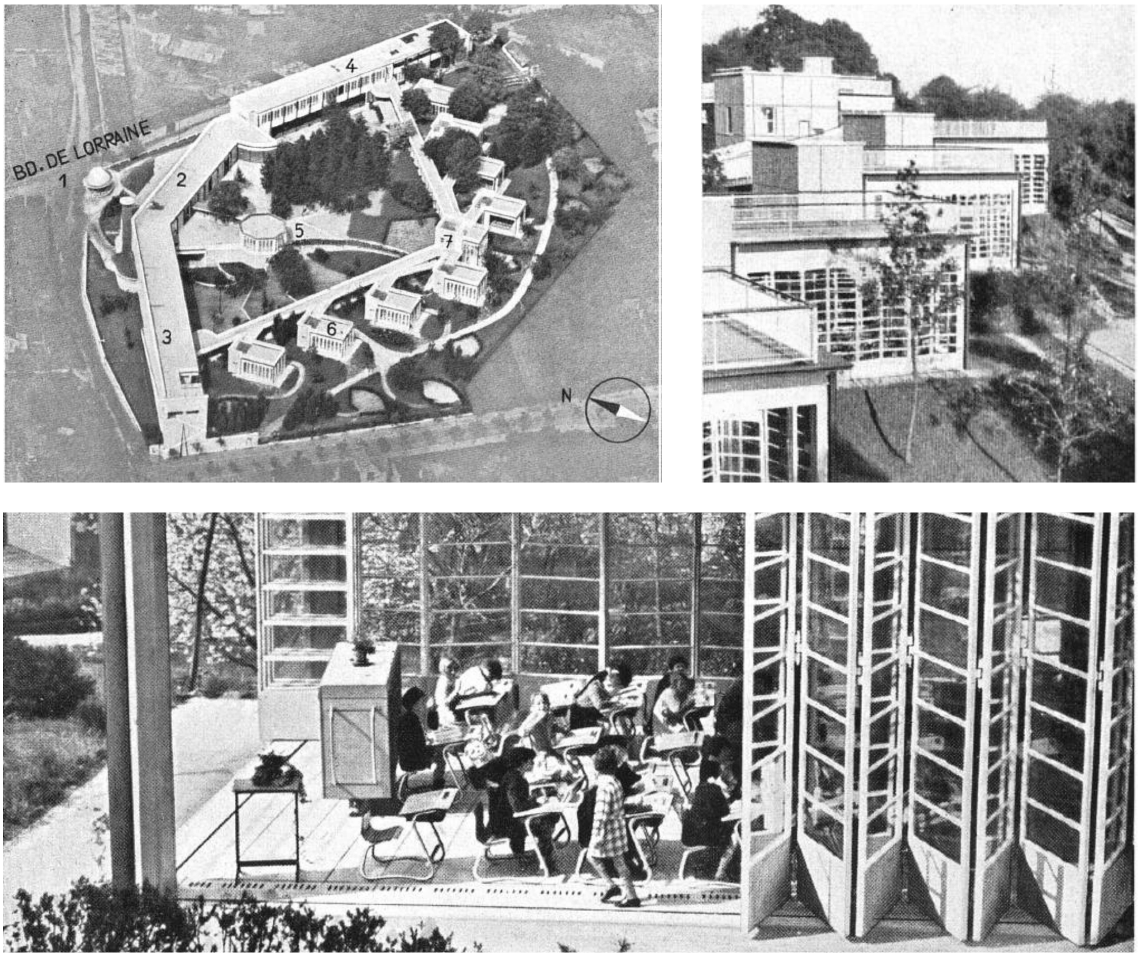


Figure 10   École de plein air de Suresnes, overview and pavillions

3.1.2 Freiluftschule Floridsdorf - Open Air School Vienna

With the spreading of open-air schools, architects and school construction authorities began to develop architectural concepts for the design of open-air classrooms. Wilhelm Schütte, who worked in the school construction department of the city planning program "Neues Frankfurt", developed concepts and basic elements for the design of open-air schools together with educators during the 1920s. His focus was on natural light exposure and fresh air rather than a natural surrounding environment. To improve his designs, he constructed test pavilions in 1929 and 1930 (Figure 11) which were used for daylight exposure measurements. His typological elements included double-sided daylight exposure, fully opening foldable glass wall and the free arrangement of the individual tables (Lorbek and Stosch, 2003).

Wilhelm Schütte optimized his concept throughout the years, however the realization of such a school type project was delayed because of World War II. It was not until 1961, when he finally was able to put his theoretically and experimentally elaborated concept into practice by designing the open-air school for special education in Vienna Floridsdorf (Figure 12), the 21st district of Vienna. Unlike the early open-air schools, this school was built in a more urban environment as a two-story building, which was more efficient. The school included 12 classrooms, a sports hall, workshop and handicraft rooms and classrooms for natural science. The classrooms on the ground floor and the 1st floor have double-sided daylight exposure, which is softened by a cantilevered loggia plate to avoid glare by direct sunlight. On one side, the story high glazing is fully foldable, which allows the loggia to be a part of the classroom. On the opposite side, the glazed partition wall provides softened lighting. Although the design fulfilled the requirements of an urban open-air school, it was realized outside the social-political environment of the open-air school movement and therefore was not able to succeed without committed reform pedagogues. Throughout the partial renovations in the 1980s and 90s, the original appearance and concept of the school have been significantly changed. Because of reduced user comfort due to large radiation surfaces of the glazing and weather damaged wooden windows, the folding walls were removed and replaced by smaller window areas (Lorbek and Stosch, 2003).

Figure 11 test pavillion, Frankfurt am Main (1929/1930)

Figure 12 Freiluftschule Floridsdorf, Vienna (1961)

3.2. Education for sustainable development

Within the framework of the United Nations Conference on Environment and Development in Rio de Janeiro in June 1992, the Agenda 21 was declared as a comprehensive plan of action about environment and sustainable development. It was one of the first official documents which introduces education as a part of sustainable development. The objectives in this field are described as reorienting education towards sustainable development, increasing public awareness and promoting training.

"Education is critical for promoting sustainable development and improving the capacity of the people to address environment and development issues. While basic education provides the underpinning for any environmental and development education, the latter needs to be incorporated as an essential part of learning. Both formal and non-formal education are indispensable to changing people's attitudes so that they have the capacity to assess and address their sustainable development concerns. It is also critical for achieving environmental and ethical awareness, values and attitudes, skills and behaviour consistent with sustainable development and for effective public participation in decision-making" (AGENDA 21, UN, 1992, chapter 36.3).

The United Nations Decade of Education for Sustainable Development (2005 – 2014) aimed on the integration of principles, values, and practices of sustainable development into all aspects of education and learning and was followed by the Global Action Program (GAP) on Education for Sustainable Development (2015 – 2019) with the aim to scale up and accelerate progress towards sustainable development. One of the priority action areas on transforming learning and training environments promoted sustainable learning environments, for instance green campuses and eco-schools to encourage sustainability in every aspect of school life. Education for Sustainable Development (ESD) is considered as a major aspect of quality education and was adopted by the Sustainable Development Goals (SDGs) for 2030. In particular, SDG 4 on education, target 4.7 addresses ESD and similar approaches such as Global Citizenship Education (GCED). The learning content of ESD consists of the integration of critical issues into the curriculum by teaching and learning in an interactive and learner-centered method that allows an exploratory, action oriented and transformative way of learning. Among others, the critical issues are climate change, biodiversity, and sustainable consumption and production. The promotion of core competences such as critical and systemic thinking, collaborative decision-making and taking responsibility for present and future generations are learning outcomes of ESD, which are achieved by empowering people to be engaged and proactive "global citizens" and enabling a transition to more sustainable economies and societies (UNESCO, 2017).

3.3. Educational use of green space

The implementation of educationally used green spaces in schools creates an inspiring learning environment and allows to include themes and sub-themes of ESD into the curriculum and thus makes a contribution to the achievement of SDG 4.

Green spaces in schools and gardening also have a positive impact on social and environmental behavior of children and young people, as it is shown by qualitative studies in the USA. In addition, quantitative studies have shown positive outcomes in student's science achievement and food behavior by gardening in school (Blair, 2009). The personal impact of a garden-based learning program were observed during an experimental educational course in a secondary school in the southeastern of Spain as an improvement of student's self-esteem and self-confidence and a reduction in the dropout rate (Ruiz-Gallardo et al., 2013).

To create, maintain and sustain green spaces for school, such as a school garden, some aspects have to be considered. Green spaces provide the opportunity to strengthen the school community by creating a collaborative infrastructure which involves the participation of teachers, school children and other school personnel as well as community volunteers including family members (Figueroa, 2016). In addition, a collaboration between schools, universities, professional schools for agriculture, horticulture and landscaping, and municipal departments would allow to ensure the exchange of theoretical and practical knowledge and a sustainable maintenance of vegetation. To include all involved participants the green spaces have to be accessible for all users, especially for those with disabilities.

In the following some school construction projects are described based on the use of building greening measures and their educational purpose. The greened elements and spaces are for instance used for environmental education, biology and plan studies, outdoor learning, and recreational areas. They also provide space for creativity and interdisciplinary lectures, such as the growing of fruits, vegetables and herbs which can also be integrated in nutrition and cooking classes and therefore allow a direct connection between effort and results.

3.3.1 École des Sciences et de la Biodiversité - Biodiversity and Science School

The School for Sciences and Biodiversity in Paris consists of a primary school with day care and elementary school classrooms and a secondary school. The site is located on former industrial area, which has turned into a densely built urban area now. The aim of the project is the growth of nature and biodiversity in urban areas. The roof of the school creates an artificial landscape as a functional ecosystem, which is used for educational purpose. It also creates a new perspective and view for the surrounding buildings. The green roof varies in its thickness from 50 centimeters below the prairie up to 150 centimeters below the shrubs and tree groups, which form an urban forest. The walls are constructed of prefabricated concrete blocks of varying depth, orientation and height, which create a habitat for vegetation (climbing plants, rock plants) as well as for small birds through niches and gaps (DIVISARE, 2015).

Architecture	Chartier Dalix architectes
Specialists	EVP (structure), Cferm (HVAC), F. Bougon (cost analysis), F. Boutté (Hqe), A.E.U. (ecologist), Biodiversita (biodiversity), Begc (kitchen design), Peutz (accoustics)
Location	Boulogne-Billancourt, Paris, France
Year of construction	2014
Area	6 766 m^2 (constructed area)
Costs	€ 18 mio.
Functions	• 540 children in 7 day care groups (maternelles) and 11 elementary school classrooms (élémentaires) • secondary school with 250 students • school restaurant and outdoor facilities
Greening measures / environmental as-pects	• 1650 m^2 greened roof terrace (thickness of substrate 50 – 150 cm) • meadow, shrubs, trees • facade greening: prefabricated concrete blocks of varying depth, orientation and height create a habitat for vegetation (climbing plants, rock plants) as well as for small birds through niches and gaps

Table 8 École des Sciences et de la Biodiversité - project description (Deramond, 2017)

Figure 13 École des Sciences et de la Biodiversité, roof gardening and terraces

3.3.2. Groupe scolaire à Rillieux-la-Pape - school complex

The school complex consists of a nursery school, an elementary school and a gym, which was later added in 2014. The buildings are placed into the sloping terrain while creating a second landscape by the greened inclined roof planes. The arrangement of the buildings creates enclosed internal spaces in the form of a garden for the nursery school and a patio for the elementary school. The outdoor open spaces also contain a vegetable garden and a discovery path. The characteristics of the exterior and interior of the school complex is defined by using wood panels for the inner walls and façade and massive boards for the ceiling. The natural surface texture creates a solid impression and depth while large windows and strips of top lights allow natural lighting of the internal spaces (TECTONIQUES, 2013).

Architecture	TECTONIQUES ARCHITECTURE & INGÉNIERIE
Specialists	Itinéraire Bis (landscaping), Arborescence (wood structures), Indiggo Environnement (technical environment design office), Saunier devenu Somival (roads, geotechnics, services), Veritas (quality control), Socotec (health and seafety)
Location	Rillieux-la-Pape, Métropole de Lyon, France
Year of construction	2013
Area	5 038 m² (constructed area)
Costs	€ 8,94 mio.
Functions	• nursery school (école maternelle) and elementary school (école élémentaire) • addition of a gym in 2014 • library, music and computing rooms in elementary school • enclosed open spaces (garden and patio)
Greening measures/ environmental aspects	• vegetation on the upper and lower levels • extensive roof greening with discovery path • vegetable garden • minimizing excavation and foundation work

Table 9 Groupe scolaire à Rillieux-la-Pape - project description (TECTONIQUES, 2013)

Figure 14 Groupe scolaire à Rillieux-la-Pape, roof greening

3.3.3. GRG 7 Vienna - secondary school for language and natural sciences

In order to investigate green facade and roof systems, the existing building of the secondary school GRG 7 was chosen to be greened. In the interior of the school vertical greening systems were installed on selected walls. The exterior walls were partly greened by different facade-based system and the roof greening of the flat roof was combined with semi-transparent photovoltaic cells. The students and teachers were included in the participatory greening process by integrating monitoring, maintenance, and research into the school lessons. The different systems were investigated and analyzed regarding their ecological and economic aspects while considering the entire life cycle in each case. The monitoring system measured the U-value of the building elements, indoor thermal comfort, air quality, humidity, and indoor acoustics. The results showed that the measured U-value of the wall decreased due to the facade greening and an increase of hydrothermal comfortability was noticed because of the interior green wall. Furthermore, the combination of photovoltaic modules and greening systems leads to a lower operating temperature of the module on heat days, which increases their efficiency (Korjenic et al., 2019).

Project	GrünPlusSchule@Ballungszentrum
Project management	Technical University Vienna (TU), Institute of Material Technology, Building Physics and Building Ecology, Prof. Dipl.-Ing. Dr. techn. Azra Korjenic
Cooperation partner	University of Natural Resources and Life Sciences, Vienna (BOKU), Kräftner Landscape Architecture, ATB-Becker (photovoltaic and energy storage)
Location	Vienna, Austria
Year of construction	1910
Year of project	2018
Greening measures/ environmental aspects	• System A: linear facade greening system • System B: modular facade greening system • System C: photovoltaic modules, partly planted behind • System D: roof greening with photovoltaic unit

Table 10 GRG 7 Vienna - project description (Korjenic et al., 2019)

Figure 15 GRG 7, facade greening systems

Figure 16 GRG 7, facade greening climbing plants

3.3.4 Oberland Realschule Holzkirchen - secondary and elementary school

As the site of the secondary and elementary school was formerly used as a lowered cow paddock, a intensively greened landscape plate of 180 x 70 meters was built into the terrain. Due to the existing height difference of 4 meters, it was possible to create a continuous connection to the neighboring meadows and surroundings, which was also the aim of the design. In order to ensure natural lighting for the ground floor and the sports hall, four courtyards were cut into the vegetated landscape plate (Kramer, 2010). The classrooms with wood structured walls are located on the upper level while offices, labs and the sports hall, which is built 6,5 meters below ground level, are placed beneath the greened plate (Matzig, 2006). The surrounding of the former cow paddock is now densely built, however, the artificial landscape allows cows to pasture on the roof at times.

Architecture	rheinpark_r
Specialists	Latz und Partner (landscaping), ArGe werkbureau + IB Marcon (construction management)
Location	Holzkirchen, Germany
Year of construction	2005
Area	12 719 m^2 (constructed area)
Costs	€ 24,5 mio.
Functions	• elementary school with after-school care • secondary school • science labs, triple sports hall • outdoor sports facility • school canteen
Greening measures	• vegetated landscape plate with intensive greening • continuous connection to neighboring meadow by placing into natural topography allows cows to pasture • greened court yards

Table 11 Oberland Realschule Holzkirchen - project description (Kramer, 2010)

Figure 17 Oberland Realschule Holzkirchen, vegetated landscape plate

3.3.5. Tour de la biodiversité - M6B2 Tower of Biodiversity

The tour de la biodiversité is a mainly residentially used tower of 50 meters. Besides the 140 housing units, a dormitory, shops and a community nursery school are located in the building. The tower is planted with various local species from wild natural habitats with the aim, to allow their seeds to be spread by the wind and thus enable a development and regeneration of the vegetation in its surrounding urban environment (MEF, 2016). The greening of the facade, roof and open space is planned to develop in different stages. At first, climbing vines will cover the steel netting, which functions as a climbing frame. Secondly, conifer and oak trees will develop in the next ten to twenty years (ArchDaily, 2016).

Architecture	Maison Edouard François
Specialists	BASE (landscaping), École Du Breuil (gardening), ARCADIS (structural engineering), ARCOBA (engineering)
Location	Paris, France
Year of construction	2016
Area	730 m^2 (constructed area) 13 830 m^2 (gross floor area)
Costs	app. € 33 mio.
Functions	• family housing units and social housings • community nursery school • shops • semi-public green space
Greening measures/ environmental aspects	• planter based facade greening and roof garden • climbing vines with steel netting as climbing frame • plants species from natural habitats

Table 12 Tour de la biodiversité - project description (MEF, 2016)

Figure 18 tour de la biodiversité

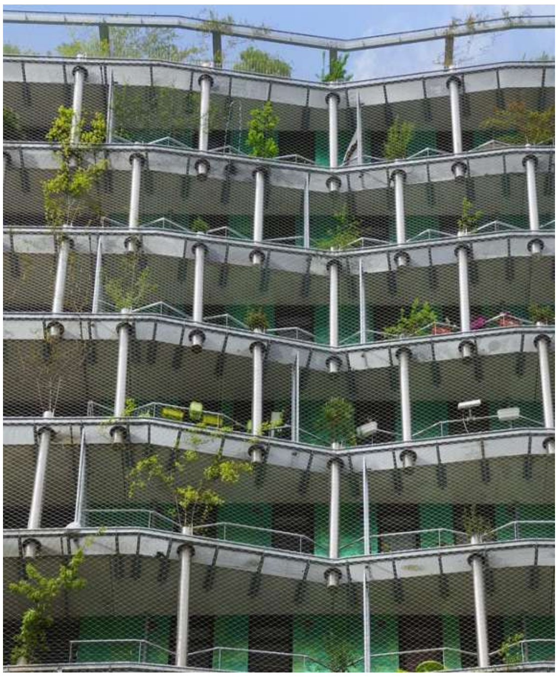


Figure 19 tour de la biodiversité

3.3.6. The Calhoun School - 81st Street Green Roof Learning Center

With the expansion of the Calhoun School four stories were added to the five-story building, which was built in 1975. The new construction added a performing arts center with a theater and science labs to the school and included the planning of a green roof for educational use. The Green Roof Learning Center is used for outdoor chemistry and physics lessons and environmental and plant biology studies. The grass area functions as an outdoor classroom, while planting beds for flowers and herbs are planted by the children during the lessons (Kramer, 2010). The herbs are used to support the school's lunch program, which sets priorities to health and nutrition. The Rockefeller University, the Black Rock Forest Consortium and the Earth Pledge Foundation are collaborating with the Calhoun's faculty to develop joint programs (GREENROOFS).

Architecture	FXFOWLE ARCHITECTS
Specialists	Town and Gardens, LTD (landscape), Anastos Engineering (structural engineer), FJ Sciame (construction management), Roofmeadow (green roof consultant), Carlisle (roof system)
Location	New York City, USA
Year of construction	2005 (four-story addition, green roof) 1974 (original building)
Area	700 m^2 (constructed area) 8 000 m^2 (new gross floor area)
Functions	• children from 3rd to 12th grade • private school with two-story performing arts center with 234-seat theatre • science labs, large sports hall • Green Roof Learning Center for environmental and plant biology studies
Greening measures/ environmental aspects	• 232 m^2 semi-intensive green roof • grass and sedum area • planting beds for flowers and herbs for educational use

Table 13 The Calhoun School - project description (Kramer, 2010)

Figure 20 Calhoun School, Green Roof Learning Center

Figure 21 Calhoun School

3.3.7. Pine Jog Elementary School and FAU Environmental Education Center

The Pine Jog Elementary School is a joint-use public school campus between the School District of Palm Beach County and Florida Atlantic University. Traditional education is combined with ecological and environmental education and the green space between and around the campus buildings is mainly used for educational use, such as sustainable agriculture, botany, environmental issues, water conservation and ecological restoration. The property of 135 acres consists of a protected pine flatwood area, a pond with surrounding wetland and the school area. The joint campus allows university students to tutor younger children during field trips, summer camp or afterschool programs. The Environmental Education Center also offers the Master's Degree in Environmental Education as an transdisciplinary and open program (FAU).

Architecture	Zyscovich Architects
Specialists	Pirtle Construction (construction, indoor air quality management, waste management)
Location	West Palm Beach, Florida, USA
Year of construction	2008
Area	11 918 m^2 (constructed area) 135 acres (property)
Functions	• children from preschool to 5th grade • joint-use public school campus between Florida Atlantic University (FAU) and the School District of Palm Beach County • outdoor classrooms
Greening measures/ environmental aspects	• educational use of green space • butterfly gardens, water re-use demonstration areas, biological life cycle study areas and habitats for native grasses and amphibians • use of regional and recycled materials • LEED gold certification (Leadership in Energy and Environmental Design)

Table 14 Pine Jog Elementary School - project description (Kramer, 2010)

Figure 22 Pine Jog school property

3.3.8. FMOS - Mosfellsbær Preparatory High School Iceland

FMOS is a secondary school in Mosfellsbær, 17 kilometers north of the capital city of Iceland Reykjavik. The school consists of two slightly shifted parallel buildings which are connected by a central glass wing. The landscape defines the character of the school as ramps and steep sloping roofs merge the building with the ground. The green ramp functions as an extension of the surrounding meadow and enables a direct connection to the green roofs. Common areas such as the entrance hall, library and canteen and the art department are located on the ground floor. The learning areas of the other departments for social science, natural science, sports, public health, and horsemanship are on the upper level. The combination of concrete and wood defines the exterior and the interior of the school. As a contrast, large indoor window openings let natural light from the central glass wing reach the deeper parts of the buildings. The school has a natural ventilation system which operates by sensor controlled openings behind the curtain wall facade (Meuser and Hoffmann, 2014).

Architecture	A2F arkitektar
Specialists	Birkir Einarsson (landscaping), Almenna verkfræðistofa (structural engineering), EFLA (acoustics and sound insulation)
Location	Mosfellsbær, Iceland
Year of construction	2014
Area	1 820 m^2 (constructed area) 4 100 m^2 (gross floor area)
Costs	€ 7,9 mio.
Functions	• secondary school with 400 to 500 students from age 16 to 2 • educational programs for social science, natural science, arts, sports, public health and horsemanship • library, school canteen and art department • learning areas on the upper level
Greening measures/ environmental aspects	• roof greening with direct access to the surrounding meadow by a green ramp • connection to natural landscape and topography

Table 15 FMOS - project description (Meuser and Hoffmann, 2014)

Figure 23 FMOS, roof greening with connection to natural landscape

04 GREENING CONCEPT FOR SCHOOLS

4.1 Functional categories

The greening concept for school buildings must serve a variety of purposes and should be integrated into the architectural and landscape design. The distinction between the following proposed functional categories of the greening should be done in an early design stage and helps to develop a coherent greening concept.

4.1.1. Aesthetic greening

The aesthetic greening is a very important component because it affects the impressions of users while entering the building or passing-by. The planned vegetation is not intended to be changed by the users directly. However, aesthetic greening can create a comfortable atmosphere which improves concentration due to its calming effect and communication by offering a meeting point. The plants add structure and color to the building and create a contrast to flat materials. Living walls are very suitable for aesthetic greenery due to their dense vegetation and various arrangement possibilities by mixing plants with different colors and appearances. Hanging plants can be applied over passages to emphasize an entrance or the transition to a different section of a building. Depending on the selection of plants, both types of greenery can be implemented indoor or outdoor.

4.1.2. Educational greening

The purpose of educational greening is to be integrated in the lessons and teaching methods. It enables the possibility to alternate theoretical classes with interactive and practical assignments to extend the learning process. Furthermore, educational greenery allows to apply a variety of teaching methods for diverse lessons and therefore reach more students. The vegetation is planted by the school children under guidance of supervisors, such as teachers, scientists, and experts in the field of gardening and landscaping. Urban farming is a key component of educational greening since this knowledge is very practical and useful, especially after graduating from school. Experimental gardens with different substrate materials and plants can be used to observe the impact of surrounding conditions on vegetation. Beside the planting and experimenting, the monitoring skills are also encouraged by observing biodiversity. This can be supported by creating for instance breeding and nesting places for birds and habitats for insects and bees. Roof greening is very suitable for educational greening since the space can be well divided into different planting beds and the access is restricted to internal users. If experimental gardens are in public or semi-public areas, the plants should be robust and protected against contamination and damages. Vertical gardening can be placed along the walls at a reachable height, also on areas with public or semi-public access since the framework protects the plants to a certain amount.

4.1.3. Creative greening

Creative greening provides green space for school children to unfold their creativity with free choice of design. The purpose is to allow children to spend time individually or in groups with planting flowers, gardening and designing miniature gardens. While the framework, such as materials and tools, is provided by the school and a supervisor is present to assist if necessary, the children can work on their own projects before the school starts in the morning, during breaks, between or after classes and during hours for creative work. This helps the children to relax and regenerate, especially on long and busy school days, and improves their concentration during other classes. Furthermore, it helps children to process emotions such as anxiety, anger, frustration and tension by creating a balance. Areas for creative greening can be on open spaces, such as the schoolyard, roofs and on vegetated terraces, where each classroom can have its own planting beds.

4.1.4. Environmental greening

To complete the categorization, environmental greening in this case is defined as vegetation, that is not directly used or influenced by users, but provides significant environmental services. Trees and shrubs with dense canopies regulate the microclimate by shading, evapotranspiration, and improvement of air quality. Furthermore, they are valuable habitats and food source for living organisms and contribute to preserve biodiversity and a healthy ecosystem. By planting fruit trees, they can also be integrated in the concept of urban farming. A composition of different tree and shrub species increases biodiversity by offering a variety of food supply and habitats. The selection of plants must be done under consideration of local climate and soil conditions. It must be noted that plants with toxic components should not be used near playgrounds, schoolyards or areas where children could easily come into contact with them.

4.2. Guideline for Green Architecture in Schools

The Guideline for Green Architecture in Schools was published in March 2020 by the members of the research project “GRÜNEzukunftSCHULEN” and is based on the experiences that were made during the implementation of greening measurements in two schools in Vienna. The aim is to support the planning and realization of green architecture in schools. In addition to information about the structural realization, suggestions for maintenance management are described in detail. A top-down approach from the principal and administration regarding organization of responsibilities is suggested in order to adjust and integrate the care and maintenance of plants, substrate, light and watering system into the school’s time schedule. By creating task groups, some responsibilities can be transferred to teachers, children and students and the school staff. It is important to assign several people with the same task to be able to change shifts in case of absence, especially during school breaks and holidays. Regular visual inspections ensure that problems are detected in an early stage and solved quickly. By including the school environment into the greening process, some tasks can even be done by children’s family members or interested people in the direct neighborhood. By cooperating with universities and professional schools in the field of gardening and landscaping, students can assist in the maintenance and tutor school children as an internship or in exchange of credits (Korjenic et al., 2020).

4.2.1. Indoor greening of classrooms

The walls inside classrooms have the potential to be used for vertical greening systems with herbs, grasses, or indoor plant species, which are cultivated all year round and often originate from tropical regions. In general, the selected plants should have natural growth conditions like those in an indoor environment regarding air temperature and humidity. Furthermore, plants which grow flat, bushy, or overhanging with a limited growth are well suited for wall-bound interior greening systems. When selecting plants, the location of the greenery, the light intensity and humidity in the room must be considered. The plants should be as robust as possible against maintenance errors and be less vulnerable to diseases and harmful pests. To achieve a long-term success of the vegetation, the plants should harmonize regarding their requirements. A mixed substrate of expanded granules is common for indoor greenings, while the composition has to be adjusted to the requirements of the plants (Korjenic et al., 2020).

4.2.2. Tray systems

Tray systems (Figure 24) are suitable for indoor and outdoor vertical greening and can be installed on various types of walls and facades with a corresponding substructure. The system consists of metal construction with thin trapeze shaped profiles and allows a flexible arrangement of the individual trays with approximately 25 - 30 cm to each other for substrate and plants. A thin layer of fleece fabric on the inside of the trays serves as a water distributor and filter by preventing fine particles of the substrate from washing out. The irrigation system can either function by a direct water connection for inflow and outflow or, if this is not possible, by a water tank and an indoor circulation pump. The amount of water is determined regarding to the requirements of the plants and the watering functions automatically by drip tubes. in addition, the substrates store the water in case of irrigation failures and keep it available for the plants for shorter periods of time. Tray systems are ideal for the use in schools, since they can be planted by the students themselves due to their construction and thus can be installed in the classrooms and biology/environmental studies classrooms to be worked on during or in between the lessons (Korjenic et al., 2020).

4.2.3. Fleece systems

Fleece greening systems (Figure 25) are suitable for indoor application and consists of a combination of different fleeces, which serve as a vegetation carrier. Attached to a carrier board, the three-layered fleece fabric provides sufficient water distribution and root habitat for flat spreading houseplants that are inserted into corresponding pockets. Fleece systems are installed by aluminum wall brackets to the building construction with 5 cm spacing in order to allow sufficient air circulation and prevent waterlogging. The irrigation can work similar to tray systems either by direct water connection or an indoor circulation pump, while excess water is collected by a gravel bed with a drain below the greenery (Korjenic et al., 2020).

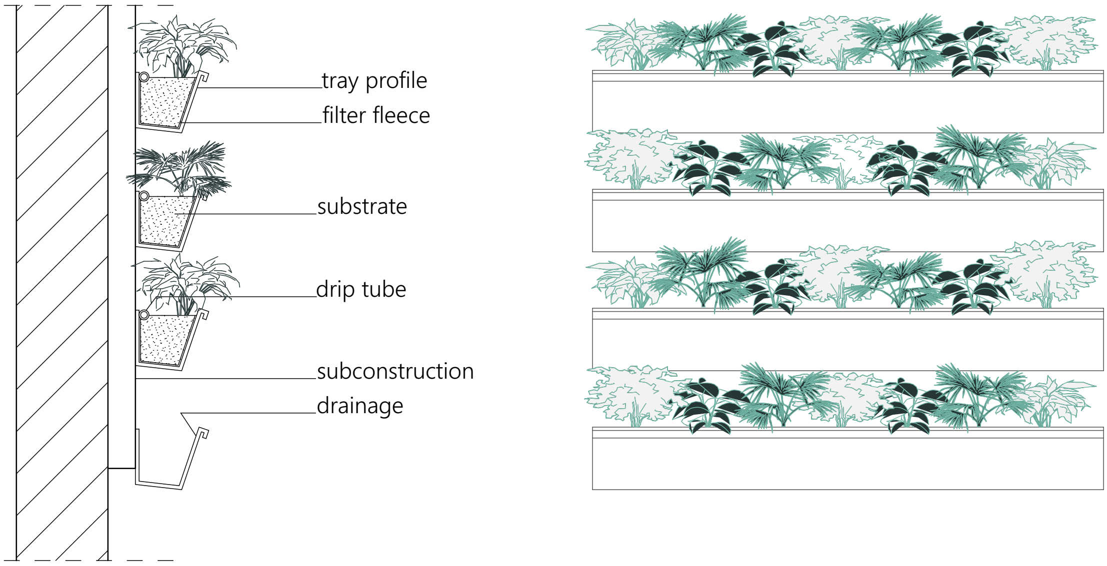


Figure 24 schematic detail of tray systems, own illustration based on Hollands (2017)

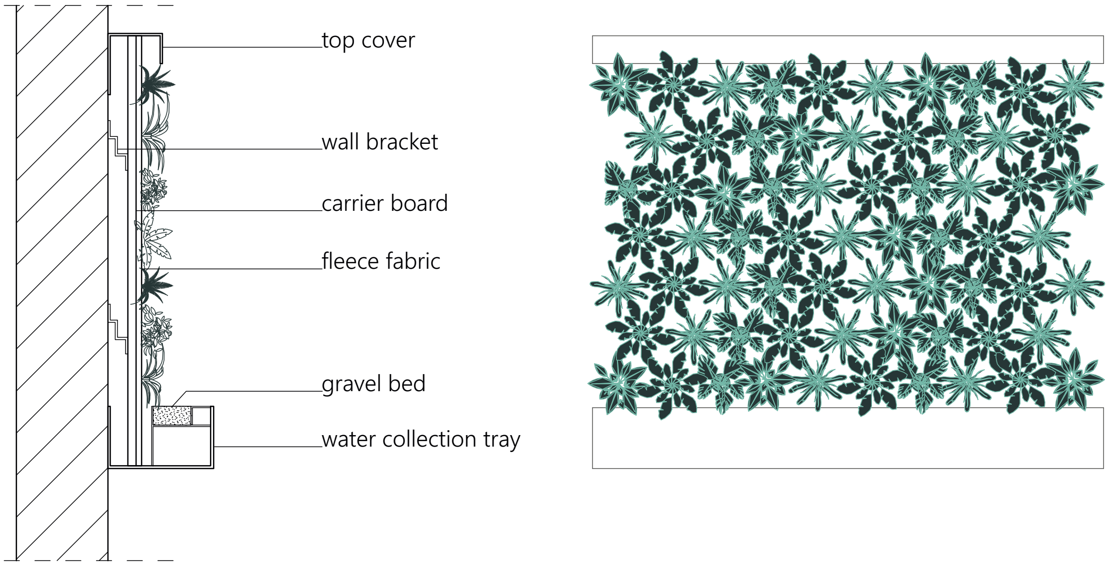


Figure 25 schematic detail of fleece systems, own illustration based on Hollands (2017)

05 URBAN GREEN SCHOOL - DESIGN

The following chapters describe the practical part of this project and connect the main topics of research. The aim is to design a conceptual showcase project of a secondary school in Vienna with a focus on environmental education by including vegetation in the overall concept. Furthermore, the impacts of the implemented greening concept on the environment and microclimate are demonstrates by a microclimate simulation and evaluation.

5.1 Site selection criteria

The site for the design of a prototype school was chosen under consideration of the following aspects. To display the impact of urban green infrastructure, it was important that the site is in an urban area. Green spaces in the direct surrounding are an advantage because they allow the design to connect with the existing green infrastructure and expand its range. Another important parameter was the potential of the site to improve the quality of life for the neighborhood. To reduce the sealing of natural areas for building purposes, the use of fallow land is preferred. Therefore, the search was restricted to empty sites with former (industrial) usage or buildings which were likely to be demolished because of their poor structural condition.

According to the German Sustainable Building Council (DGNB) land consumption (ENV 2.3) is an assessment criterion for ecological quality for district development, which contributes to the overall sustainability goals SDG 8 decent work and economic growth, SDG 11 sustainable cities and communities, SDG 12 responsible consumption and production, and SDG 15 life on land. One of the indicators is the amount of fallow land, which is used for district development. Land recycling in the context of land cycle management means that area is not "consumed" but used differently. Re-use of land, re-densification and measures for inner development prevent from urban sprawl and contribute to an efficient and considerate use of land and soil, which is valuable resource. Beside the ecological benefits like the improvement of microclimate, land recycling also has advantages from the economical point of view such as lower infrastructure development fees, wastewater charges, and reduction of the competition of space (DGNB, 2020).

5.2 Site analysis

5.2.1 Location and Green Infrastructure

The site is in the 16th municipal district of Vienna Ottakring. Figure 26 and 27 show maps with green and blue infrastructure of Vienna. Approximately one third of the district in the west of Vienna is covered by green space and most of it belongs to the Ottakring forest with a size of 193 hectare, which makes 2,5% of Vienna's forested areas. The Ottakring forest connects with the forested areas in the 14th and 17th district, which are all part of the Wienerwald, one of the largest contiguous deciduous forest areas in Europe. The Ottakring forest reaches relatively far into the urban settlement area along with open cultivated landscape including meadows, vineyards and orchards. The forest coverage in the district is mainly closed without larger cleared woodland. Oak and beech growths are dominant with coniferous reforestations such as spruce, red pine, and larch in between. The protected landscape area provides natural space for recreation and is of essential importance for the quality of life in the district (Scheiblhofer and Schranz, 2019).

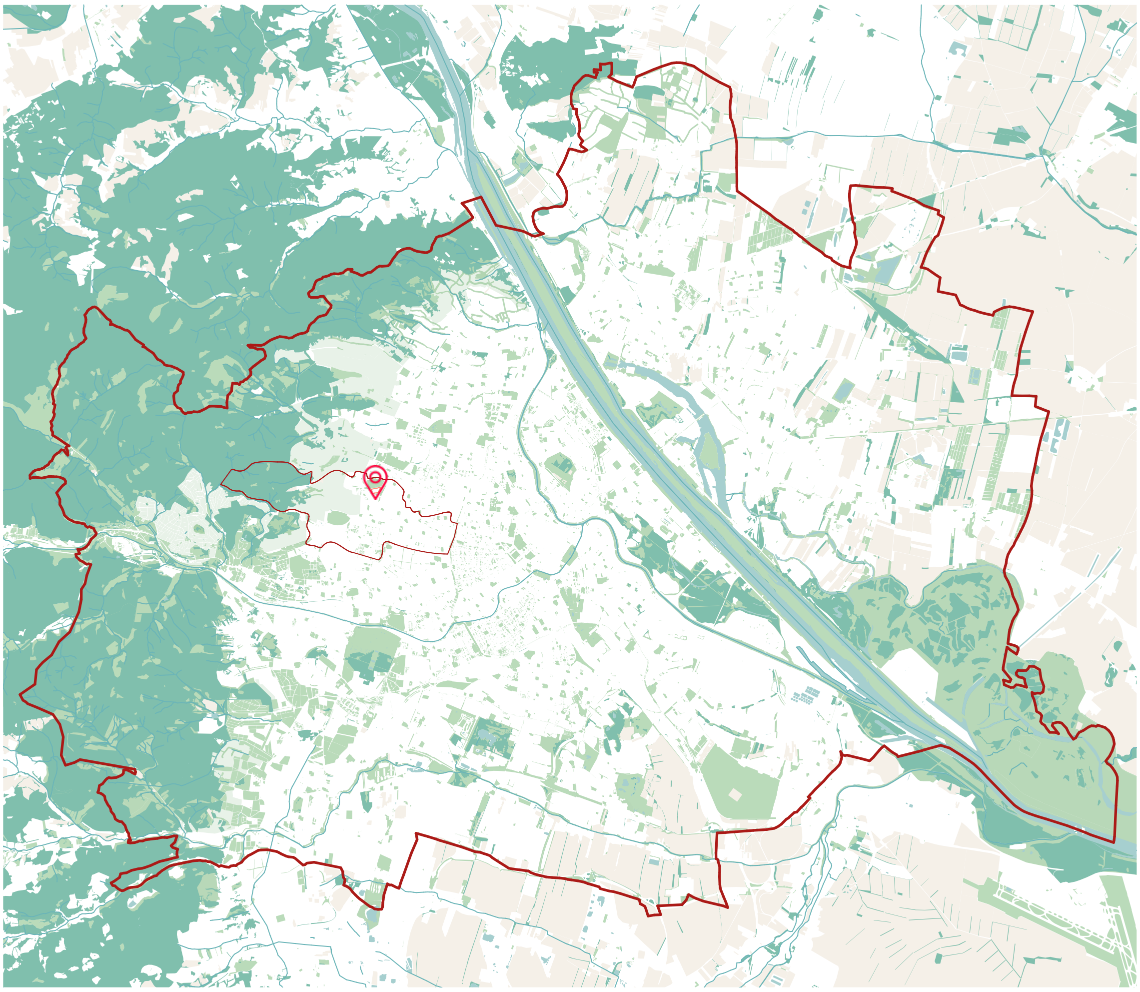


Figure 26 green and blue infrastructure map of Vienna *1:200 000*

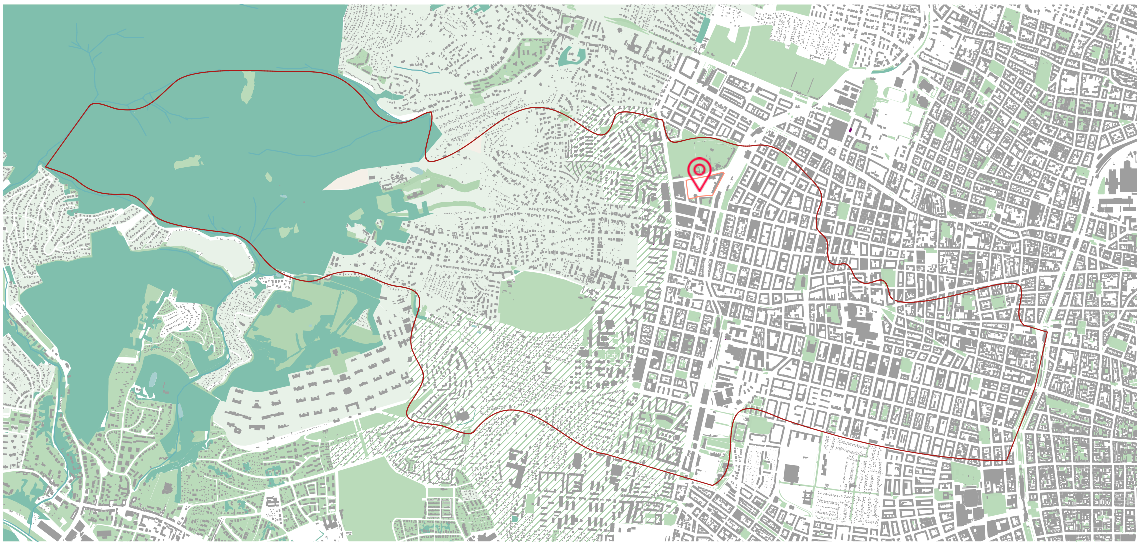


Figure 27 green network map of Ottakring *1:50 000*

5.2.2 Urban structure

The urban structure of the neighborhood (Figure 28) is characterized by block perimeter development in the north, south and east of the site which is disconnected by the railway of the suburban train. The urban structure in the western direction of the site is very inhomogeneous, including courtyard structures and building arrangements of the municipal housing complexes Sandleitenhof and Dr. Adolf Schärf Hof followed by ribbon development, single-family and duplex houses and allot settlements. The Congress Park and public outdoor swimming pool in the direct proximity to the site serve as a local recreational area.

Figure 28 area analysis - municipal social housings and public educational facilities 1:10 000

5.2.3 Urban Heat Vulnerability Map

The Urban Heat Vulnerability Index Map (Figure 29) shows that the project site is at the border to a red zone, which means that many residents in are part of a heat sensible population group, either children under 14 years or residents older than 60 years. This part of the 16th district of Vienna is among the most affected areas by the UHI effect because of a dense building structure and a high percentage of heat sensible population. Therefore, the site has a great potential to reduce thermal load and improve the microclimate, which also affects surrounding areas. The direct connection to the Congress Park also allows an extension of green infrastructure and living environment in this area.

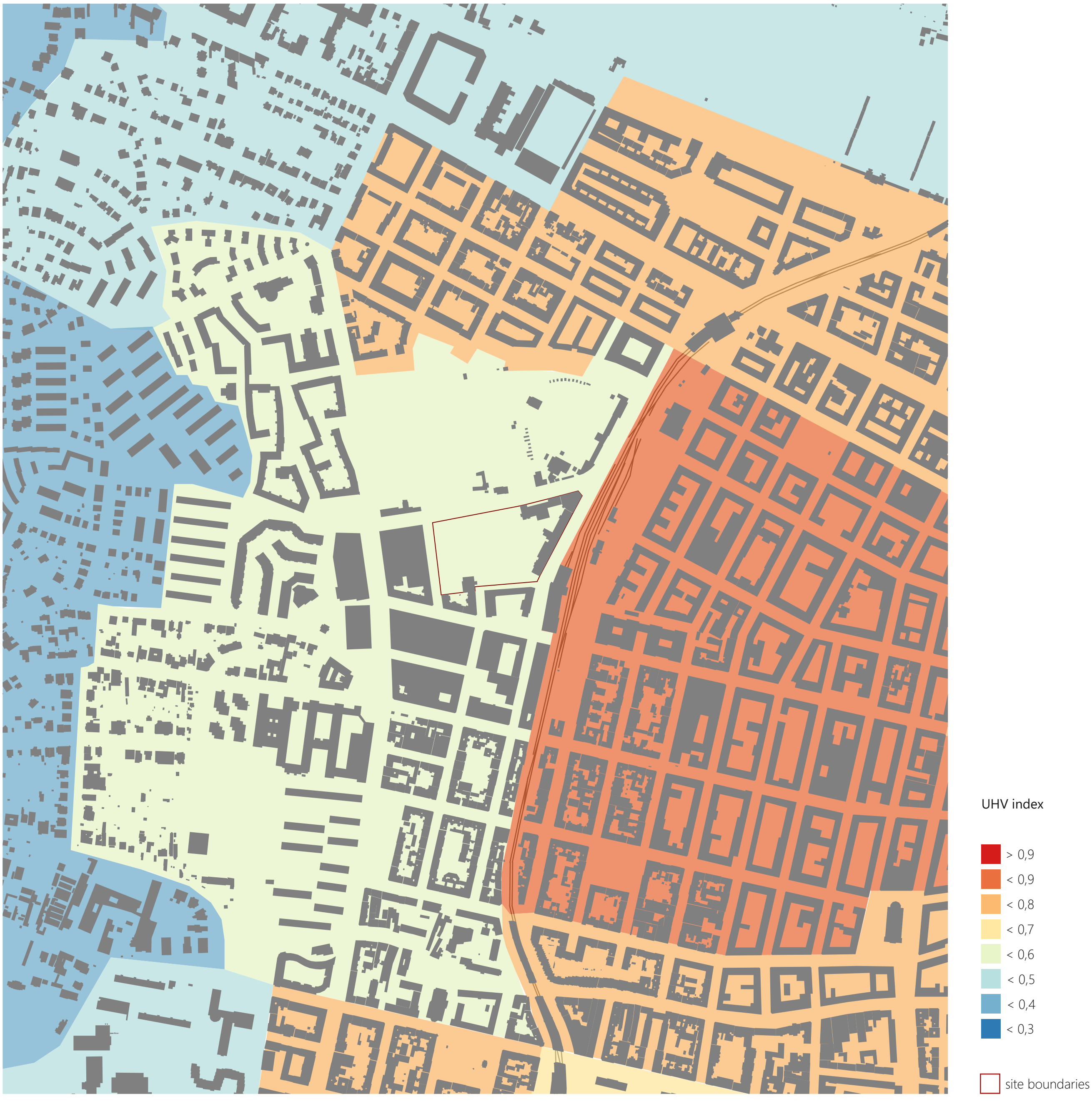


Figure 29 Urban Heat Vulnerability Index Map for the site and surrounding areas *1:10 000*

5.2.4 Site history

1900

1920s

The project site served as the former Julius Meinl coffee factory, which was founded in 1862 and built around 1900.

Figure 30 Julius Meinl headquarter (1925)

Figure 31 Julius Meinl factory yard (1925)

1990s

Some buildings were rebuilt after 1945, including a factory wing (Figure 33).

Figure 32 street view Franz-Peyerl-Gasse (1999)

Figure 33 Julius Meinl factory yard (1999)

2007

While most of the factory buildings were demolished in 2007, the historical coffee roastery and some storage buildings are still existing (Figure 34).

Figure 34 existing storage building

2020

The remains of the original factory can still be seen due to a ruin-like construction, which was built in the construction phase between 1848 and 1918 (Figure 35). The building harmonizes with the grown nature and has become a part of it. Therefore, it will be integrated into the design concept since it tells the story of this place. The buildings in the east of the site are assumed to be used for events, coffee art workshops, storage, and offices. The remained building complex consists of a historical administration building and a factory wing which were built around 1900 and a factory wing which was probably rebuilt after 1945 (Figure 34). The fallow land is used as a parking space (Figure 36).

Figure 35 factory ruin

Figure 36 fallow land

5.2.5 Site current situation

The site is surrounded by a partly preserved brick wall which used to be part of the external walls of the former factory buildings. What used to be windows are now openings allowing small glances of the site where nature has returned over time. It almost seems like nature is breaking out of the framing walls even though most of the gaps were closed with boards. While the brick wall itself is a characteristic element, the closed gates represent a barrier which makes accessibility and the connection between the neighboring elementary school to the congress park area more difficult.

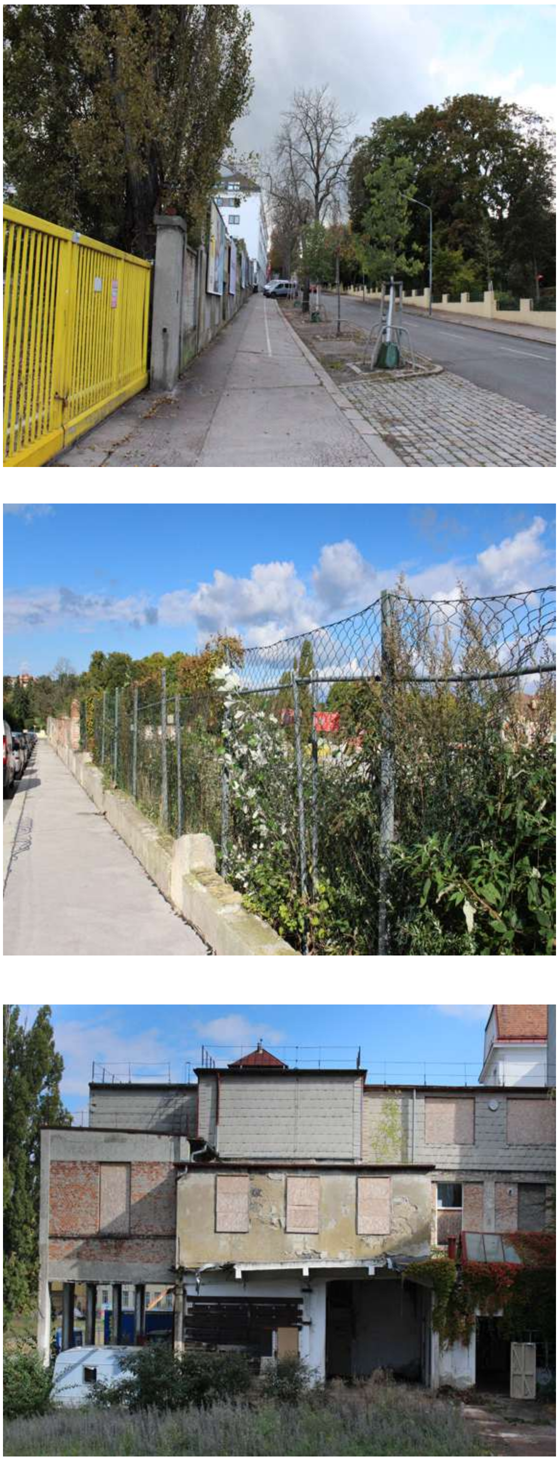


Figure 37 impressions of the site (2020)

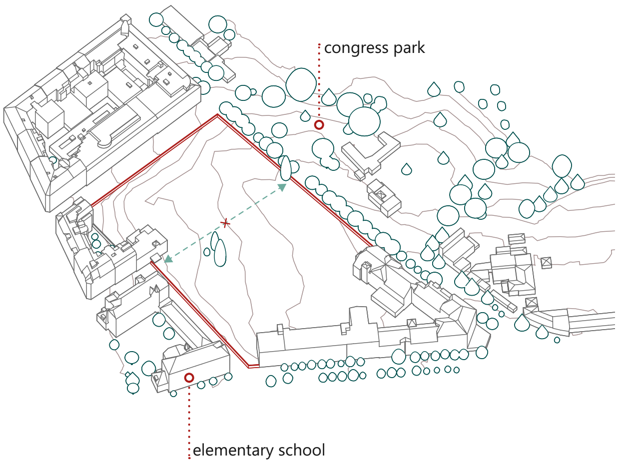
Figure 38   site wall

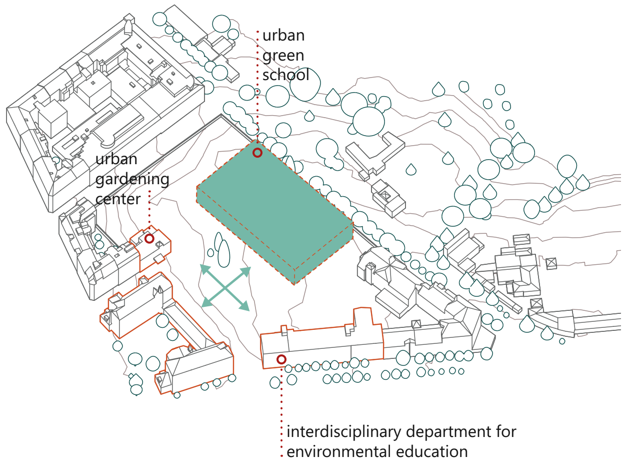
5.3 Design concept

5.3.1 Urban concept

analyzing the urban structure of the environment and finding possibilities for improving the connection between the existing elementary school, the new *Urban Green School* and the park area.

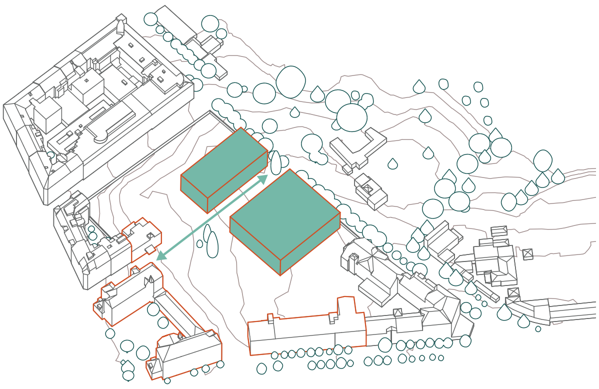
creating space by opening the wall between the site and elementary school, placing the building volume and converting surrounding buildings to form a new campus for environmental education.

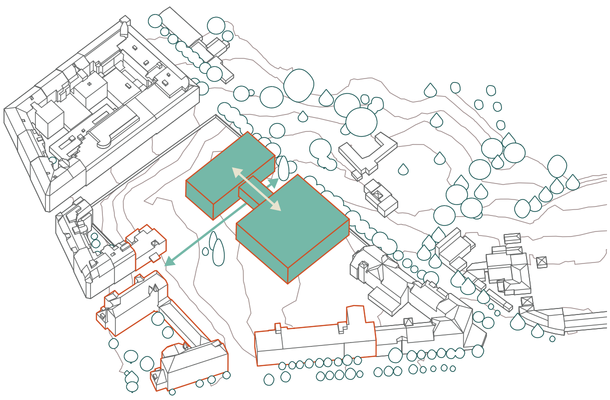




connecting the campus with the Congress Park by splitting the building volume into a narrow and a deep part with different functions according to required room depth and natural lighting.

linking the building volumes through a greened bridge which enables an indoor connection and emphasizes the entrance space of the *Urban Green School* and the outdoor campus area.





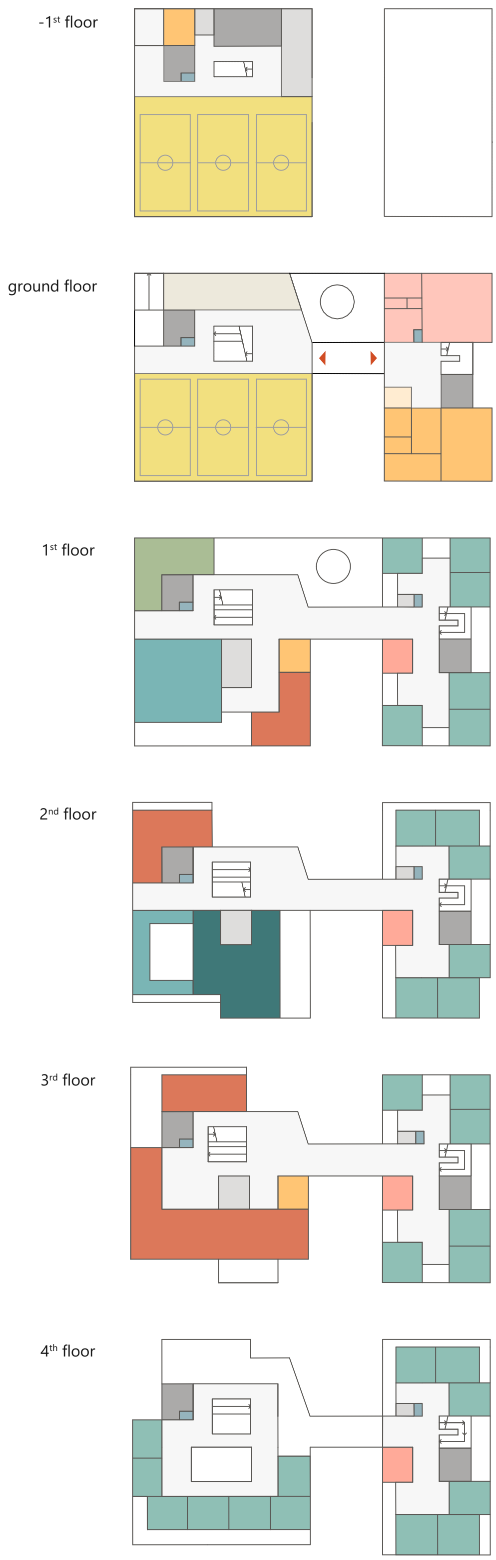
5.3.2 Spatial concept

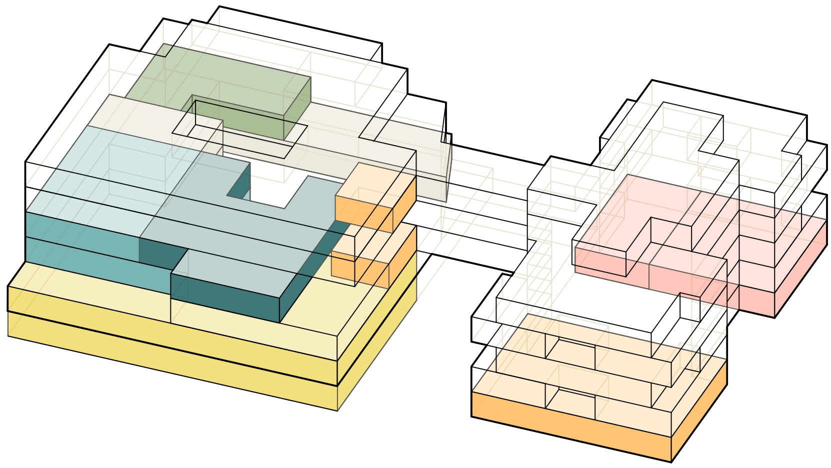
The arrangement and shape of the building components reflect the functional concept. The narrow building contains the classrooms from 1st to 6th grade. Since the school is organized as a full-day school with lessons until the afternoon the students spend more time in their home classrooms compared to a half-day school. The narrow shape and the shifted arrangement of classrooms allows natural light exposure from three directions. The class terraces provide additional open space which can be used during the breaks and lessons. The ground floor of the narrow building functions as a cafeteria during lunch break with afternoon supervision for younger students. Also located on the ground floor are the school's management and administration and teachers' offices.

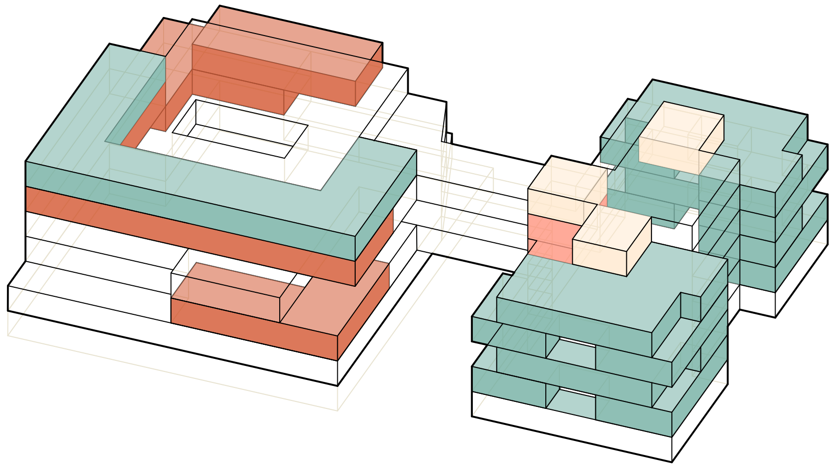
The deep building provides sufficient space for subject specific education, a library, a tripple-sports-hall and an event hall. Together with the open learning zones for self-directed studying and resting areas, this building unit creates an open ambiance with a lot of exchange between different classes. Natural lighting is provided by an atrium and the terraces, which are either assigned to a subject specific classroom or are an expansion of the open learning zones.

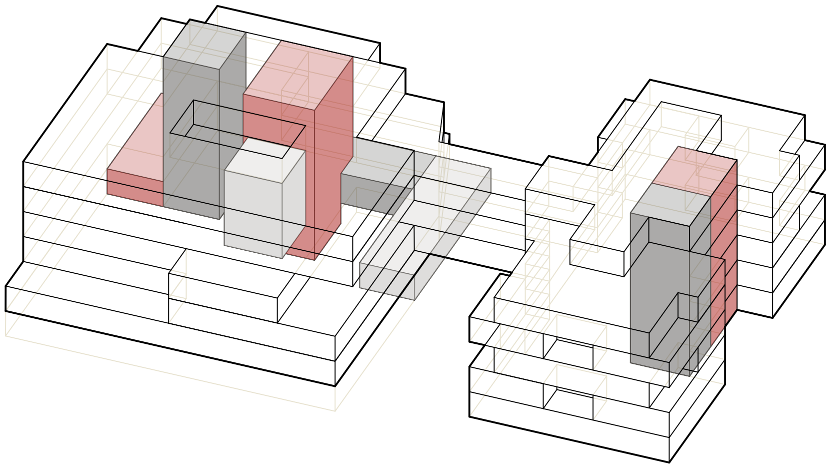
The classrooms for 7th and 8th graders are located at the top floor of the deep building. This separation supports the preparation for final exams and graduation since their timetable and break times are differ from the younger grades. The bridge connects both building units while also functioning as a gallery and an extension of the library.

The school has a capacity of 30 to 32 classrooms with each 24 to 26 students. The group rooms can be transformed into main classrooms, if necessary. This allows a flexible adaptation to demographic fluctuations.

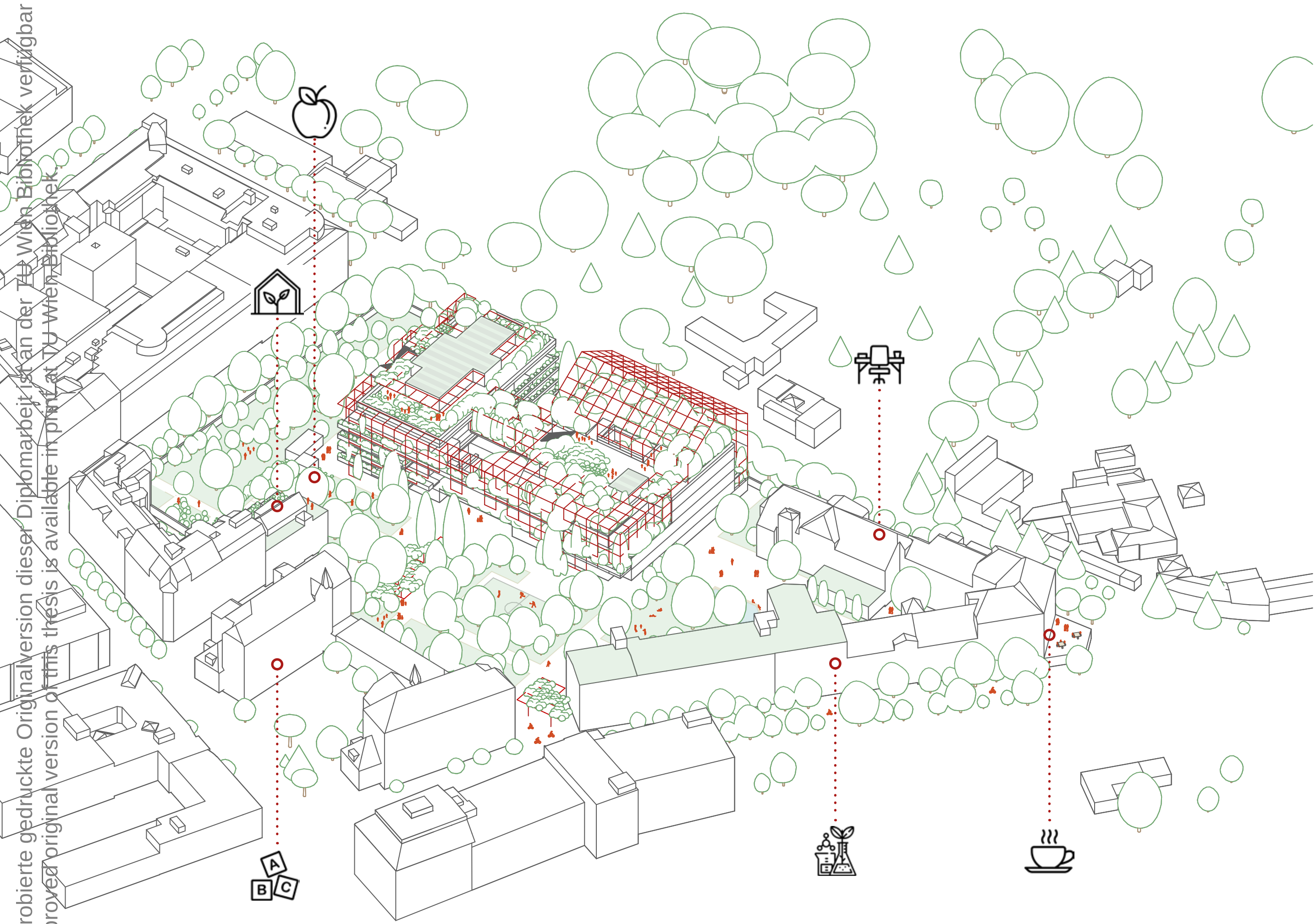



ground floor
-1st floor
sports hall
event hall
library
open study area
multi-functional areas
school kitchen / cafeteria
administration / offices / team rooms


ground floor
main classrooms
special classrooms
group rooms
open air classrooms


ground floor
vertical circulation
sanitary facilities
storage area

5.3.3 Masterplan



urban gardening center

A meeting place for the neighborhood with community gardens and a rooftop greenhouse. The revitalization and conversion of the former industrial building provides space for workshops, meetings and lectures related to sustainable urban gardening. Flower roofs with lavender support the existence of bees, bumblebees and butterflies. Hives on the roof allow a local production of honey.

public fruit trees

The public fruit trees, which are part of the urban farming concept, are accessible for pedestrians and can be harvested for own use.

elementary school

The nearby elementary school is included in the Urban Green School campus. The exchange between children and adolescents of different ages encourages communication skills. The shared use of common areas and open spaces provides additional space for the children of the elementary school.

office and co-working space

The historical factory wing will partly function as office space for the Julius Meinl company and can partly be rented as a co-working and office space by small-businesses and self-employees. The green environment and nearby campus bistro provide an attractive workplace.

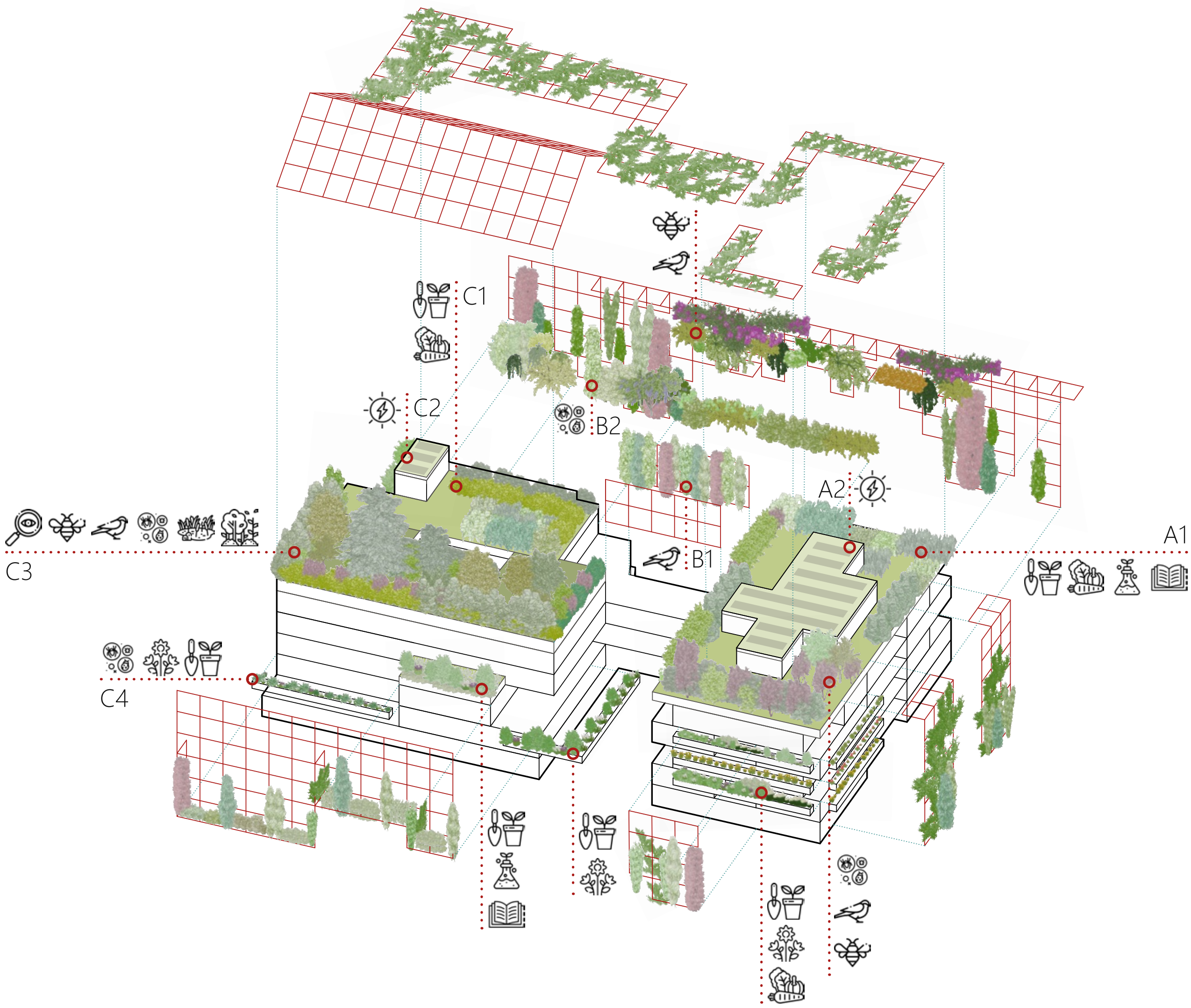
interdisciplinary department for environmental education

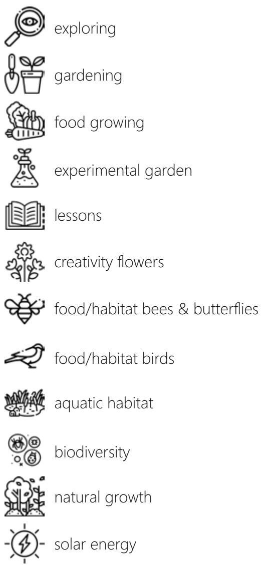
The cooperation between universities, schools and the neighborhood increases the number of people who are involved and committed to improve microclimate and biodiversity in their district. Students from different universities and professional schools, and study fields related to sustainability, environmental science, ecology, urban climate, horticulture, agriculture, urban planning, landscape design, architecture, and many more can work on projects in interdisciplinary teams. The maintenance of the school's green areas during summer can be carried out with participation of students through internships. Student labs and working spaces provide a creative and open learning environment. The exchange between university students and the Urban Green School gives adolescents perspectives and inspiration for their future educational path.

campus bistro

The historical building of the former Julius Meinl coffee factory will serve as the campus café and bistro. With a second function as a flagship store, new coffee flavors from sustainable and fair cultivation can be offered. The tables on the elevated street-side terrace enliven the surroundings and bring back the coffee house culture to the historical building.

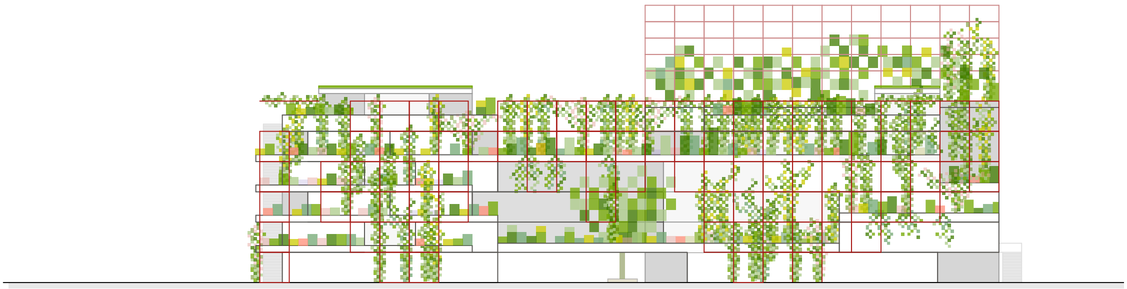
5.3.4 Greening concept



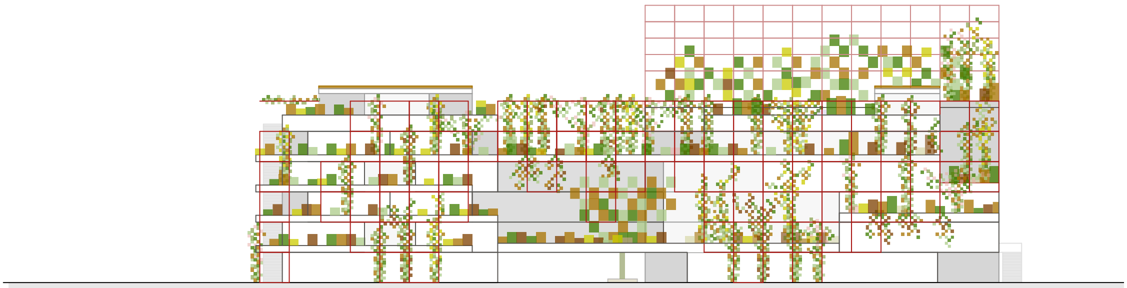


area	**description**
A1	educational roof garden *semi-intensive / intensive*
A2	green photovoltaic roof *extensive*
B1	the bridge *tray greening*
B2	bee's buffet *tray greening*
C1	educational roof garden *semi-intensive / intensive*
C2	green photovoltaic roof *extensive*
C3	roof biotope *super-intensive, natural growth*
C4	shaddow garden *try greening*

schematic seasonal elevations



conceptual south elevation - late spring / summer



conceptual south elevation - autumn

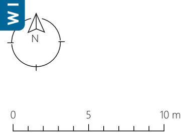
species examples

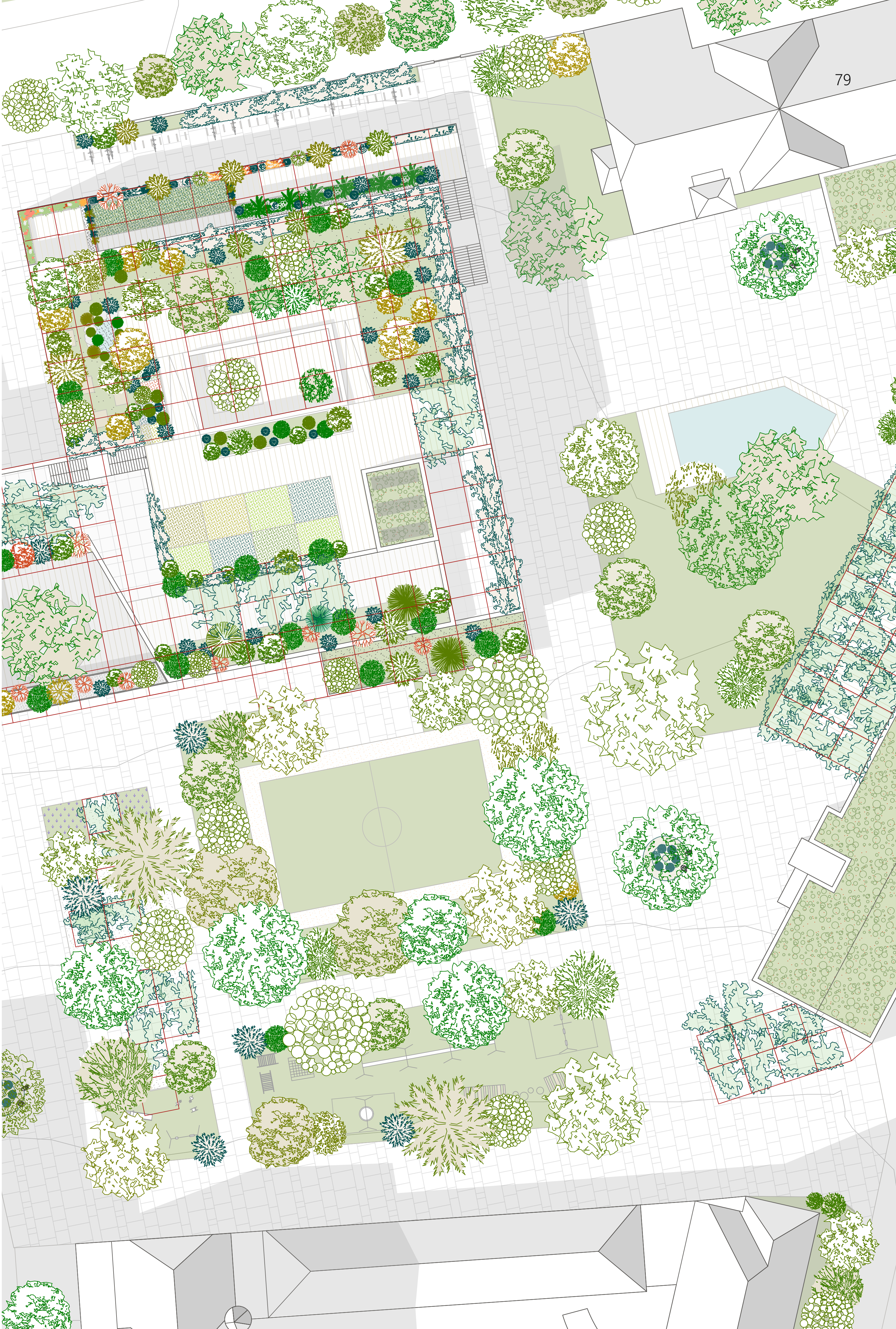
herbs and vegetables: Allium schoenoprasum, Thymus serpyllum, Cucurbita, Solanum lycopersicum, Capsicum, Solanum tuberosum, Solanum melongena
mix of sedum, herbs and grasses
climbing plants: Parthenocissus tricuspidata, Humulus lupulus, Rubus sect. Rubus
Paeonia Lactiflora-Hybr., Eryngium planum, Lavandula angustifolia, Rudbeckia ful., Jasminum nudiflorum
herbs and vegetables (same as A1)
mix of sedum, herbs and grasses
perennials, shrubs and trees: such as Amelanchier, Cornus mas, Sambucus, Hibiscus, Salix
Dryopteris filix-mas, Epimedium x rubrum, Galium odoratum, Pulmonaria angustifolia

5.3.5 Illustrations

5.3.6 Site map - 1:1000

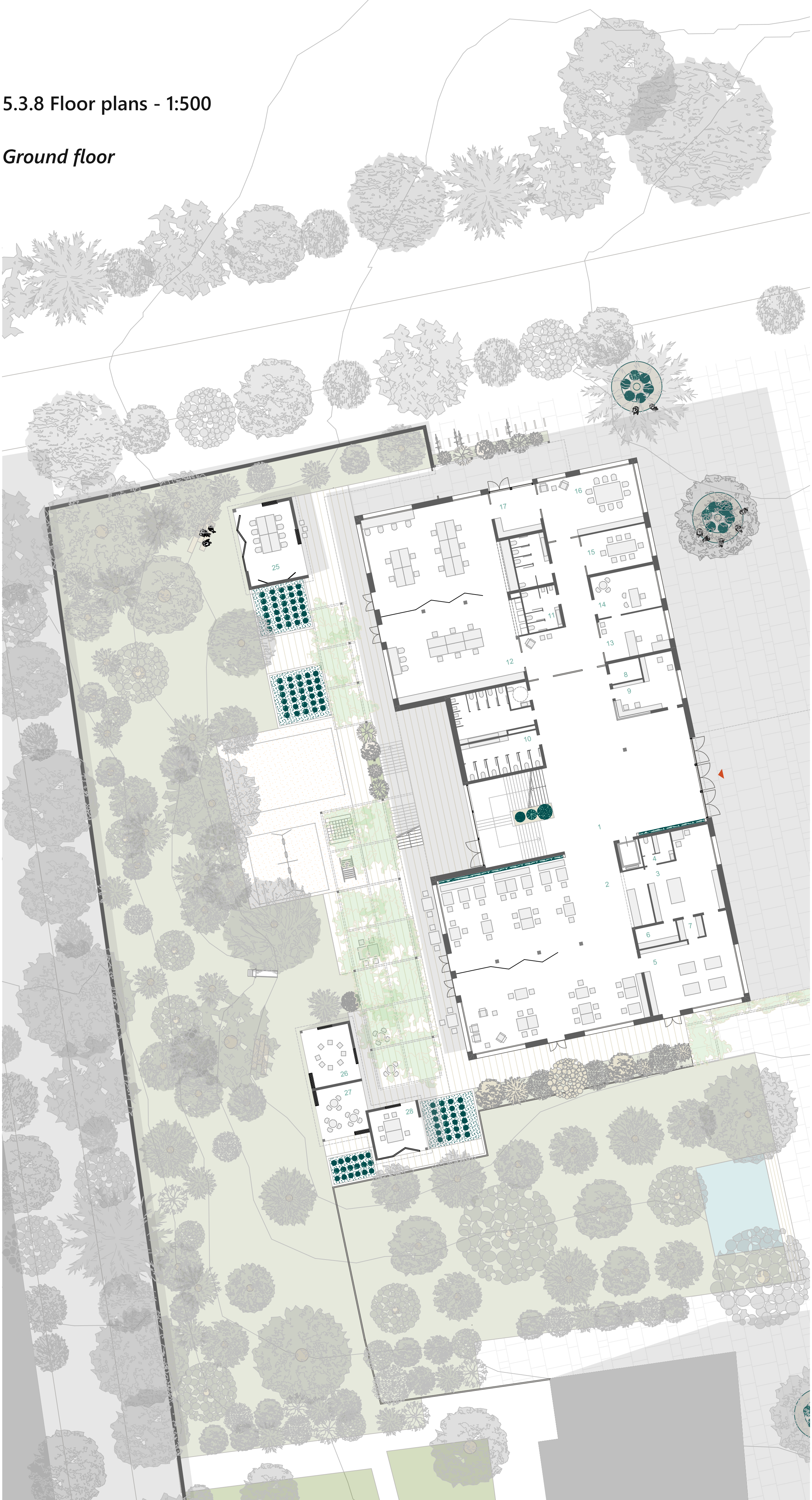
5.3.7 Site map - 1:500



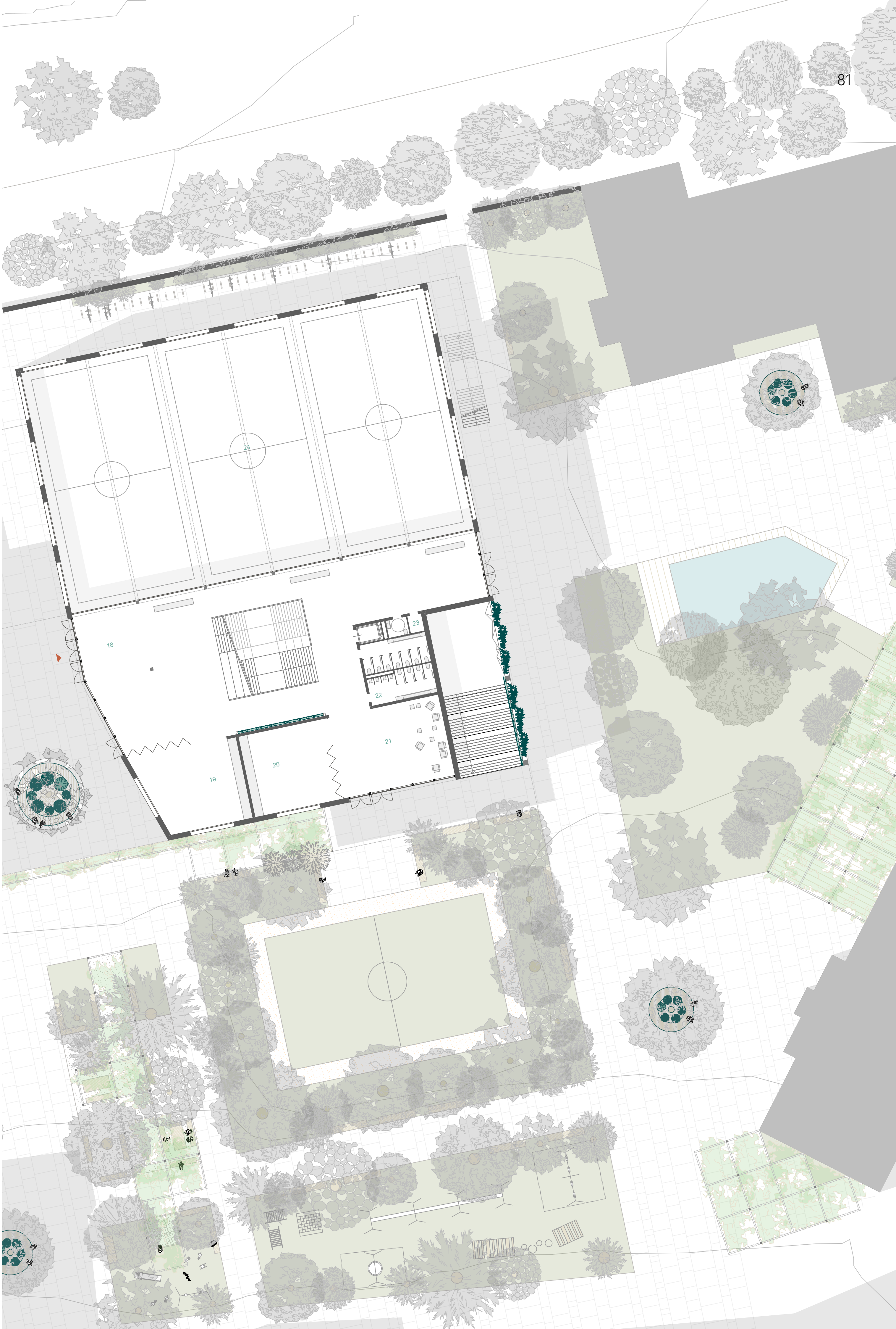


5.3.8 Floor plans - 1:500

Ground floor



1/18 - foyer
2 - school mensa
3 - school kitchen
4 - wardrobe
5 - cooking class
6 - cold storage
7/8/23 - storage
9 - facility management
10/11/22 - sanitary facilities
12 - teachers' office
13 - administration
14 - principal's office
15 - meeting room
16 -common room & kitchen
17 - teachers' entrance
19/20 - multi-functional classrooms
21 - break area
24 - tripple sports hall
(entrance -1st floor)
25-28 - open air classrooms


24
23
22
21
20
19
18

First floor

1-6 - classrooms

7/8 - break area

9 - group room

10/24 - sanitary facilities

11/20 - storage

12 - working space

13/22 - break terrace

14 - school doctor

15 - team room

16 - music classroom

17 - rehearsal room

18 - backstage area

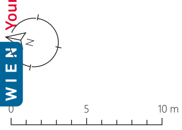
19 - instrument storage

21 - event hall

23 - event foyer

25 - seminar room

26 - open study area



Second floor

1-6 - classrooms

7/8 - break area

9 - group room

10/23 - sanitary facilities

11/17 - storage

12 - working space

13 - library

14 - library terrace

15 - meeting room

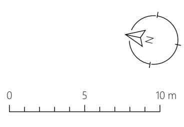
16 - movie room

18 - book storage

19 - event hall gallery

20 - event foyer

21/22 - informatics classroom



06 ENVIRONMENTAL EVALUATION

This chapter describes the environmental evaluation of the Urban Green School showcase design with the *GREENPASS Pre-Certification* tool. The result graphics and maps were produced with the *GREENPASS tool*. The descriptions and evaluation are based on the *GREENPASS Pre-Certification Report*.

6.1 Evaluation frame

The evaluation frame includes the following indicators:

Thermal Load Score (TLS)

The thermal load score provides information about the temperature of the air body flowing out of the planning area and as a result the load on the neighboring quarters. The air body which flows into the simulation model is differentiated with the outflowing air, to indicate whether the outflowing air temperature (°C) heats up or cools down on a daily average.

Thermal Comfort Score (TCS)

The Thermal Comfort Score shows how many and which areas of the project area are in the respective thermo-physiological load class (very cold - very hot). The higher the value, the better the thermal comfort of the area. The TCS is calculated on the basis of the averaged perceived temperature (PET) per simulation unit (cell) over the entire course of the day. The value can range from theoretical 0-100 points.

TCS Points	Performance
0 - 30	low
30 - 50	moderate
50 - 70	good
70 +	very good

Thermal Storage Score (TSS)

The thermal storage capacity indicates how much energy (in Joules) is stored in the materials used in the project area based on their physical and structural properties. The lower the value, the less energy is stored in the materials.

Run-off Score (ROS)

The run-off score indicates the average runoff coefficient of the project area. It shows which proportion of rainwater can be absorbed by the soil or ground material and which part runs off directly into the sewerage system without being used. A value of 1 means that all of the water drains into the sewerage system. A value of 0 means that the water is completely retained and is therefore available for plants and evaporation.

CO_2 Sequestration Score (CSS)

The carbon sequestration score shows the CO_2 storage (t) during the lifetime of the plants (in their biomass) in the project area. The value is calculated from the average CO_2 storage of plants for their average lifetime. The CSS can be 0 or a negative value (more CO_2 is stored than released). A value of 0 t means no CO_2 storage. The higher the value, the better the CO_2 storage performance of the planned green infrastructure.

PET Thermal Performance (PET)

The thermal performance shows the PET (°C) for the project area. The PET (physiologically equivalent temperature) is a human biometeorological thermal index for the perceived temperature of a standardized person. It is an abstract value that cannot be directly compared to the air temperature. The calculation of the perceived temperature (PET) includes not only the air temperature but also air humidity, wind speed, short- and long-wave radiation of the sun.

Radiation (RAD)

The radiation indicator shows the energy of solar radiation (in kilowatts) that reaches the surface materials in the project area on a hot day.

Albedo (ALB)

The Albedo indicator refers to the reflectivity or the reflective performance of surface materials. An albedo of 1 means that all light is reflected. If the albedo is low, e.g. 0, all light is absorbed and the temperature increases. The highest naturally occurring albedo is fresh snow with 0.9.

Evapotranspiration (EVA)

Evapotranspiration is the sum of evaporation and transpiration and therefore the evaporation from surfaces of plants, waters and soil. The evapotranspiration rate in the project area is measured in l/s. The higher the value, the better the cooling performance of the planned measures.

Shading Area Factor (SAF)

The shading area factor is an indicator for the shading performance. It shows the proportion of shaded surfaces in the project area. A value of 1 means that 100% of the areas are shaded. A value of 0 means no shadow at all.

Leaf Area (LA)

The indicator leaf area shows the sum of the leaf areas of all plants in the project area. The leaf area density is calculated from the sum of the leaf surfaces of the different vegetation types and the air volume. The LAR is given in square meters (m^2). A value of 0 m^2 means no leaf area. The larger the leaf area, the higher its contribution to biodiversity.

Wind (WI)

The wind indicator shows the wind field and the average wind speeds occurring on a hot day in the project area.

6.2 Scenario definition

To show the impact of the climate change adaptation measures of the showcase *Urban Green School*, two additional scenarios were created beside of the design. The definition of comparative scenarios is not always necessary for a *GREENPASS Pre-Certification*. However, they make an evaluation easier to understand.

6.2.1 Status Quo

The status quo scenario (Figure 39) represents the current situation of the site. Surface materials and vegetation were assigned according to GIS data, orthophotos and site inspection. The direct comparison with the status quo is an effective way to display, if the design improves the current microclimate conditions for the site and surrounding areas. Therefore, it is an important setting for visualizing the impacts of urban green infrastructure for authorities, planning experts and citizens in terms of decision making.

6.2.2 Design

The design (Figure 40) is the main scenario for the evaluation. Building structure, surface materials and vegetation are simulated according to planning documents. Beside the greening measures on the project site, additional trees were placed along the adjacent streets. Other than that, the buildings and surface materials of the surrounding area are identical in all three scenarios.

6.2.3 Worst Case

The worst case scenario (Figure 41) represent a variation of the design which is very disadvantageous for microclimate and climate resiliency. The building structure is identical to the design scenario, however, all climate change adaptation measures including vegetation and unsealed surfaces were removed and replaces with sealed surface materials. Since building structures are the same, the comparison with the worst case scenario shows the impact of including greening measures in the design. Although the worst case might be an unrealistic scenario, it can also help to raise awareness of the importance of urban green infrastructure for a livable city.

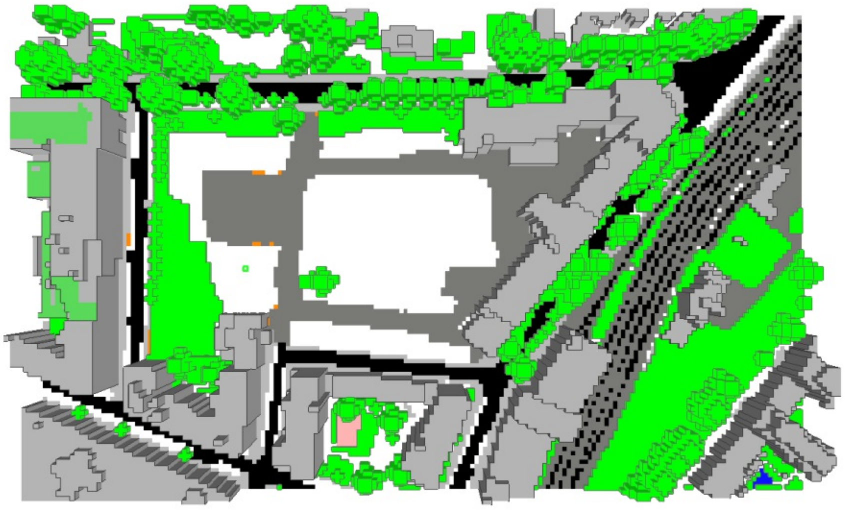


Figure 39 status quo scenario - ENVI_MET simulation model


Figure 40 design scenario - ENVI_MET simulation model

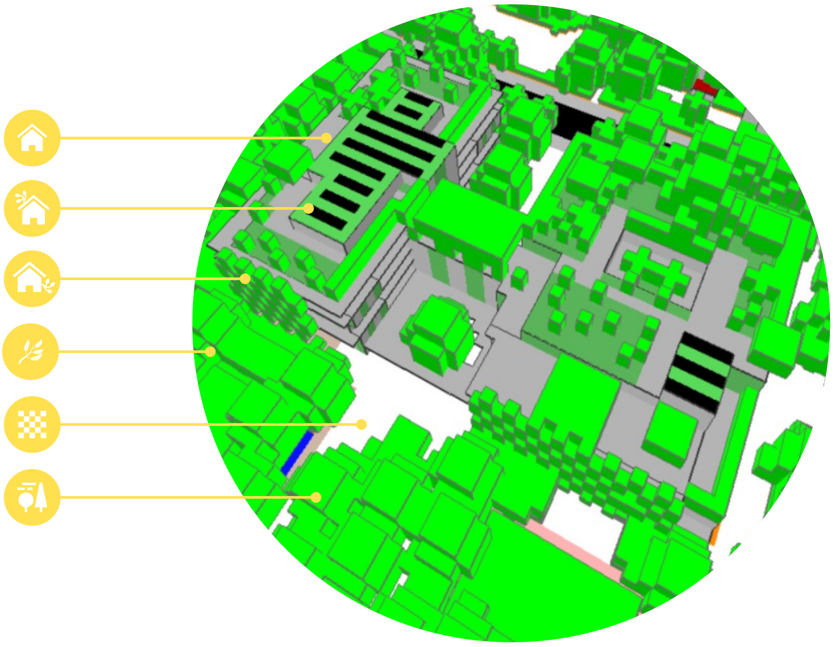

Figure 41 worst case scenario - ENVI_MET simulation model

6.3 Input data for simulation

6.3.1 Climate data

expert system	**microclimate** powered by ENVI_MET
resolution	**2x2 m** | cell size
weather data	**2010-2020** | Vienna air temperature, humidity, clouds/rain **2010-2020** | Vienna wind direction and wind speed
sun position	**21.07.2020** - idealized heat day
wind direction	**W-wind** - main wind direction in summer
wind speed	**3.8 m/s** - wind speed in summer
air temperature	min. **21.10 °C** - air temperature daily minimum max. **32.60 °C** - air temperature daily maximum
humidity	min **30.00 %** - humidity daily minimum max. **71.00 %** - humidity daily maximum

6.3.2 Materials for simulation model

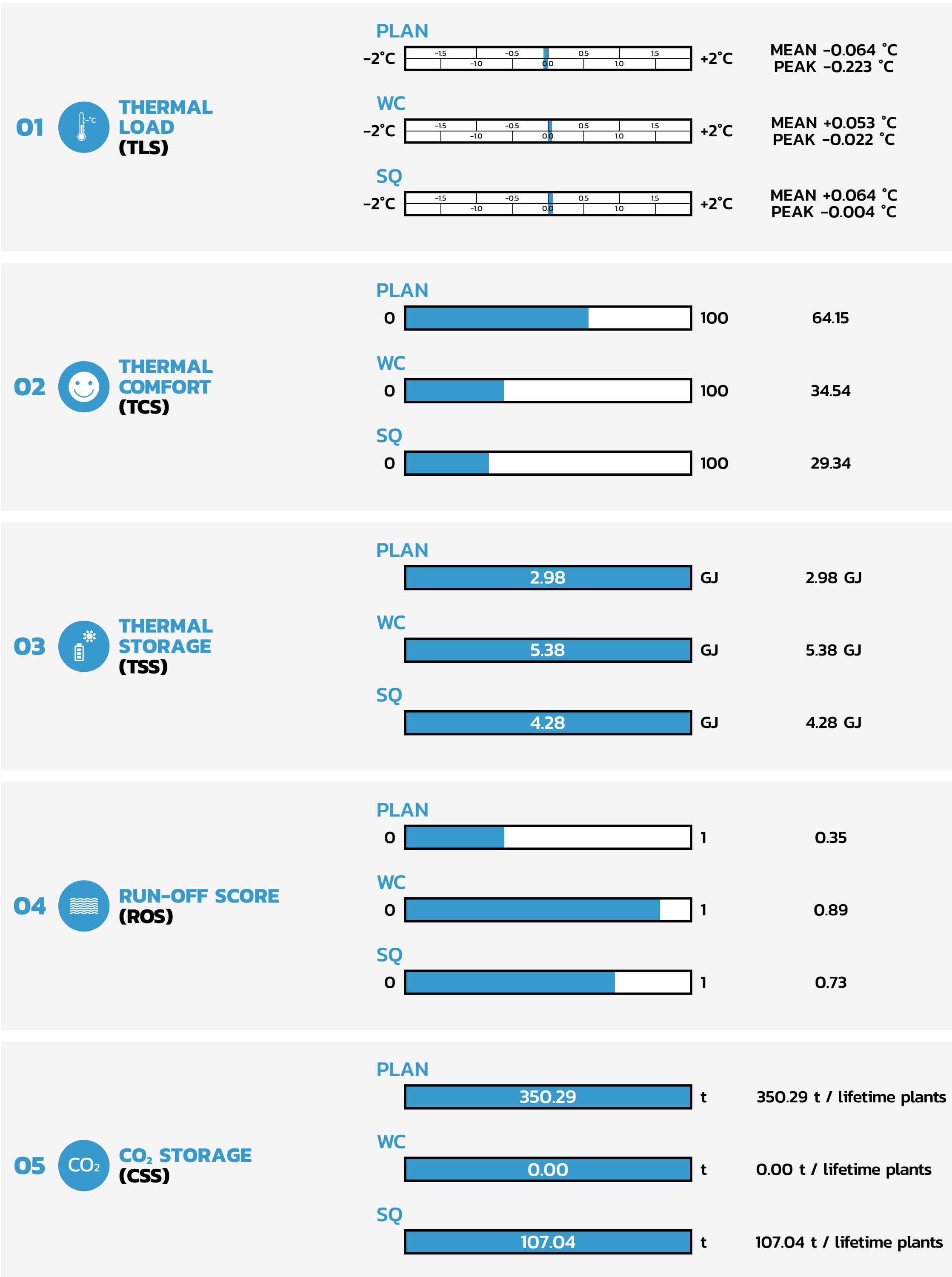


new buildings	wall - double layered brick wall / solid wood roof - concrete flat roof / wood on roof	4 607 m²
existing buildings	wall - brick wall roof - ventilated tiles	4 439 m²
roof greening	extensive semi-intensive intensive super-intensive	2 060 m² 460 m² 504 m² 764 m²
facade greening	ground based / tray based	8 262 m²
surfaces	unsealed surfaces - drainage pavement / lawn grid stone / EPDM / wood / gravel / sand	8 719 m²
green spaces	lawn perennials shrubs meadow	2 613 m² 1 086 m² 1 716 m² 1 515 m²
trees	S (5 m diameter) M (10 m diameter) L (15 m diameter)	150 x 33 x 2 x

6.4 Simulation results

6.4.1 Key Performance Scores and Indicators

The results of the design (PLAN), status quo (SQ) and worst case (WC) are compared in the following graphics.



Key Performance Indicator

KPI	Scenario	Scale / Unit	Value
06 PET THERMAL PERFORMANCE (PET)	PLAN	25°C – 45°C	33.53 °C
	WC	25°C – 45°C	39.49 °C
	SQ	25°C – 45°C	40.40 °C
07 RADIATION (RAD)	PLAN	GW	112.23 GW
	WC	GW	145.08 GW
	SQ	GW	152.76 GW
08 ALBEDO (ALB)	PLAN	0 – 1	0.19
	WC	0 – 1	0.18
	SQ	0 – 1	0.21
09 EVAPOTRANSPIRATION (EVA)	PLAN	kg/s	3.19 l/s
	WC	kg/s	0.00 l/s
	SQ	kg/s	0.24 l/s
10 SHADING AREA FACTOR (SAF)	PLAN	0 – 1	0.67
	WC	0 – 1	0.61
	SQ	0 – 1	0.59
11 LEAF AREA (LA)	PLAN	ha	11.24 ha
	WC	ha	0.00 ha
	SQ	ha	0.89 ha

GREENPASS® PRE-CERTIFIED

6.4.2 Result evaluation

The evaluation of the results is based on the *GREENPASS Pre-Certification* report.

Good performance

The results of the analysis show that the project has a **good climate resilience** performance. In comparison to **STATUS QUO** and **WORST CASE**, the **DESIGN** clearly shows an **improvement of the current situation**.

The following is an evaluation of the **Key Performance Scores (KPS)** and a brief explanation.

Thermal Load Score (TLS)

At the **peak**, the **DESIGN** cools the surrounding area by **-0.223 °C** and in the **daily average** by **-0.064 °C** on a hot day. Therefore, the **DESIGN** contributes to the reduction of the Urban Heat Island Effect. The **STATUS QUO** emits **+0.238°C** heat to the surroundings in the daily average.

Thermal Comfort Score (TCS)

The **DESIGN** of the project area shows a **good thermal comfort** with **64.15 TCS** in the daily average. This means that large areas with high thermal comfort are ensured on a heat day. In comparison to the **STATUS QUO** with **29.34 TCS** there is a significant improvement of the thermal comfort in the project area.

Thermal Storage Score (TSS)

With a thermal storage capacity of **2.98 GJ** in the **DESIGN**, a notable reduction could be achieved by the use of facade and roof greening, compared to the **STATUS QUO** with **4.28 GJ**. This is remarkable since the area of building structures was approximately doubled in the **DESIGN**.

Run-off Score (ROS)

The run-off score was improved from **0.73** in **STATUS QUO** to **0.35** in the **DESIGN** due to greening measures and unsealing of the surfaces in the project area. This means that instead of **73%** of the rainwater, only **35%** runs off - the rest can now soak into the ground, be stored and evaporate.

CO_2 Sequestration Score (CSS)

The carbon sequestration score (CSS) was significantly increased due to the planned greening measures. In the **DESIGN**, **350.29 t CO_2** is stored during the lifetime of the plants which is more than three times as much as in the **STATUS QUO** with **107.04 t**.

The following graphics visualize the Thermal Comfort Score in the daily course and the area distribution of PET classes for every hour on a heat day from 9 a.m. to 6 p.m.

STATUS QUO

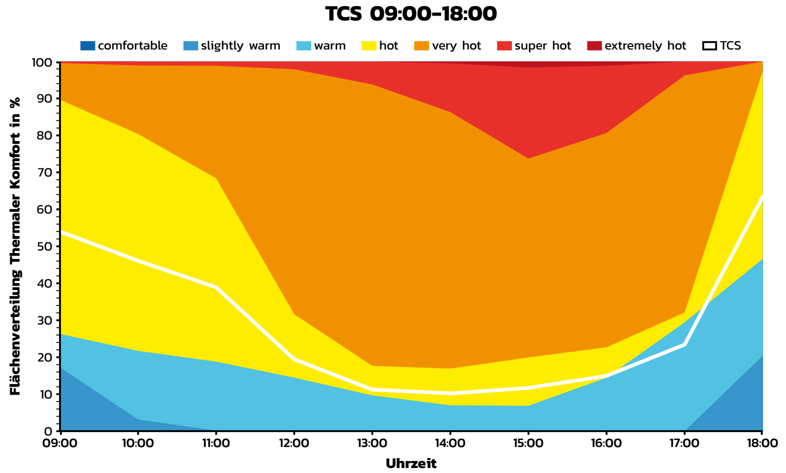


Figure 42 Status Quo - PET distribution and TCS timeline

DESIGN

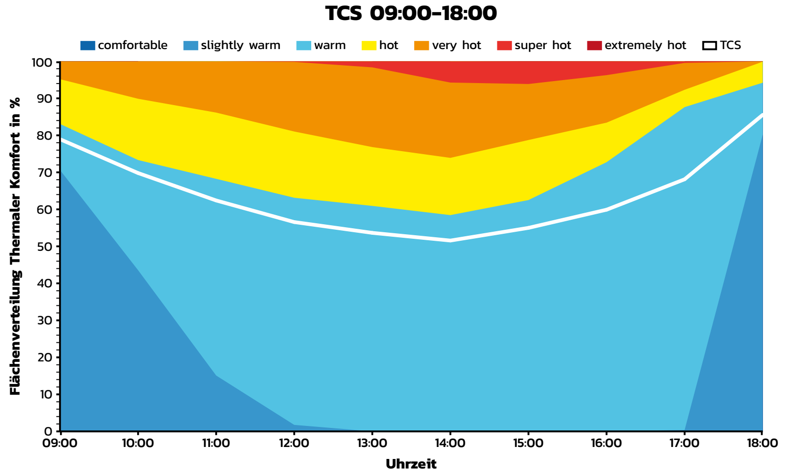


Figure 43 Design - PET distribution and TCS timeline

WORST CASE

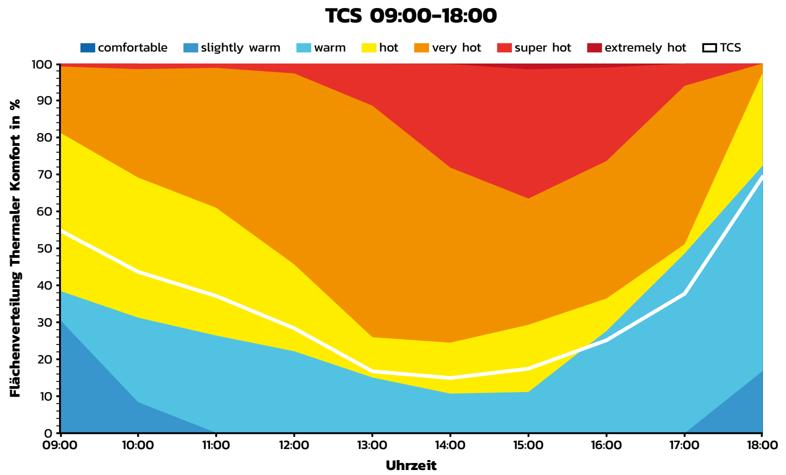


Figure 44 Worst Case - PET distribution and TCS timeline

6.4.3 PET heat maps - Thermal Comfort

The Thermal Comfort Map shows the spatial distribution of thermal-physiological stress classes in a project area and its surroundings. A climate-resilient design mainly shows areas with good thermal comfort. Areas with very low thermal comfort are classified as hot-spot areas. Large hot-spot areas have a negative impact on the quality of stay. Therefore, it is important to ensure sufficient shading for open spaces such as resting areas, children's playgrounds, and entrance areas to avoid high thermal stress on heat days. The graphical display of the perceived temperature helps to identify and locate potential problematic hot-spot areas and makes it possible to counteract with targeted measures.

The PET maps for 3 p.m. show the impact of green infrastructure in the design on. At this hour statistically the highest air temperatures are measured on a heat day. The areas with high thermal comfort at the project site predominate the areas with low thermal comfort. In addition, the shading by trees and green pergolas avoids large hot-spot areas as they occur in the status quo and worst case scenario. Additional trees along adjacent streets also lead to a higher thermal comfort in the surrounding areas.

The diagrams show the percentage of the project area within the measured PET categories according to the heat maps at 3 p.m. This visualization simplifies the interpretation of heat maps.

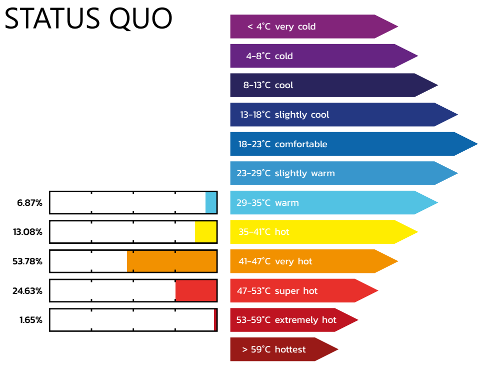


Figure 45 Status Quo - PET distribution 3 p.m.

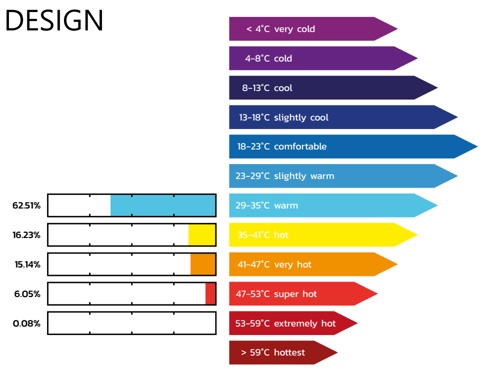


Figure 46 Design - PET distribution 3 p.m.

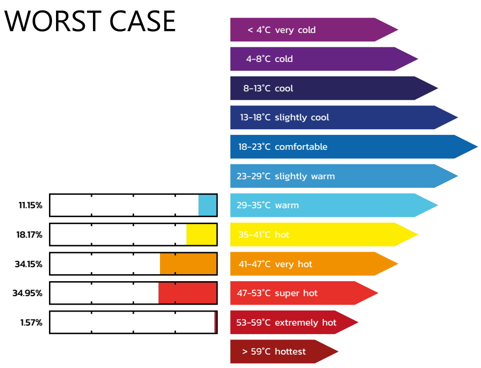
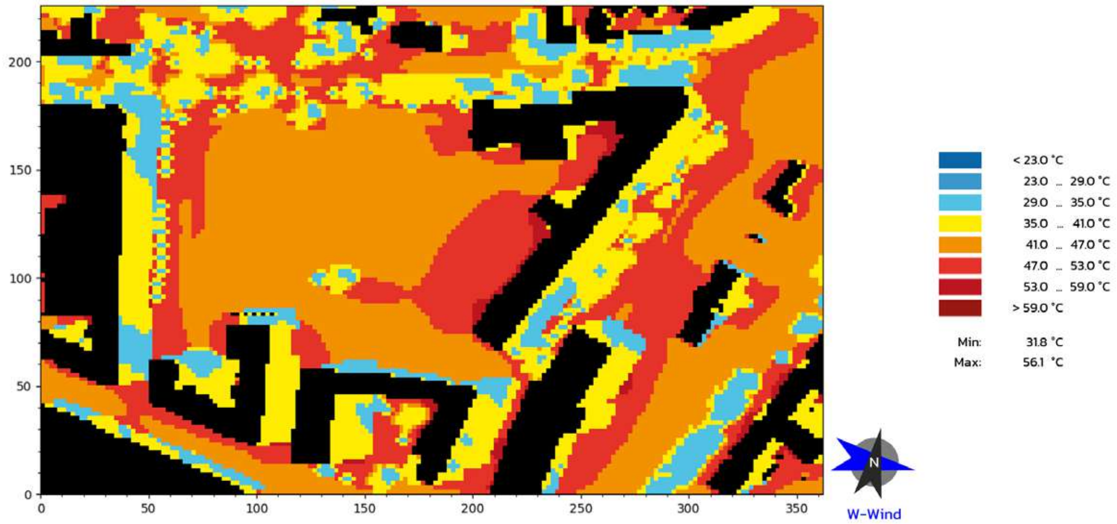
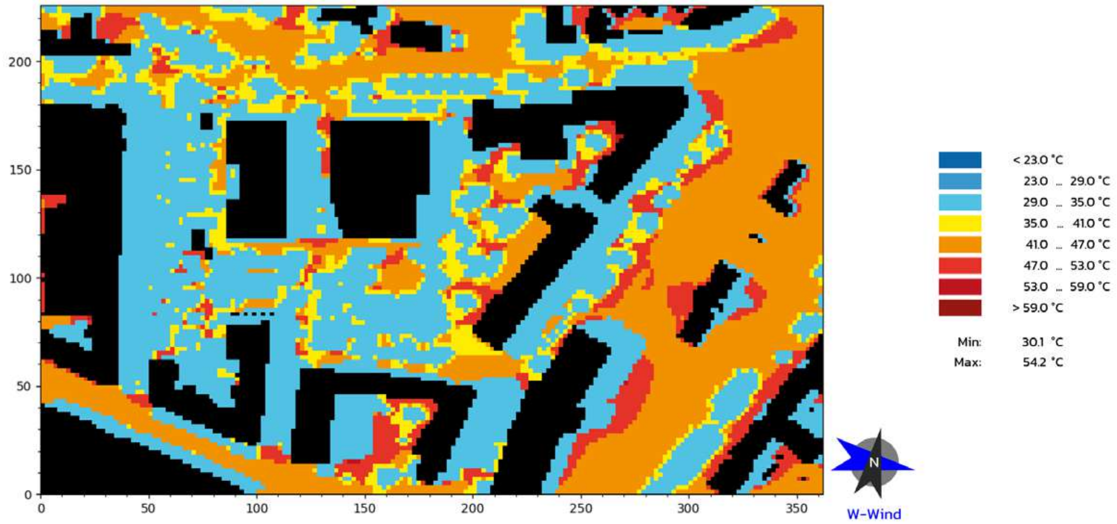


Figure 47 Worst Case - PET distribution 3 p.m.

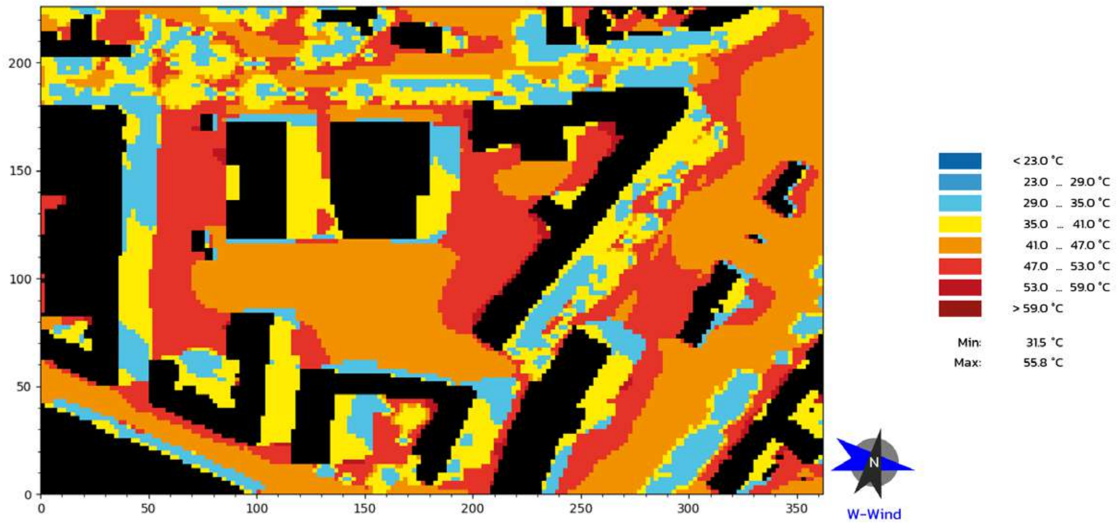
Urban Green School | SQ | PET 3 p.m. | h = 1.50 m



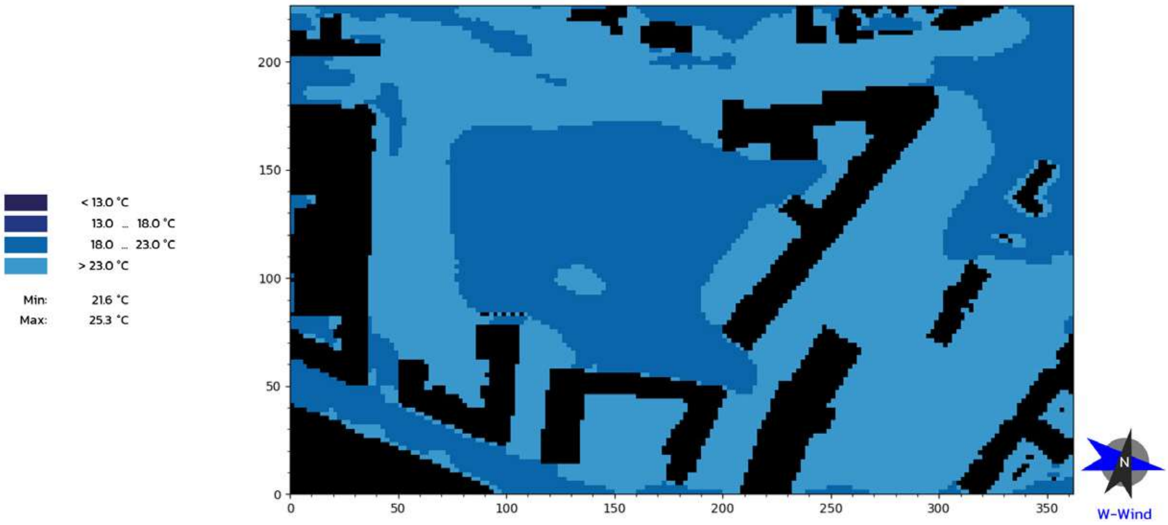
Urban Green School | PLAN | PET 3 p.m. | h = 1.50 m



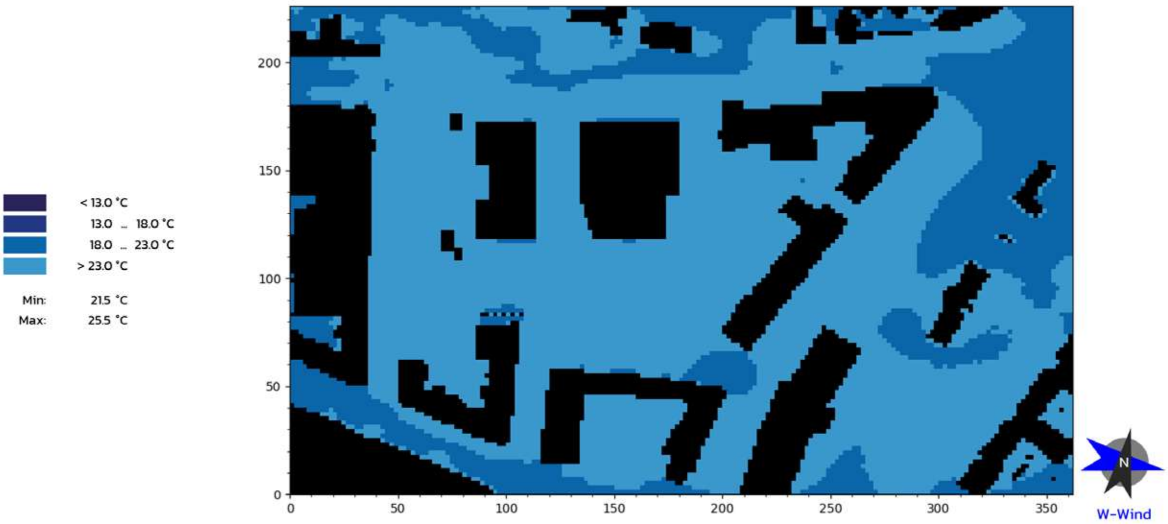
Urban Green School | WC | PET 3 p.m. | h = 1.50 m



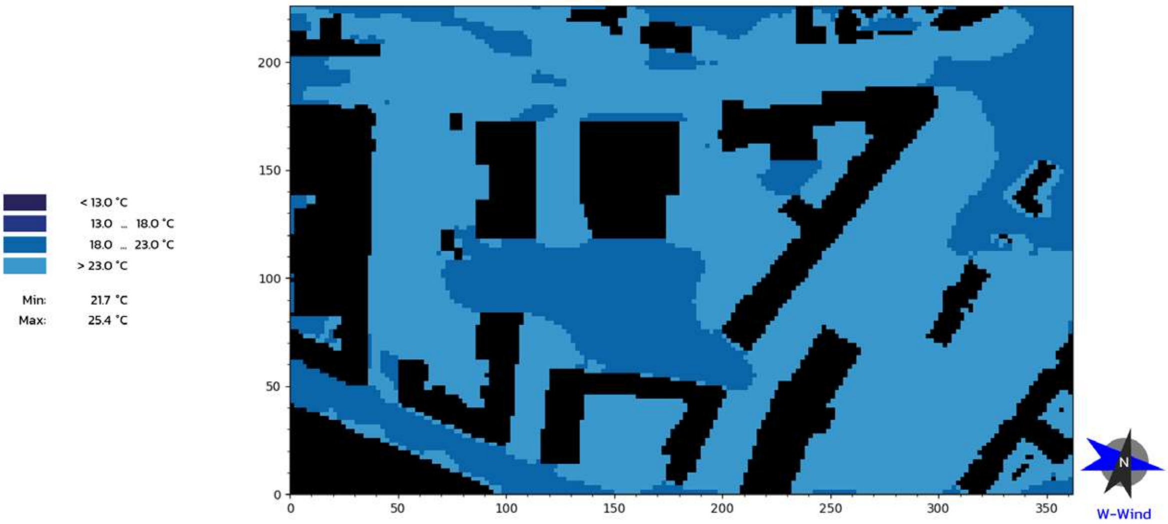
Urban Green School | SQ | PET 10 p.m. | h = 1.50 m



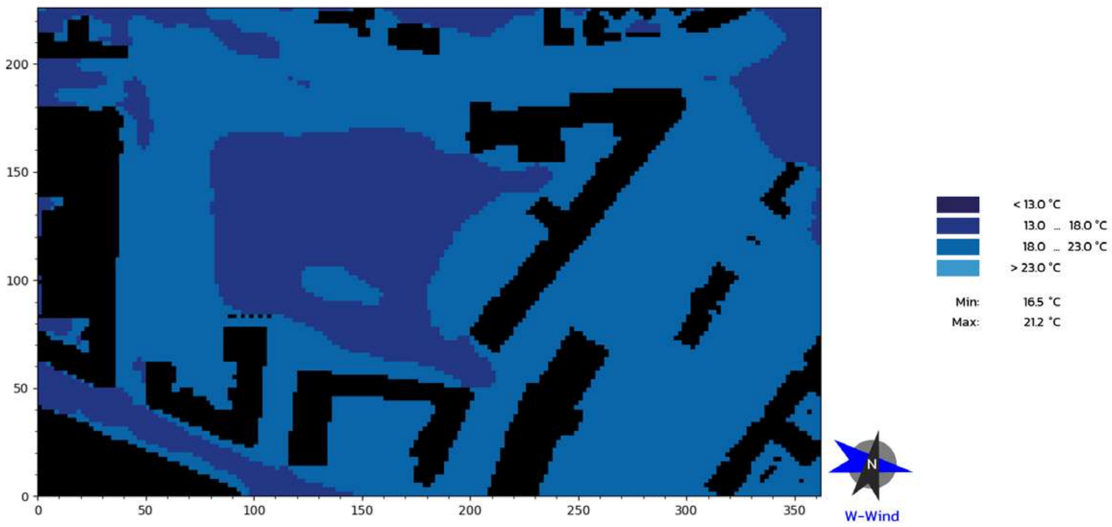
Urban Green School | PLAN | PET 10 p.m. | h = 1.50 m



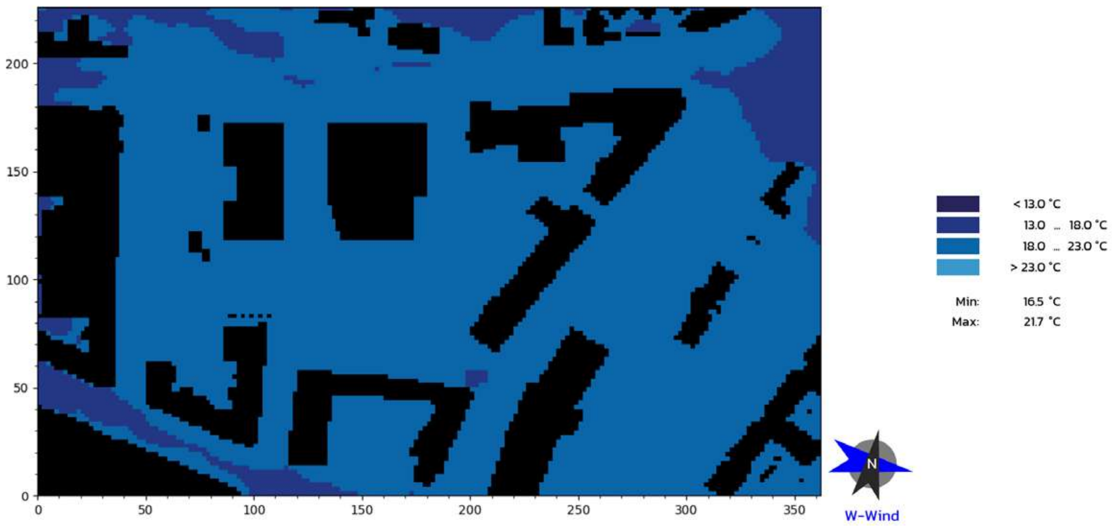
Urban Green School | WC | PET 10 p.m. | h = 1.50 m



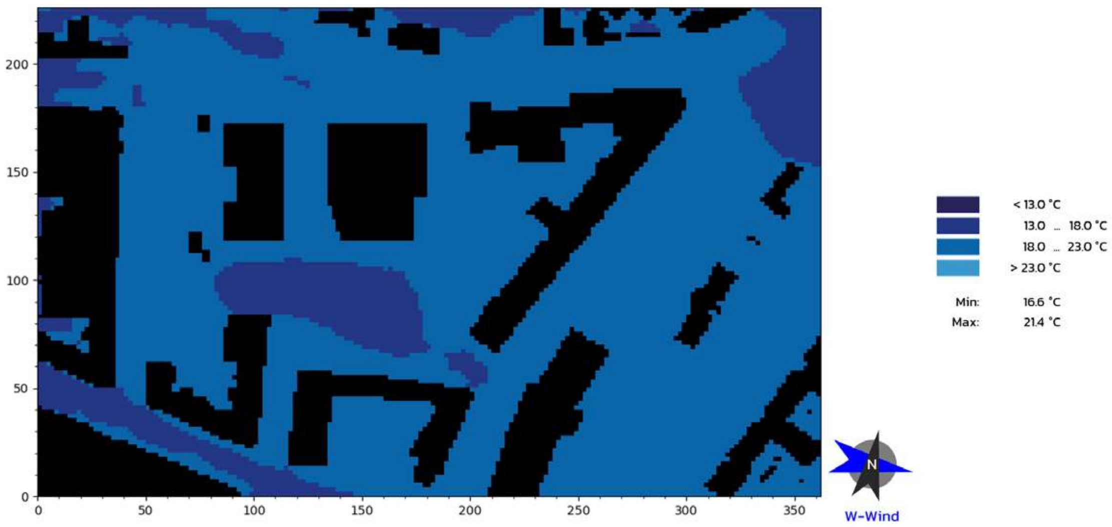
Urban Green School | SQ | PET 4 a.m. | h = 1.50 m



Urban Green School | PLAN | PET 4 a.m. | h = 1.50 m



Urban Green School | WC | PET 4 a.m. | h = 1.50 m



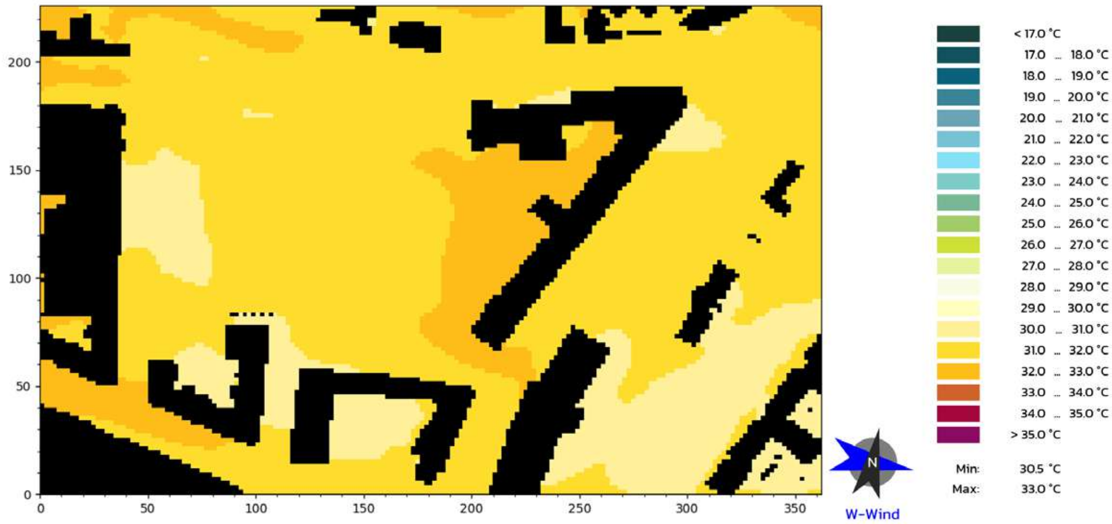
6.4.4 Heat maps - Air Temperature

The following heat maps visualize the air temperature of the project site and surrounding area on a heat day for the scenarios status quo, design and worst case. The values were calculated at the height of 1,5 m. The maps for 3 p.m. show the air temperature for the statistically most heated hour of the day. High temperatures lead to a higher absorption of heat in the surface materials, which amplifies the Urban Heat Island Effect. The maps for 10 p.m. and 4 a.m. are shown to visualize nighttime cooling, which is essential for minimizing heat waves and *tropical nights*.

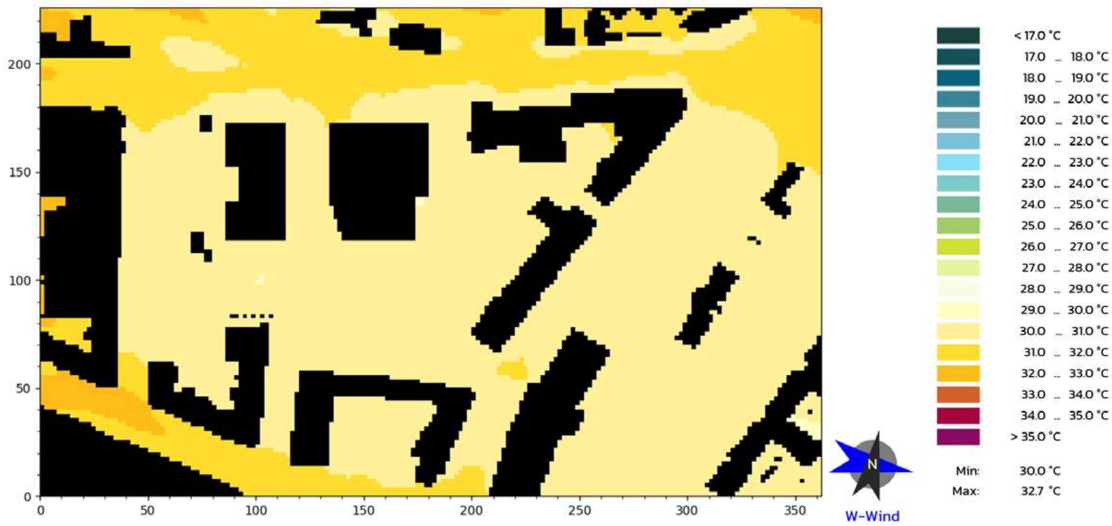
In regions with temperate climate conditions, a *tropical night* occurs on days when the air temperature does not cool down under 20°C during the night. The time span of the measurement is 6 p.m. to 6 a.m. UTC (DWD Wetterlexikon). *Tropical nights* are detrimental for human health and well-being and a risk to people with a high heat vulnerability.

The heat maps show that the cooling effect of green infrastructure in the design also improves the microclimate of the surrounding areas during the day and nighttime.

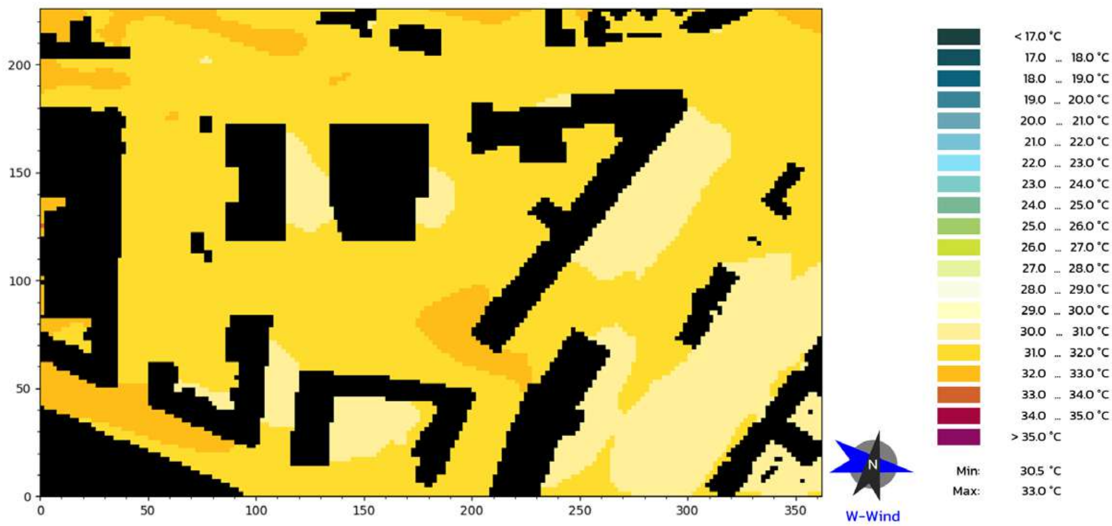
Urban Green School | SQ | Air Temperature 3 p.m. | h = 1.50 m



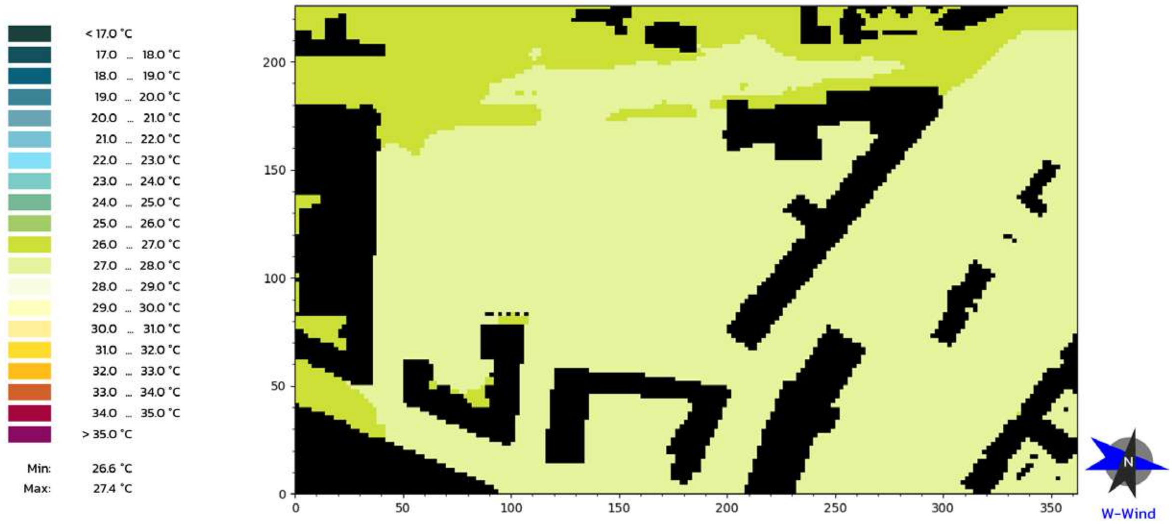
Urban Green School | PLAN | Air Temperature 3 p.m. | h = 1.50 m



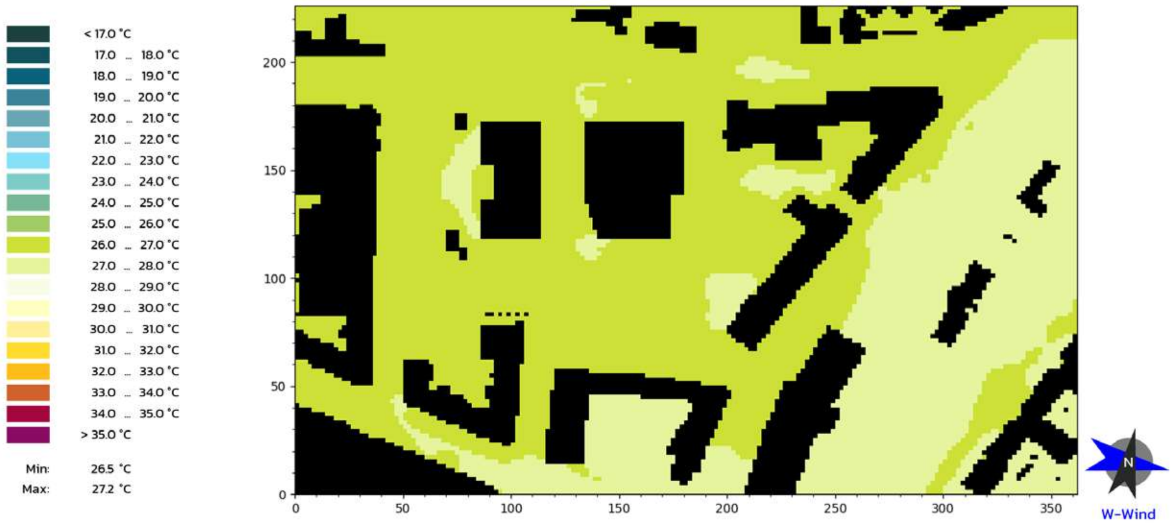
Urban Green School | WC | Air Temperature 3 p.m. | h = 1.50 m



Urban Green School | SQ | Air Temperature 10 p.m. | h = 1.50 m

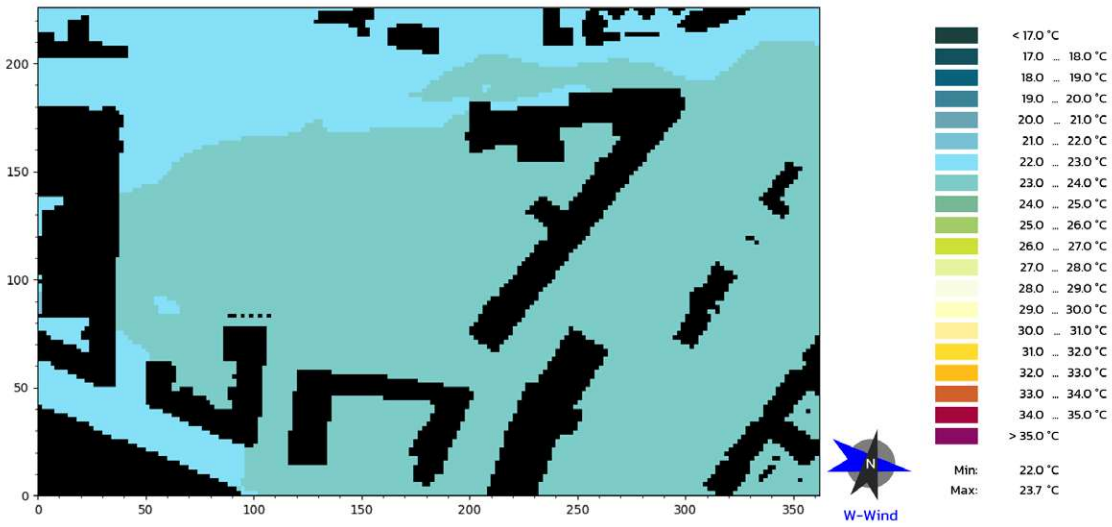


Urban Green School | PLAN | Air Temperature 10 p.m. | h = 1.50 m

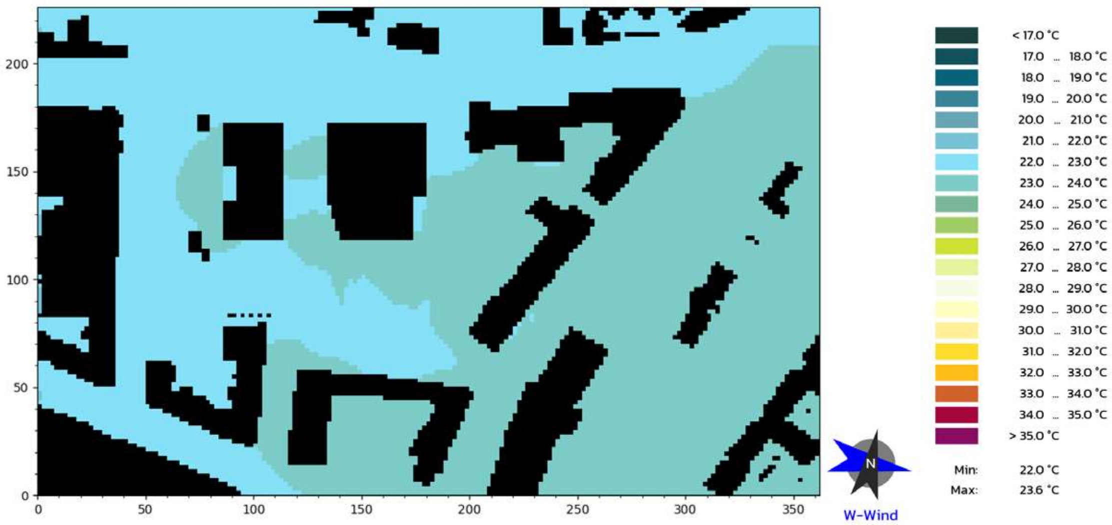


Urban Green School | WC | Air Temperature 10 p.m. | h = 1.50 m

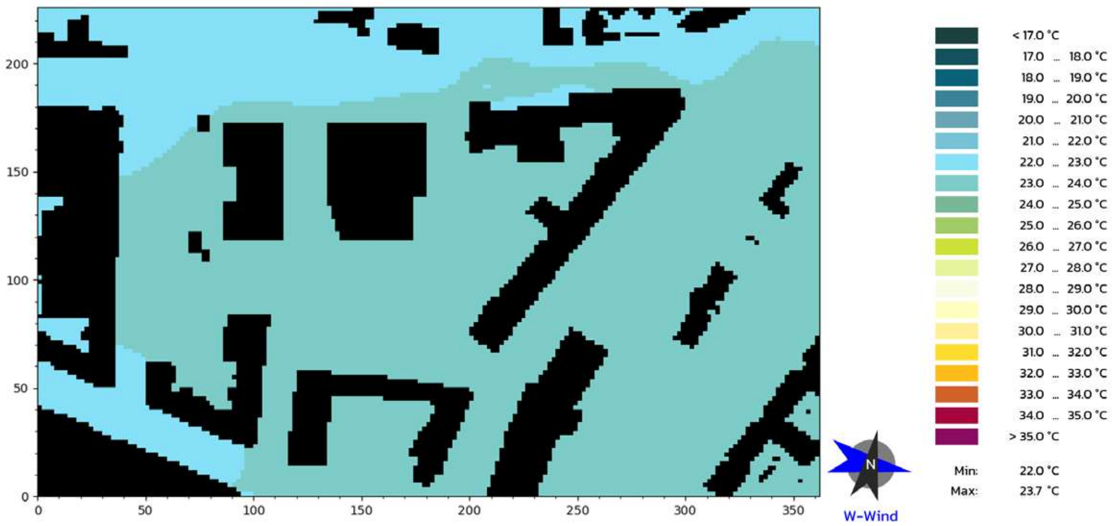
Urban Green School | SQ | Air Temperature 4 a.m. | h = 1.50 m



Urban Green School | PLAN | Air Temperature 4 a.m. | h = 1.50 m



Urban Green School | WC | Air Temperature 4 a.m. | h = 1.50 m



6.4.5 Wind Flow maps

The wind flow map illustrates the average wind field in the planning area on a hot day and shows wind speed and changes. To a certain degree, high wind speeds improve the thermal comfort, but can also reduce the quality of stay. Problematic venting effects can be identified. Passages and narrow gaps between buildings in the main wind direction can lead to wind nozzles. Wind comfort is especially important in the cold season. The wind speed shown in the maps is measured at a height of 1,5 m and can be higher on windy days.

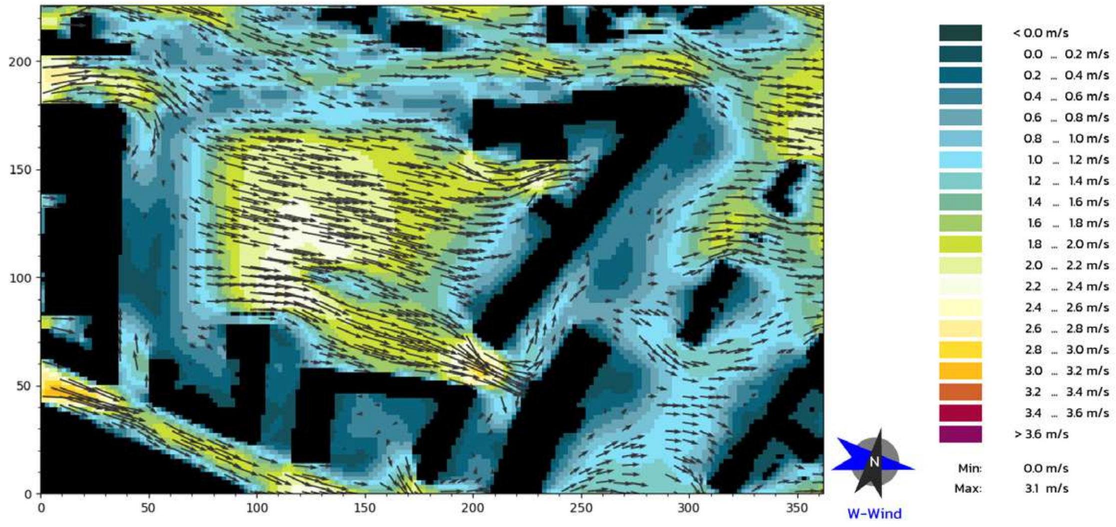
The wind flow maps for 3 p.m. show the reduction effect that green infrastructure has on the wind speed. Air ventilation of the project area is provided and at the same time resting and entrance areas are protected from higher wind speeds.

The "Beaufort Scale" (Table 16) is an empirical measure for estimating wind intensity based on visual observations. It was developed in 1805 by Sir Francis Beaufort in order to compare wind intensity in different locations on land and at sea and is still used to estimate wind strengths (NWS).

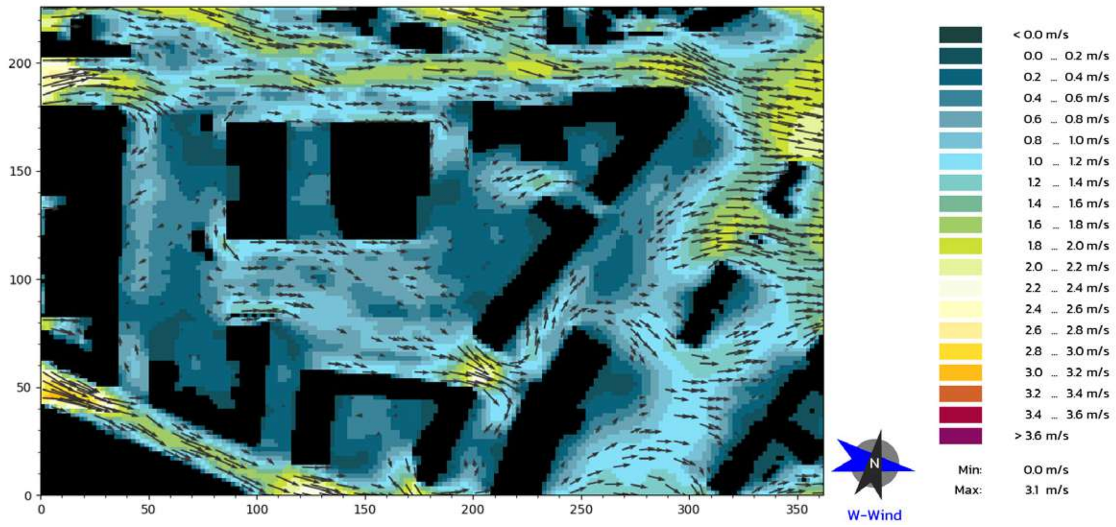
intensity	wind force speed (m/s)	description	specifications on land
0	0 - 0,2	calm	calm; smoke rises vertically
1	0,3 - 1,5	light air	direction of wind shown by smoke drift, but not by wind vanes
2	1,6 - 3,3	light breeze	wind felt on face; leaves rustle; ordinary vanes moved by wind
3	3,4 - 5,4	gentle breeze	leaves and small twigs in constant motion; wind extends light flag
4	5,5 - 7,9	moderate breeze	raises dust and loose paper; small branches are moved
5	8,0 - 10,7	fresh breeze	small trees in leaf begin to sway; crested wavelets form on inland waters
6	10,8 - 13,8	strong breeze	large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty
7	13,9 - 17,1	near gale	whole trees in motion; inconvenience felt when walking against the wind
8	17,2 - 20,7	gale	breaks twigs off trees; generally impedes progress
9	20,8 - 24,4	severe gale	slight structural damage occurs (chimney-pots and slates removed)
10	24,5 - 28,4	storm	seldom experienced inland; trees uprooted; considerable structural damage occurs
11	28,5 - 32,6	violent storm	very rarely experienced; accompanied by widespread damage
12	> 32,7	hurricane	

Table 16 Beaufort Wind Scale - specifications for use on land (NWS)

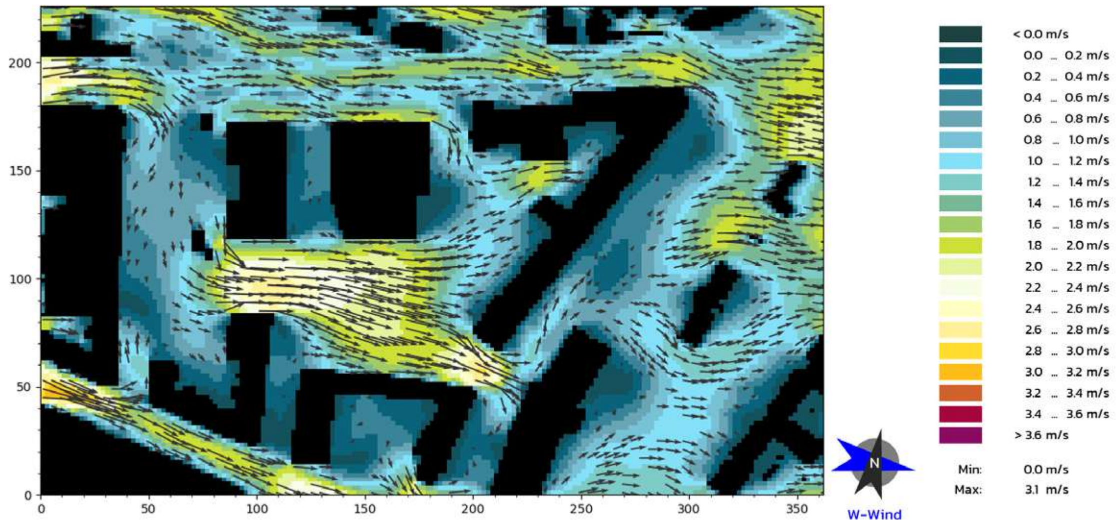
Urban Green School | SQ | Windspeed 3 p.m. | h = 1.50 m



Urban Green School | PLAN | Windspeed 3 p.m. | h = 1.50 m



Urban Green School | WC | Windspeed 3 p.m. | h = 1.50 m



6.4.6 Comparison

Design - Status Quo

The difference maps show differences between status quo and the design in PET and air temperature. The cooling effect of the design on the project area and surroundings is clearly visible compared to the status quo scenario.

The comparison of the scenarios also shows an improvement in the Key Performance Indicators, as described in the following.

climate
water
air
biodiversity
energy

up to **-2.3 °C**
air temperature

up to **-23 °C**
perceived temperature

+35 TCS
score points

+38 %
rainwater infiltration

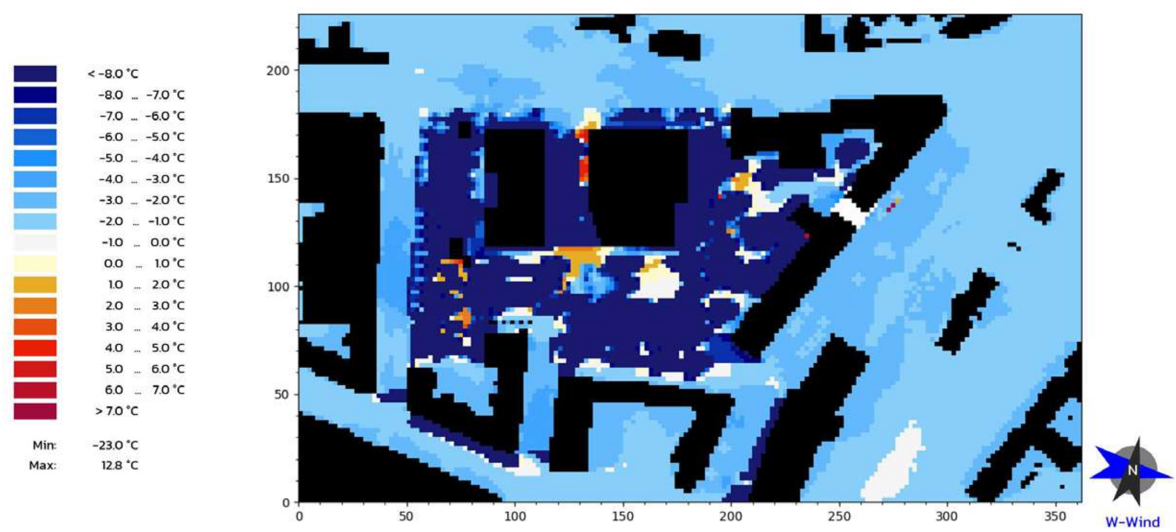
+42 %
unsealed area

more than **3x**
CO_2 storage

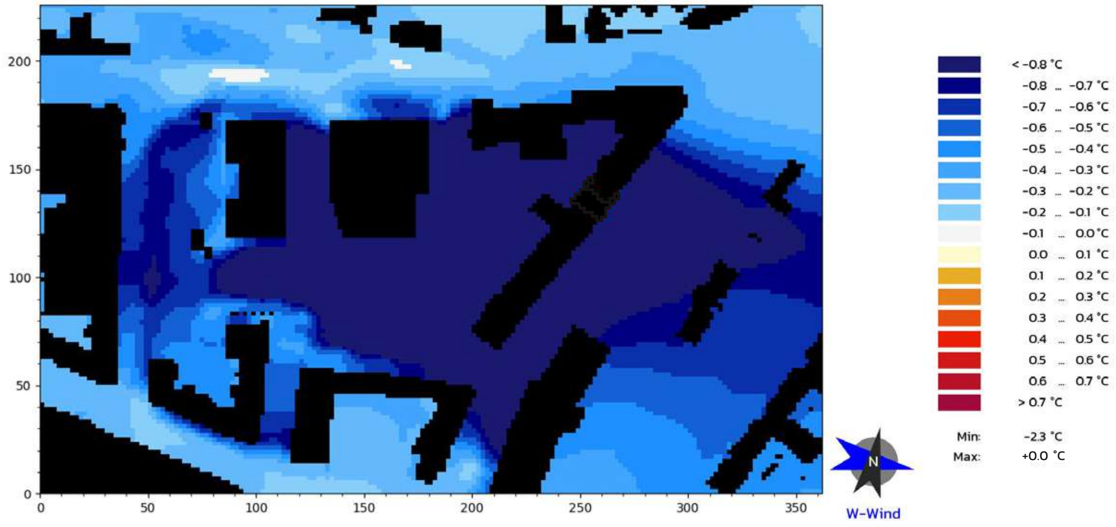
more than **10x**
leaf area

less than **1.4x**
thermal storage

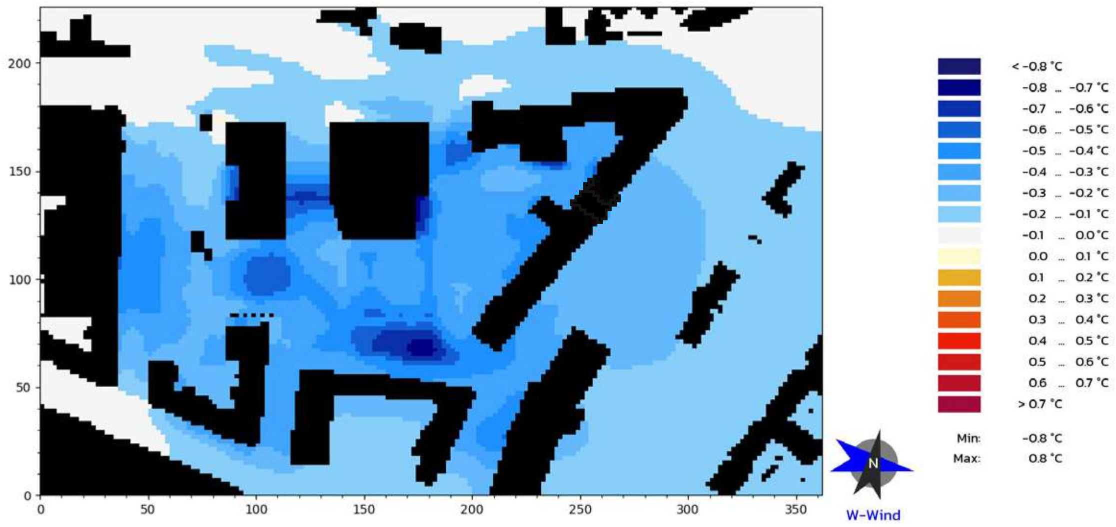
Urban Green School | PLAN-SQ | PET Difference 3 p.m. | h = 1.50 m



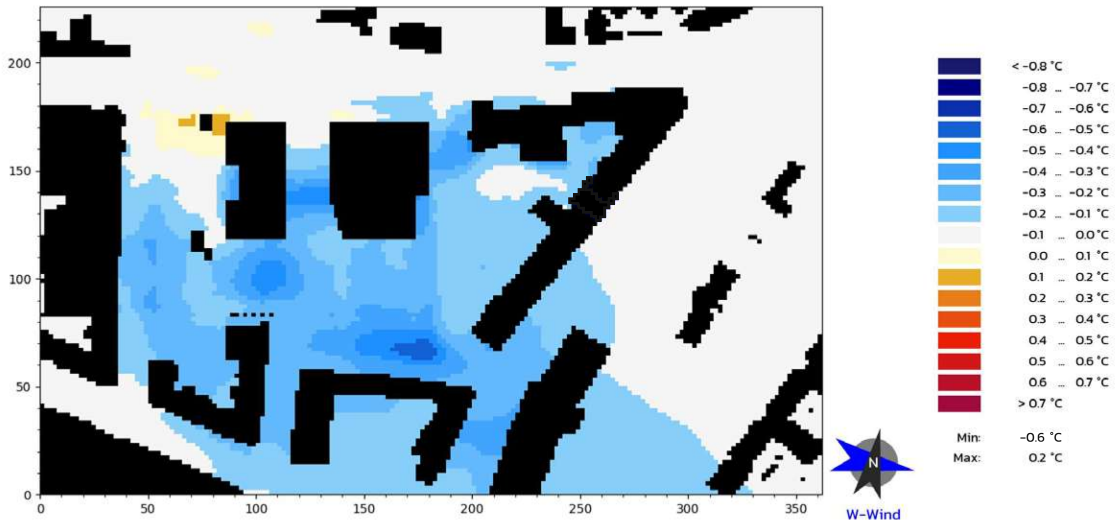
Urban Green School | PLAN-SQ | Air Temperature Difference 3 p.m. | h = 1.50 m



Urban Green School | PLAN-SQ | Air Temperature Difference 10 p.m. | h = 1.50 m



Urban Green School | PLAN-SQ | Air Temperature Difference 4 a.m. | h = 1.50 m



Design - Worst Case

The difference maps show differences between the worst case and the design in PET and air temperature. The cooling effect of the design on the project area and surroundings is clearly visible compared to the worst case scenario.

The comparison of the scenarios also shows an improvement in the Key Performance Indicators, as described in the following.

climate
water
air
biodiversity
energy

up to **-1.9 °C**
air temperature

up to **-22 °C**
perceived temperature

+30 TCS
score points

+54 %
rainwater infiltration

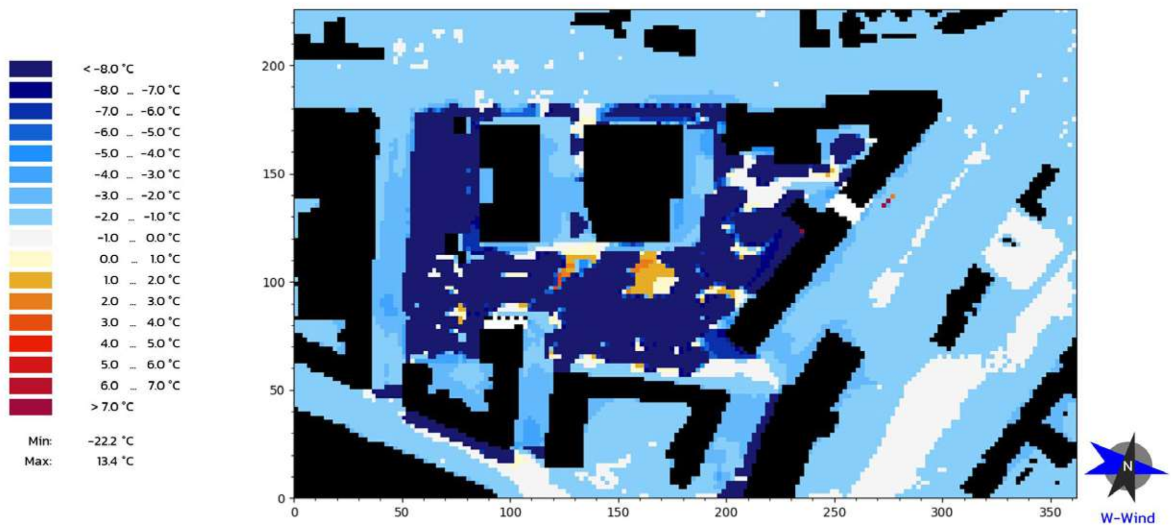
+80 %
unsealed area

+350 t
CO_2 storage / lifetime of plants

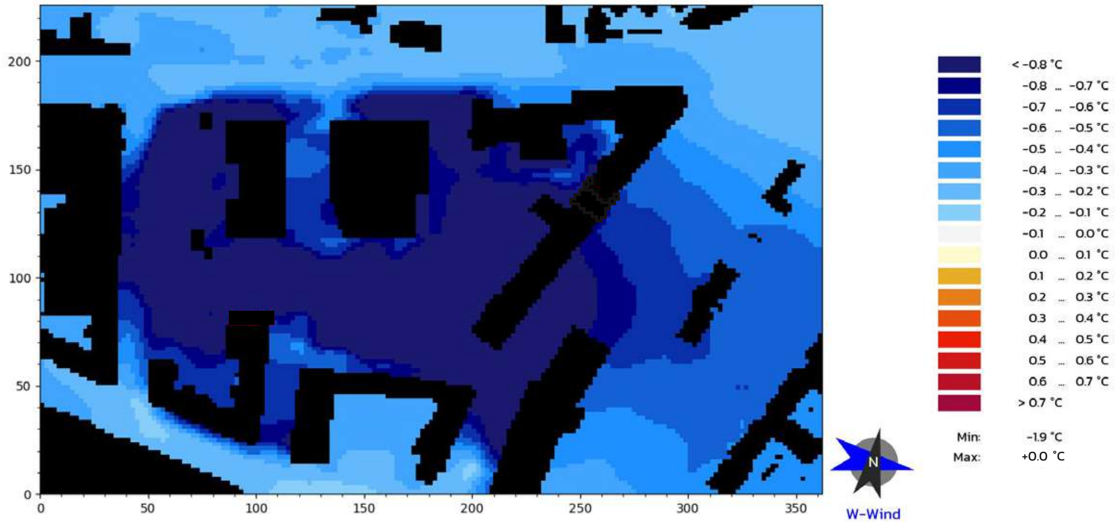
+ 11 ha
leaf area

less than **1.8x**
thermal storage

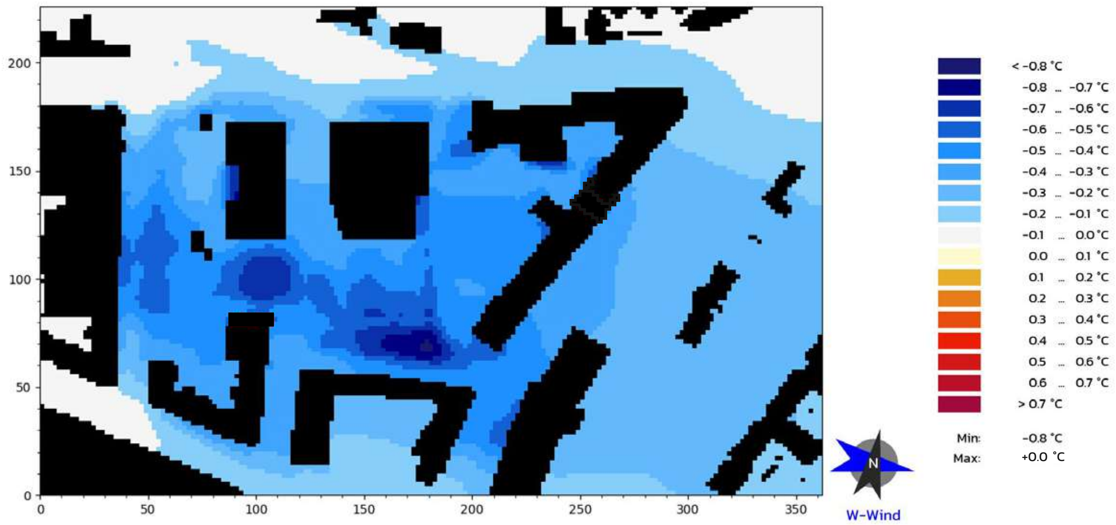
Urban Green School | PLAN-WC | PET Difference 3 p.m. | h = 1.50 m



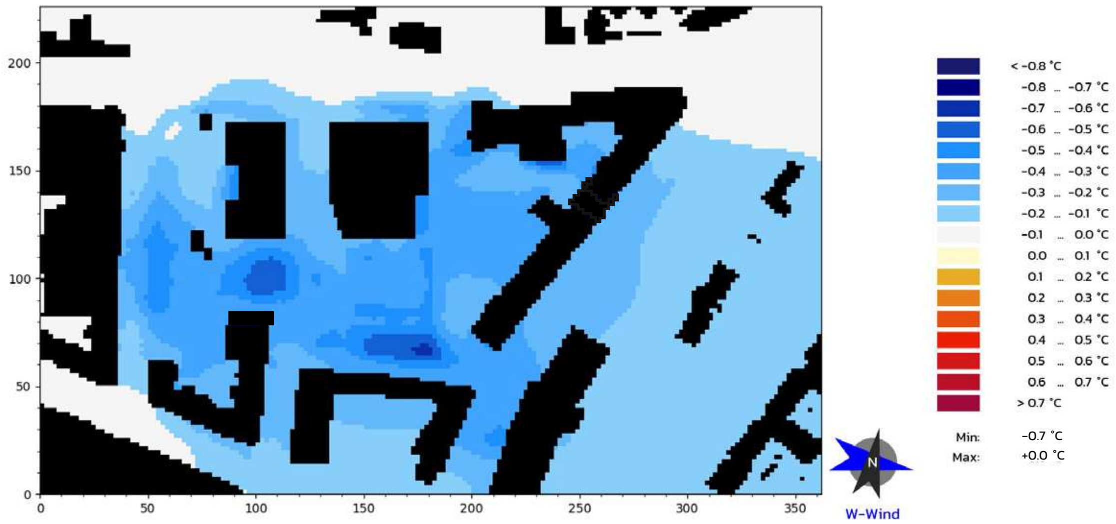
Urban Green School | PLAN-WC | Air Temperature Difference 3 p.m. | h = 1.50 m



Urban Green School | PLAN-WC | Air Temperature Difference 10 p.m. | h = 1.50 m



Urban Green School | PLAN-WC | Air Temperature Difference 4 a.m. | h = 1.50 m



07 CONCLUSION

This project started with the aim to investigate the potential of greening strategies to reduce the Urban Heat Island effect on a selected site in Vienna. A school was selected as a suitable typology for exploring and demonstrating the effect of intense greening measures. The *Urban Green School* concept addresses a variety of challenges in improving quality of life in cities. By combining education and environment, a broader scope for implementing urban green infrastructure in construction projects is created. Schools have a high potential to raise the awareness of local communities and society about the importance of ensuring a healthy environment for humans and increasing biodiversity, and more specifically reducing the Urban Heat Island effect. The question how microclimate and climate resiliency are influenced by greenery is addressed by the research. The insights are related to selecting specific Key Performance Indicators (KPIs) that have a major impact on microclimate and thermal comfort and the way in which these can be modified by greening interventions and design strategies. From the findings of the research and case studies, a greening concept was developed to be implemented in the design project.

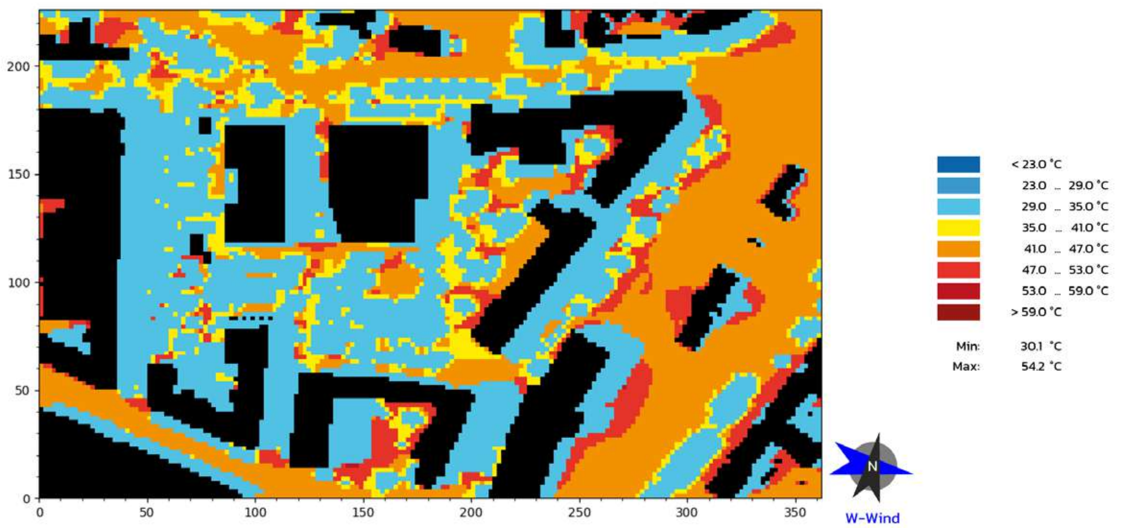
Suitable tools were needed to show the impact of the greening concept in a practical and design-related way. Microclimate simulation and environmental evaluation tools enable calculating and visualizing the impact of green infrastructure, as well as comparing the specific performances of different design scenarios. The estimation of a design's expected performance makes it possible to optimize performance in the early project stage, and saves costs and resources for subsequent adaptations. Potential amplifying factors of the Urban Heat Island effect can be detected in time and counteracted by green infrastructure integrated in urban planning and architectural solutions. The question of maintenance of the school's vegetation and green spaces was approached by including the neighborhood in the projected use, as well as by adaptation of existing buildings. By increasing the range of involved stakeholders, maintenance can be ensured during school holidays. In addition, participation of the city department of gardening would be conceivable.

The analysis of the simulation results clearly shows the potential of greening measures in reducing the Urban Heat Island effect. However, simulations can only show a simplified version of the reality. The actual degree of improvement needs to be investigated and validated through realized projects. The real size of the planted trees for example makes a major difference, i.e. whether the simulated thermal comfort can be reached immediately after the construction of the project is completed or only after some years. Empirical values can be used to increase the accuracy of the simulation to assist planners in selecting the optimal position and crown diameters of the plants in consideration of thermal comfort, vegetative aspects, open space use, and financial budget.

Although the assumption of the improvement of the microclimate by greening measures was confirmed by the carried out simulations, some results were different than expected. The Physiological Equivalent Temperature (PET) heat map for 3 p.m. shows largely areas with a high thermal comfort as a result of intense greening measures. However, in between places with a lower thermal comfort class still appear. The cast shadow of the buildings plays a key role for thermal comfort. Therefore, the orientation and urban structure of the surroundings have a major impact on thermal performance on site. The simulation supported assessment of the impact of building shadows and optimization of greening measures to improve thermal comfort.

The consideration whether modifications of the design are necessary to increase thermal comfort for specific areas must be weighed with other relevant parameters including the effect on wind flow and resulting restrictions in the use of open space. In practice this discourse would be conducted in interdisciplinary teams including experts from architecture, landscape design, and urban climate.

Urban Green School | PLAN | PET 3 p.m. | h = 1.50 m



At city level the *Urban Green School* concept can be applied in several locations across all districts to reduce the Urban Heat Island effect on a larger scale. This expands and intensifies the network of urban green infrastructure through educational facilities. The greening concept is adaptable depending on location, type and size of the school. To increase the number of involved schools, existing schools can also be included in the *Urban Green School* concept by implementing intensive greening measures.

In addition to constructional solutions and adaptation measures there is a need for adequate maintenance of *Urban Green Schools*. The success factors for a sustainable maintenance are knowledge, resources, and a participative coordination strategy. To gain knowledge, *Urban Green Schools* should include theory and practice in environmental education and urban gardening into their schedule. Learning networks for exchange between *Urban Green Schools* are necessary for collaboration on environmental, social and educational level. To provide resources and an appropriate coordination strategy, decision makers including city administration and municipal education authority should support *Urban Green Schools* to achieve affordable and social acceptable solutions for the schools and their neighborhood.

The approach is however not limited to schools. Knowledge gained in the *Urban Green Schools* approach can also be applied to other urban typologies and thereby promote climate resilient design and accelerate the development of green cities.

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8.1.2 Figures

Figure 1: thermal image of the city of Vienna and surrounding countryside in the evening
Source: BRANDENBURG, C., DAMYANOVIC, D., FLORIAN REINWALD, ALLEX, B., GANTNER, B., CZACHS, C., MORAWETZ, U., KÖMLE, D. & KNIEPERT, M. 2018. Urban Heat Island Strategy - City of Vienna. MA22. Vienna. *p.8*

Figure 2: Urban Heat Vulnerability Index Map for Vienna
Source: Stadt Wien (energie.wien.gv.at), ECOTEN, OpenStreetMap (2019) [Online.]
Available: https://wien.orf.at/stories/3007530/ [Accessed 16.05.2021]

Figure 3: schematic illustration of increased temperature in the urban area
own illustration, based on OKE, T.R. 1987. Boundary layer climates. and ZAFRIR-REUVEN, O. 2017.
Source: HIEMSTRA, J. A., SAARONI, H. & AMORIM, J. H. 2017. The Urban Heat Island: Thermal Comfort and the Role of Urban Greening. In: PEARLMUTTER, D., CALFAPIETRA, C., SAMSON, R., O'BRIEN, L., KRAJTER OSTOIC, S., SANESI, G. & DEL AMO, R. A. (eds.) The Urban Forest, Cultivating Green Infrastructure for People and the Environment. Springer. *p. 9*

Figure 4: sponge city principle
own illustration, based on 3:0 Landschaftsarchitektur
Source: DRLIK, S. & ÖGLA 2019. Das Schwammstadt-Prinzip: klimawirksame Baumsysteme schaffen. architektur.aktuell 468. *p. 26*

Figure 5: main GI typologies as a combination of different vegetation layers, ground surfaces and building structures
own illustration, based on Bartesaghi Koc et al. (2016)
Source: BARTESAGHI KOC, C., OSMOND, P. & PETERS, A. 2016. A green infrastructure typology matrix to support urban microclimate studies. 4th International Conference on Countermeasures to Urban Heat Island. National University of Singapore. *p. 7*

Figure 6: examples of Green Infrastructure integrated into an urban landscape
own illustration, based on UK Green Building Council (2015) and Arup (2014)
Source: UK GREEN BUILDING COUNCIL 2015. Demystifying Green Infrastructure. London. *p. 5*

Figure 7: Waldschule Charlottenburg, Germany, classroom and dining sheds (1908)
Photo: unknown artist
Original source: KRAFT, A. 1908. Waldschulen. Orell Füssli. Zürich.
Source: CHÂTELET, A.-M. 2008. A Breath of Fresh Air - Open Air Schools in Europe. In: GUTMAN, M. & CONINCK-SMITH, N. D. (eds.) Designing Modern Childhoods: History, Space, and the Material Culture of Children. Rutgers University Press. *p. 110*

Figure 8: escuela del bosque, Barcelona, indoor classroom (1918)
Photo: unknown artist
Source: DOVEL. 2014. 100 años de la ,escola de bosc. Barcelona, ahora y siempre [Online]. Available from: http://orgullosademiciudad.blogspot.com/2014/05/100-anos-de-la-escola-de-bosc.html [Accessed 28.04.2021].

Figure 9: escuela del bosque, Barcelona, outdoor classroom (1918)
Photo: unknown artist
Source: DOVEL. 2014. 100 años de la ,escola de bosc. Barcelona, ahora y siempre [Online]. Available from: http://orgullosademiciudad.blogspot.com/2014/05/100-anos-de-la-escola-de-bosc.html [Accessed 28.04.2021].

Figure 10: École de plein air de Suresnes, overview and pavillions
Photos: unknown artist
Source: BEAUDOUIN, E. & LODS, M. 1943. Ecole en plein air à Suresnes (Paris) 1935/36. L'oeuvre : architecture et art, 30, 186. Available: http://doi.org/10.5169/seals-24281 [Accessed 15.05.2020]

Figure 11: test pavillion, Frankfurt am Main (1929/1930)
Photo: unknown artist
Source: LORBEK, M. & STOSCH, G. 2003. Schulen bauen, Schulen sanieren. In: ÖSTERREICHISCHE GESELLSCHAFT FÜR ARCHITEKTUR (ed.) ALTE (UN)BEKANNTE Architekturstiftung Österreich.

Figure 12: Freiluftschule Floridsdorf, Vienna (1961)
Photo: unknown artist
Source: LORBEK, M. & STOSCH, G. 2003. Schulen bauen, Schulen sanieren. In: ÖSTERREICHISCHE GESELLSCHAFT FÜR ARCHITEKTUR (ed.) ALTE (UN)BEKANNTE Architekturstiftung Österreich.

Figure 13: École des Sciences et de la Biodiversité, roof gardening and terraces
Photos: Myr Muratet, Takuji Shimmura, Cyrille Weiner
Source: DERAMOND, S. 2017. Biodiversité et architecture, Le groupe scolaire de Boulogne-Billancourt. 16th meeting of the U2B club, Insights on the integration of biodiversity in schools. Ecole des Sciences et de la Biodiversité (Boulogne Billancourt): Chartier Dalix architects.

Figure 14: Groupe scolaire à Rillieux-la-Pape, roof greening
Photos: Renaud Araud and Tectoniques
Source: TECTONIQUES 2013. Groupe scolaire à Rillieux-la-Pape (69). Architecture nature. Tectoniques Architecture & Ingénierie. *p. 2, 5*

Figure 15: GRG 7, facade greening system
Photo: unknown artist
Source: KORJENIC, A., TUDIWER, D., MOREN, M. S. P., HOLLANDS, J., SALONEN, T., MITTERBÖCK, M., PITHA, U., ZLUWA, I., STANGL, R., KRÄFTNER, J., GUMP, K. & BECKER, G. 2019. Hocheffiziente Fassaden- und Dachbegrünung mit Photovoltaik-Kombination. Berichte aus Energie- und Umweltforschung. *p. 47*

Figure 16: GRG 7, facade greening climbing plants
Photo: TU Wien
Source: BMK Infothek. 2019. Grün statt grau: Wie lebendige Fassaden wachsen [Online]. Available from: https://infothek.bmk.gv.at/gruen-statt-grau-wie-lebendige-fassaden-wachsen/ [Accessed 17.05.2021].

Figure 17: Oberland Realschule Holzkirchen, vegetated landscape plate
Photo: Stefan Müller-Naumann, rheinpark_Architekten
Source: rheinpark_r. Realschule - Grundschule - Dreifachsporthalle Holzkirchen 2005 – 2002 [Online]. Available from: https://www.rheinpark.org/index.php?id=2005realschuleholzkirchen [Accessed 17.05.2021].

Figure 18: tour de la biodiversité
Photo: Pierre L'Excellent, 2016
Source: MEF. Tour de la biodiversité [Online]. Available from: https://www.edouardfrancois.com/projects/tour-de-la-biodiversite [Accessed 17.05.2021]

Figure 19: tour de la biodiversité
Photo: Nicolas Janberg, 2018
Source: structurae. Tour de la biodiversité [Online]. Available from: https://structurae.net/de/medien/297224-tour-de-la-biodiversite [Accessed 17.05.2021]

Figure 20: Calhoun School, Green Roof Learning Center
Photo: Beth Krieger, 2005
Source: GREENROOFS.COM. Calhoun School Green Roof Learning Center [Online]. Available from: https://www.greenroofs.com/projects/calhoun-school-green-roof-learning-center/ [Accessed 17.05.2021]

Figure 21: Calhoun School
Photo: unknown artist
Source: Sciame. Calhoun School [Online]. Available from: https://sciame.com/portfolio/calhoun-school/ [Accessed 17.05.2021]

Figure 22: Pine Jog school property
Photo: unknown artist, 2013
Source: Zyscovich Architects. Pine Jog Elementary & FAU EEC [Online]. Available from: http://www.zyscovich.com/project/23-58-pine-jog-elementary--fau-eec [Accessed 05.07.2020]