COOLING THE STREETS OF CAIRO

DESIGNING CLIMATE-ADAPTIVE STREETSCAPES IN UNPLANNED URBAN AREAS IN ARID CLIMATES

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Designing climate-adaptive streetscapes in unplanned urban areas in arid climates

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ABSTRACT

Urban Heat Islands (UHI) and the resulting heat stress poses a serious threat to the livelihood of urban populations. This issue affects many residents of unplanned urban areas in arid climates and will be intensified by rising global temperatures. Yet only few research projects focus on measures to regulate microclimates in these neighborhoods. This research therefore aims to explore the potential of the implementation of climate-adaptive interventions within the Shubra district in Cairo. To do so, a research for design (RFD) approach is applied to develop a toolbox, containing effective and feasible climate-adaptive design interventions. A research through design (RTD) approach is then employed to test the feasibility and effectiveness of these interventions within representative street typologies, resulting in different design prototypes. To test the applicability of the prototypes within the study area, a site-specific design is developed.

The 16 climate adaptive interventions selected for the toolbox affect the urban microclimate through one of the three identified cooling strategies: adaptation of urban materials, implementation of shade, increasing evaporative cooling. The application of these interventions within the identified street typologies showed, that within narrow street profiles the number and scale of interventions is limited due to limited space. Additionally, non-flexible interventions and vegetation can lead to heat trapping and reduce ventilation. In the other typologies (medium and wide streets, open spaces) the implementation of interventions is primarily limited by their functionalities (e.g., mobility, economic activity). The design introduces pocket parks with a high cooling potential in the most frequented areas, connected by a network of cool streets. Interventions are designed as flexible as possible to reduce potential heat trapping and locally adapted plant species are chosen to reduce irrigation requirements. This explorative study describes the potential of climate adaptive interventions to reduce heat stress in unplanned areas. Further research will though be needed to quantify these cooling effects (modeling) and further evaluate feasibility together with residents.

PREFACE

This thesis forms the final part of my master's degree in landscape architecture at Wageningen University. Over the course of this research, I got the chance to acquire an in-depth understanding of climate-adaptive design interventions and their potential to regulate urban microclimates. The process of then integrating these interventions in an unplanned urban area in Cairo has posed challenges related to data availability and accessibility, but also allowed me to reflect on key aspects of what it means to be a designer.

Having grown up and studied in the Netherlands, I am used to the fact that public space is designed and has a clearly assigned purpose. A park for example serves for recreation and a road is primarily used to satisfy mobility needs. This is different in the case of streetscapes in central Cairo, and even more so within the unplanned Shubra district. Here it is the residents that form public space. Streetscapes are dynamic and serve a multitude of functions such as commercial activity, different forms of mobility and social interaction to just mention a few. This is off course not as dualistic as described here, with multifunctionality also being a fact in the Netherlands and aspects of streetscapes in Cairo being planned, but a clear difference can be observed. Designing as an outsider in a setting where residents are used to collectively define public space made me reflect on my role as a designer. While in this case it is obvious to all of us, that for the design and implementation of interventions it is key to include residents, I take this as a lesson also for contexts that I am more familiar with.

Working in a arid climate, which is affected by the effects of climate change very directly in the form of increasing heat stress was a hands-on lesson for my future career. I will, independent of the context no longer be able to think about design without considering climatic aspects and future challenges.

I would like to express my sincere gratitude to my supervisor João Cortesão who guided me on this journey. I further would like to thank Gert-Jan Steeneveld for his co-supervision of this thesis and his highly appreciated inputs on the microclimatic interventions, and Homero Marconi Penteado for his inputs and flexibility. In addition to my supervisors, I would like to thank all the experts who contributed to the evaluation of the developed solutions: Aynaz Lotfata, Samah El Khateeb, Wendy Tan, Josephine van Zeben and Zac Taylor. Finally, I would like to extend my gratitude to my friends and family who were there for me during this last year, supporting my work, but also helping me to focus my mind on other aspects of live!

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1. INTRODUCTION

1.1 PROBLEM DESCRIPTION

Climatic shocks and stresses due to climate change affect urban areas and their population worldwide. Specifically, more intense and frequent heat waves induced by rising global temperatures influence urban heat islands (UHI) (Cheng et al., 2021). The UHI contribute to increased levels of heat stress within cities, posing serious threats to the livelihood of urban populations (Ebi et al., 2021). Currently, more than half of the world's population lives in cities and with continuing urbanization this percentage is expected to increase the coming decades (United Nations, 2019; Quintana-Talvac et al., 2021). Urbanization is mainly driven by urban growth rates, rural-urban migration, and reclassification of neighboring rural settlements (United Nations, 2019). Projections indicate that by 2050 68% of the global population will be living in cities, with around 90% of this urban growth taking place in Asia and Africa. Although other geographic regions have higher urbanization levels (e.g., North America), Asia and Africa are urbanizing more rapidly than any other region worldwide. By mid-century, the majority of the global urban population will be concentrated in Asia (52%) and Africa (22%) (Van Bueren et al., 2012; United Nations, 2019; Faragallah & Ragheb, 2022).

Rapid urbanization processes have been associated with the development of informal growth of urban areas, both within and beyond the city's official borders. The rapid increase in population leads to a gap between housing demands and available houses, resulting in the building of informal housing (Bek et al., 2018; Badwi et al., 2021). Currently, a third of the global urban population lives in informal areas, and this number is predicted to double by 2030 (Van Bueren et al., 2012). These areas are defined as residential areas where citizens build their own houses, representing informal development regarding law or urban status (or both) (El-Shahat & El Khateeb, 2013). A type of informal areas are unplanned areas, which are built and developed far from formal plans, but existing buildings are often in acceptable physical conditions. Unplanned urban areas are further characterized by distorted urban fabric, narrow and unpaved streets, lack of utility infrastructure (clean water, sanitation, or reliable public transport) and high population density (Bek et al., 2018). These characteristics influence the thermal balance of neighborhoods i.e., increased ambient temperatures. This makes unplanned areas and their residents specifically vulnerable to the effects of urban heat stress.

Urban heat stress, manifested by phenomena such as the UHI or heat waves, depends on a variety of factors such as urban morphology, characteristics of urban materials, anthropogenic influences, and climatic conditions. The expansion of urban population, and

therefore the increase in economic and infrastructural developments, affects the urban morphology. Factors like high density of buildings, low albedo values, built geometry, low percentage of vegetation and high concentration of impervious surfaces lead to higher temperatures in cities and increased levels of heat stress (U.S. Environmental Protection Agency, 2008b; Hereher, 2017; Faragallah & Ragheb, 2022). The thermal balance of cities is further affected by anthropogenic heat caused by for example air conditioners, cars, and industrial activities (Ebi et al., 2021; Marincic & Ochoa, 2021). Besides the influence of these factors, site-specific climatic conditions may also affect urban heat stress.

Depending on these different drivers and their combinations, changes in temperatures lead to a multitude of hazardous effects for urban areas and their populations. Effects on the urban microclimate are among others increased surface temperatures, solar radiation absorption, concentration of air pollution, heat storage capacity, impaired water quality, altered wind and turbulence patterns (Abulibdeh, 2021) and reduced natural ventilation (Van Bueren et al., 2012). Naturally, residents of urban areas are affected by these phenomena, causing increased energy consumption for cooling, water demand (Haashemi et al., 2016; Simwanda et al., 2019), thermal discomfort and higher mortality rates (Coates et al., 2022) due to heat stress.

Such chains of events are particularly serious in urban areas in arid climates since extremely hot conditions are typical of these latitudes, especially during the summer periods (Marincic & Ochoa, 2021).

Unplanned urban areas are particularly vulnerable to heat stress, as they are often inhabited by heat-vulnerable groups, namely elderly, children, and urban poor (Bek et al., 2018; Simwanda et al., 2019; Quintana-Talvac et al., 2021). Lack of financial resources, limited access to facilities and services, and physical or mental health conditions are examples of why people in unplanned urban areas are more vulnerable to the effects of heat stress (Parvin et al., 2013; Coates et al., 2022). Often socio-economic and physical risks conflate. Physical influences such as the compact spatial layout of buildings and lack of open spaces in unplanned urban areas, affect the microclimatic conditions near the ground (e.g., altered wind patterns, surface radiation balance, and air temperatures) (Lenzholzer, 2015). Furthermore, high height-to-width ratios (H/W) and low sky-view factors (SVF) may trap night-time longwave radiation within local streetscapes and impede natural ventilation (Ali-Toudert et al., 2005). Additionally, buildings in informal areas are typically constructed with low albedo building materials, which lead to increased heat storage within buildings, posing the risk of further increased night-time temperatures (Galal et al., 2020; Jaber, 2022).

1.2 KNOWLEDGE GAP

There are various studies on how to deal with heat stress trough climate-adaptive design in cities. Interventions such as reshaping urban morphology (Rodríguez-Algeciras et al., 2018), installing irrigation systems (Broadbent et al., 2018), increasing vegetation (Klemm, 2018; João Cortesão et al., 2020), installing cooling urban water environment (Steeneveld et al., 2014; Jacobs et al., 2020) or modifying building and surface materials (J. Cortesão, 2013; Lenzholzer, 2015; Tsoka, 2017) are proposed within current literature. However, the focus of these studies lies on temperate climates and planned areas (Runting et al., 2017). In turn, research on climate-adaptive design for unplanned urban areas in arid climates and developing economies remain relatively understudied.

There is, thus, an urgent need for studies on climate-adaptive design for unplanned urban areas in arid climates and developing economies. This is of relevance since the impacts of climate change are likely to affect countries in the Global South disproportionately, because of the already harsh climatic conditions and the limited resources to adapt to these impacts (Srinivasan, 2010). Additionally, considering that arid regions are likely to expand geographically, under the impact of climate change, climate-adaptive design research into arid climates can potentially benefit a broad range of countries and cities worldwide.

1.3 CONTEXT

This thesis is part of an ongoing research project called 'Climate-adaptive streetscapes in unplanned urban areas in desert climates'. The project falls under the 4TU.Resilience Fellowship Programme and is a collaboration with Wageningen University & Research, Chicago State University and Ain Shams University. As the author of this thesis generated data for this project, some of the results presented in this thesis will therefore overlap with the outcomes of the research project.

Due to the collaboration between the three universities and based on the knowledge gap within recent research, an unplanned urban area within Cairo was selected as study site. This site is used as a study case to develop prototypical climate-adaptive spatial interventions, which aim to be replicable across other unplanned urban areas within Cairo, and potentially other cities in arid climates. The area is situated within the district of Shubra, located on the east bank of the Nile River and north of the historical center of Cairo (Figure 1). The criteria which determined the choice of study area are among others high density urban fabric (typical for an unplanned urban area), proximity of the Nile (potential impact on microclimate), contrast and interaction of the surrounding planned areas and relatively high data availability (e.g., spatial data, previous research done by Ain Shams University).

Fig. 1 True color satellite image illustrating the location of the study site situated in the Shubra district. Image taken on date 30-08-2022.

1.4 RESEARCH QUESTIONS

Fueled by the knowledge gap presented above, this thesis aims to answer the question: **How to design streetscapes in unplanned urban areas in arid climates making use of climate adaptive interventions to deal with urban heat stress?**

This research question unfolds into three sub-research questions:

1. What climate-adaptive interventions have the most potential for climate regulation and, simultaneously, for feasibility in unplanned urban areas in arid climates?

2. How to implement the shortlisted climate adaptive interventions in the representative street profiles of Shubra?

3. How can the developed design prototypes contribute to improving microclimatic conditions within a site-specific design in Shubra?

1.5 OBJECTIVE AND RELEVANCE

The objective of this thesis is to inform decision-makers and designers on how to address heat stress within the streetscape of unplanned urban areas, through spatial design interventions feasible for its population and arid climate contexts.

Although unplanned urban areas are challenged by limited space and resources, this thesis aims to present simple interventions that can be used to design habitable outdoor spaces. By doing so, this thesis aims to contribute and raise awareness to the ongoing knowledge development on how to design climate resilient cities within arid climates. The climate-adaptive interventions are presented as an overview in a toolbox, within different representative streetscapes and within a site-specific design. This allows users to consult this thesis and use it as a guide and reference study during the decision-making and design process.

2. CONCEPTUAL FRAMEWORK

This chapter presents the concepts and theories essential to understand the research topic addressed in this thesis.

2.1 UNPLANNED URBAN AREAS

As described previously, unplanned urban areas can be categorized as a type of informal area. The development of informal areas is a global phenomenon, typical for cities with rapid urban growth (Bek et al., 2018) and accelerated in particular in cities within the Global South (El-Shahat & El Khateeb, 2013). The concept of informal urban areas can be defined as *"a residential area in societies where its inhabitants build their own shelter"* (Bek et al., 2018, p. 3170). This development is driven by the disbalance between the high demand for and the low supply of adequate and affordable housing. This process is a result of rapid urbanization processes and the failure of governments or the private sector to offer formal housing to the urban poor (Khalifa, 2015; Bek et al., 2018). The term 'informal' refers to the fact that these areas are developed without any legal approval and/or lack an acceptable physical structure.

As this thesis focuses on unplanned urban areas, it is important to shortly define and describe the concept. Unplanned urban areas are defined as: "*Any area that was developed or built by individual efforts including one-floor buildings or more, or strews in the absence of laws…The buildings may be in good condition or they can be environmentally and socially unsafe. In addition, they may lack the basic services and facilities.*" (Bek et al., 2018, p. 3170).

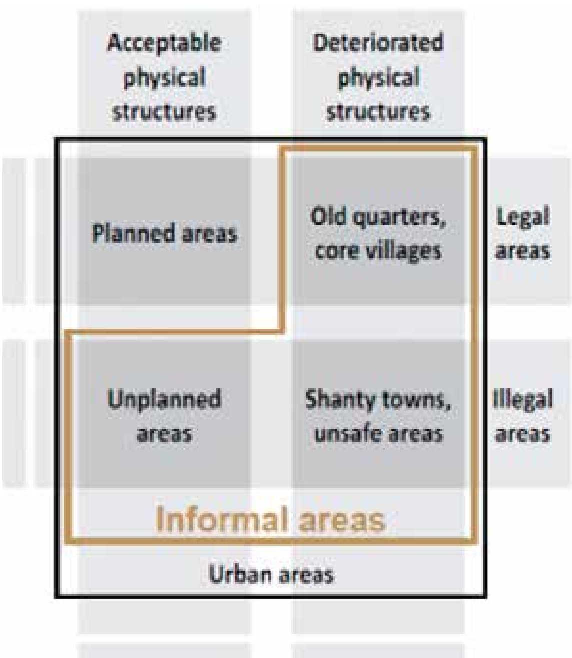


Fig. 2 Classification system to define and distinguish different types of informal urban area, based on their legal status and physical condition (source: El-Shahat & El Khateeb, 2013).

In summary, unplanned urban areas are developed far from formal plans but are distinguished from unsafe areas and deteriorated neighborhoods by the fact that existing buildings have acceptable physical structures (Figure 2). Most of the informal areas within Cairo are categorized as unplanned areas (El-Shahat & El Khateeb, 2013). Unplanned urban areas can be furthermore characterized by a distorted urban fabric, uncontrolled building heights, high population density, narrow and unpaved streets, and lack of utility infrastructure (e.g., electricity, water or sanitation) (Bek et al., 2018; French et al., 2021). Due to these spatial aspects, but also in combination with social and environmental aspects, unplanned urban areas are especially vulnerable to the effects of heat stress (Bek et al., 2018; French et al., 2021). To illustrate, narrow streets and high population density within unplanned urban areas can lead to a lack of natural ventilation, increased pollution and high levels of heat stress (Bek et al., 2018).

2.2 URBAN CLIMATE

Climates in cities differ substantially from climates of the surrounding landscapes. This phenomenon is referred to as the urban climate. Due to the characteristics of cities, urban climates have typically higher temperatures (especially at night), lower humidity rates, changes in radiation balances, distorted wind patterns and restricted atmospheric exchange (Kuttler, 2008; Lenzholzer, 2015). The interrelation between local climate conditions, characteristics of the urban fabric and population related variables influence urban climates. A temperature phenomenon typical for urban environments is the UHI (Memon et al., 2008; Lenzholzer, 2015). The following paragraph will expand further on the formation of UHI and its influence on outdoor thermal comfort.

2.2.1 Urban Heat Island (UHI)

Defined as the difference in temperature between urban areas and their surrounding landscapes, the UHI contribute to higher levels of heat stress (increased daytime temperatures and reduced night-time cooling) (U.S. Environmental Protection Agency, 2008b; Jandaghian & Berardi, 2021). The formation of the UHI depends on many factors and their interaction (Figure 3) (Memon et al., 2008). These factors can be described as either controllable or uncontrollable variables. Controllable variables include population related aspects and urban form (e.g., material properties and geometry), while uncontrollable variables refer to climatic conditions of a specific location. The key driver within the process of UHI formation is the incoming solar radiation (i.e., shortwave radiation) that reaches the earth's surface (U.S. Environmental Protection Agency, 2008b).

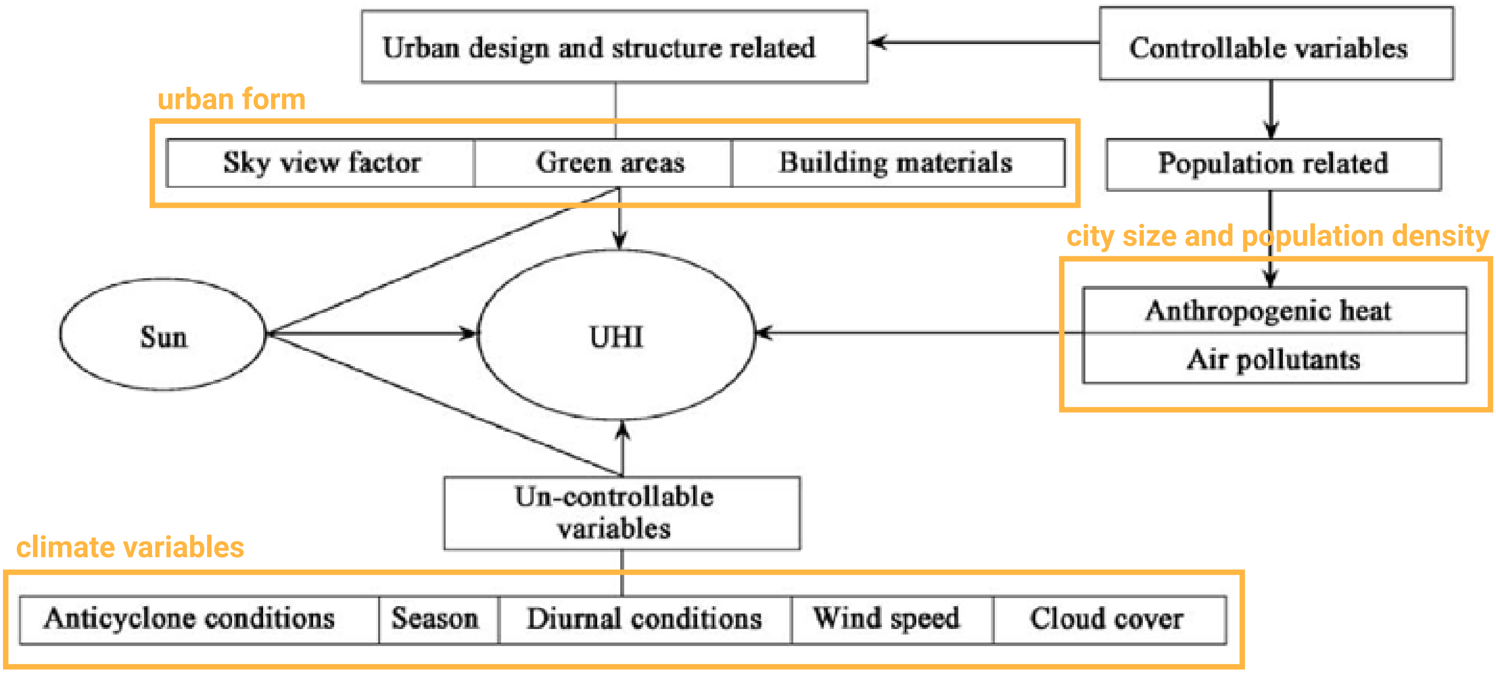


Fig. 3 Formation of Urban Heat Islands depends on 1) urban form 2) population 3) climate variables (source: Memon et al., 2008).

Urban form

Urban surfaces reflect less shortwave radiation back into the atmosphere, compared to their surrounding (rural) landscapes. Instead, they absorb and store shortwave radiation during the daytime which leads to increased surface temperatures during the day and increased air temperatures during the night.

This increased thermal storage is mainly attributable to radiative and thermal properties of urban materials. Radiative properties determine how shortwave radiation is reflected (i.e., albedo) and longwave thermal radiation is emitted (i.e., emissivity). While thermal properties determine how much heat energy is transferred and stored by materials (i.e., specific heat capacity and thermal conductivity). The UHI is mainly influenced by albedo and specific heat capacity values. Surface materials in urban areas, like roofing and paving, often have lower albedo and higher heat capacity values compared to vegetation and other natural ground cover. Hence, the percentage of paved and impervious areas compared to vegetated areas within a city is a determining factor for the development of UHI. Vegetated and pervious areas have an additional cooling potential by providing shade and evapotranspiration (i.e., latent heat) (U.S. Environmental Protection Agency, 2008a; Mills et al., 2021).

Tall buildings can also provide cooling by casting shadows within urban canyons. However, the multitude of surfaces increases reflection and absorption of shortwave radiation (Figure 4), decreasing the city's overall albedo (Memon et al., 2008; U.S. Environmental Protection Agency, 2008a).

The heat energy stored within an urban area during daytime is released to the environment as longwave radiation during the night. However, depending on the density of the urban geometry (spacing and dimensions of buildings) this heat is trapped. The reduced night-time cooling within cities leads to increased health risks for urban populations, especially during heat waves. Due to the different cooling rates of urban areas compared to their non-urban surroundings, the UHI intensity peaks a few hours after sunset. A simple measure to estimate the effect of the urban geometry on UHI formation is the 'sky view factor' (SVF), defined as the visible area of the sky from a given location (Memon et al., 2008; U.S. Environmental Protection Agency, 2008b; Mills et al., 2021).

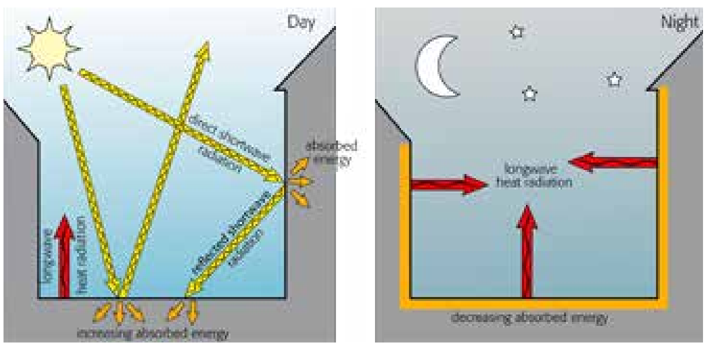


Fig. 4 Patterns of shortwave radiation and longwave radiation in urban canyons during day- and nighttime conditions (source: Lenzholzer, 2015).

City size and population density

The UHI intensity is positively correlated with the population density and size of an urban area (Memon et al., 2008). Both anthropogenic heat and increased levels of pollution contribute to enhanced urban temperatures. Anthropogenic heat is defined as the heat produced by human activities, generated by use of vehicles, air conditioners, power plants, industrial activities, and excess heat from buildings (Marincic & Ochoa, 2021). This heat gets trapped and re-radiated within the complex urban structures of cities, creating a positive feedback loop of heat fluxes.

The intensity of anthropogenic heat fluxes often depends on the energy use within an urban area (i.e., the average energy uses per capita multiplied by population density). However, previous studies point out that this heat flux is highly location specific and varies with diurnal and seasonal trends (Memon et al., 2008; Ebi et al., 2021). For hot-arid climates, where summer temperatures can extend up to 8 months a year, the use of air conditioning is almost constant (day and night) (Marincic & Ochoa, 2021).

Climate variables

Cities in hot-arid climates are sensitive to high levels of heat stress because of their climatic conditions and cycles (seasonal and diurnal). Anticyclonic conditions, high pressure areas where dry air is descending, are typical for arid regions. Limited cloud cover associated with these conditions, results in significant amount of direct solar radiation. Increased surface and air temperatures, combined with low precipitation rates, lack of evapotranspiration and low wind speeds intensify heat stress levels in hot-arid climates (Bailey, 1979; Rosenlund, 2000; Golden, 2004). The input and strength of incoming shortwave radiation additionally depend on the solar angle of incoming rays, which varies depending on the geographic location and the time of year and hour of the day. Close to the poles, the radiation is spread over a larger part of the earth's surface, while at the equator the radiation is more direct and concentrated (Lenzholzer, 2015; Mills et al., 2021).

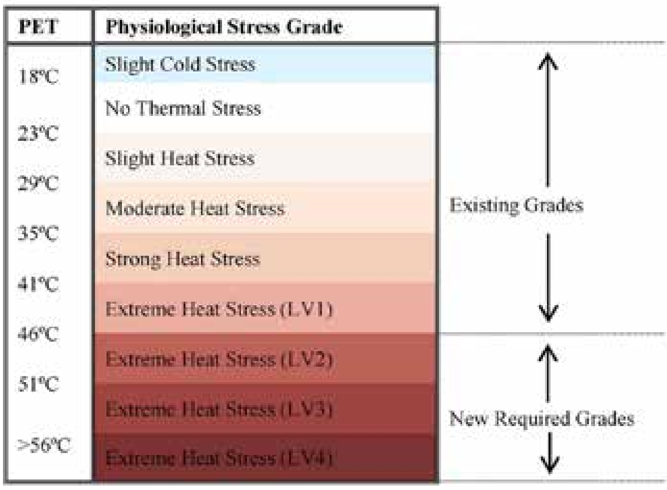
Arid climates are mainly found between the 15°-30° latitude belts, where the almost vertical incoming solar rays in summer months lead to extremely high temperatures. During spring and autumn, and especially in winter, the angle of incidence decreases, leading to more moderate temperatures and longer shadow patterns. Diurnal conditions make summers increasingly hot because long days increase the amount of solar radiation (up to 14 hours of sun/day in Egypt) (Faragallah & Ragheb, 2022).

2.2.2 Outdoor thermal comfort

Improving outdoor thermal comfort conditions is not only important for reducing health risks and improving wellbeing, but it also helps in providing habitable public spaces where people can gather (Nikolopoulou, 2021). In hot-arid climates, most people often spend their time outdoors, which highlights the importance of prioritizing thermal comfort within urban design (Marincic & Ochoa, 2021; Faragallah & Ragheb, 2022) in these regions.

How people experience different microclimatic conditions depends not only on external physical factors, such as wind speed and air temperature, but also on individual physical and physiological factors (Lenzholzer, 2015). Therefore, the concept of thermal comfort can be defined as the "*condition of mind in which satisfaction is expressed with the environment*" (Nikolopoulou, 2021, p. 56). Environmental key factors which influence outdoor thermal comfort are air temperature, radiant environment (influenced by shortwave and longwave radiation derived from the sun and surrounding urban materials), humidity and air movement. Personal key factors which influence outdoor thermal comfort are clothing insulation and a person's specific metabolic rate (this is affected by activity) (Nikolopoulou, 2021).

A common way to analyze and measure thermal comfort in outdoor spaces is through comfort indices. An indicator which is extensively used is the Physiological Equivalent Temperature (PET) index, based on the thermal balance of the human body. Through combining both meteorological and thermo-physiological factors, the index includes an analysis of the interaction between human thermal perception and outdoor thermal conditions. The index translates effects of thermal outdoor conditions, including radiation, wind speed, humidity, and air temperature on humans in terms of environmental stress or comfort (Figure 5).



PET	Physiological Stress Grade	
	Slight Cold Stress	Existing Grades
18°C	No Thermal Stress	
23°C	Slight Heat Stress	
29°C	Moderate Heat Stress	
35°C	Strong Heat Stress	
41°C	Extreme Heat Stress (LV1)	
46°C	Extreme Heat Stress (LV2)	New Required Grades
51°C	Extreme Heat Stress (LV3)	
>56°C	Extreme Heat Stress (LV4)	

Fig. 5 Gradual representation of physiological stress grade with corresponding PET temperatures (source: Nouri et al., 2018).

Represented by a temperature value, the PET index enables a clear comparison for different outdoor situations (Krüger et al., 2017; Mills et al., 2021), which makes it particularly useful in climate-adaptive design studies. Since this thesis is explorative and qualitative of nature, calculations of PET values will not be included. However, the concept of thermal comfort and how this relates to thermal perception is used for the assessment of the interventions, prototypes, and site-design.

2.3 URBAN CLIMATE RESILIENCE

Urban climate resilience can be defined as "*the capacity of an urban area to maintain or quickly return to desired functions in the face of climate-related chronic stresses and/or acute shocks, to adapt to changing and uncertain climatic conditions, or to rapidly transform in ways that build climate-adaptive capacity across temporal and spatial scales*" (João Cortesão & Copeland, 2022, p. 1). In this context, resilience describes the development of interventions which aim to reduce the impact of disruptions caused by issues that are uncertain and complex (e.g., climate change).

Enhanced adaptive capacity ensures climate regulation and resilience of urban spaces, as it potentially improves thermal comfort, livability and conviviality of public spaces, health and well-being of urban communities, infrastructure and networks, and urban ecological restoration (Nikolopoulou, 2021). The high concentration of people, services, and infrastructure, make urban areas specifically vulnerable to cascading system failures caused by climate change. Particularly as urban areas continue to grow the coming decades, the demand for infrastructure, food, and energy will increase accordingly. Considering this, urban areas are urged to focus on strategies and interventions within the built environment to mitigate and adapt to climate change.

Climate adaptation aims to reduce vulnerability and strengthen resilience of urban communities, by adapting practices, processes, and structures (Henstra, 2012; João Cortesão & Copeland, 2022). Although cities worldwide experience the effects of climate change, their vulnerability largely depends on the exposure to hazards and the sensitivity of urban infrastructures and/or coping capacity of urban communities (Henstra, 2012). When developing climate-adaptative strategies and interventions it is important to consider that the vulnerability, and therefore the resilience, will vary depending on the city or area within a city (e.g., unplanned urban areas) (French et al., 2021).

2.4 CLIMATE-ADAPTIVE DESIGN

Climate-adaptive design can be defined as the development of site-specific design interventions that shape or reshape an urban area, contributing to urban resilience in response to climate phenomena (João Cortesão & Copeland, 2022). More specifically, climate-adaptive design interventions aim to control the amount of solar radiation (sun and shadow patterns), balance air temperature and relative humidity, control wind exposure, increase evaporative cooling and enable heat losses from surfaces and buildings (reflection, emissivity, and heat conductivity) (Lenzholzer, 2015; João Cortesão & Copeland, 2022). The design of spatial elements (e.g., vegetation, paving, building materials) and geometry-related parameters (e.g., building and street orientation or height-to-width ratio), define micro-climatic attributes and urban climate resilience of a specific urban area.

As urban climate resilience aims to include temporal and spatial scales when increasing climate-adaptive capacity, interventions range from quick to gradual responses in case of disruption and from micro-climatic to local climate scale. In this context, microclimate scale refers to spaces where the climate variables are mostly influenced by the immediate surrounding, such as streets or squares. Local climates refer to areas roughly the size of one (or more) urban districts where the climate is mostly influenced by local climate conditions (João Cortesão & Copeland, 2022). Although small-scale microclimatic interventions result in small scale effects, the combined effect of multiple small-scale interventions can change local climates significantly (e.g., temperature decrease) (Kuttler, 2008; Lenzholzer, 2015).

STREETSCAPES

This research focuses on the microclimatic scale, that is, streetscapes in unplanned urban areas in arid climates. Streetscape is defined as the horizontal and vertical surfaces (e.g., street surface and building exterior) within an urban canyon. Horizontal surfaces outside the streetscape, namely rooftops, are excluded from this study because although implementing interventions on the roof of a building can be effective to decrease the UHI on a larger scale, they have no impact at the microclimatic scale (Hoag, 2015).

3. METHODOLOGY

This chapter presents the methodology used for this research (Figure 6). The research is structured into two main research approaches: research for design (RFD) and research through design (RTD). RFD and RTD were selected based on their applicability to answer the design-driven main- and sub-research questions herewith addressed. Furthermore, these research approaches ensured the internal validity and replicability of the design prototypes.

3.1 METHODOLOGICAL STRUCTURE

During the first phase (RFD), different spatial climate-adaptive design interventions were identified and selected (SRQ1). The second phase (RTD) consisted of three iterations of design and testing, focused on the development of design prototypes (SRQ2) and site-specific design (SRQ3).

To understand how the different interventions could be applied to the study site in Shubra, different representative street typologies were developed. The identified design interventions were subsequently applied to the selected street typologies in different combination and configurations. These different design propositions were assessed based on seven criteria: climate-adaptive design, urban climate, land use planning, equity, affordability, mobility, and sense of place. These criteria were selected to rate the climate regulation effectiveness (i.e., climate-adaptive design and urban climate) and feasibility within the specific context (i.e., land use planning, equity, affordability, mobility, and sense of place).

This process of design and testing resulted in a set of final design prototypes, adapted to the spatial layout and functionality of each street typology and its microclimatic regulation needs. Ultimately, these prototypes were applied in a site-specific design.

During the iterations, designing comprised the use of sketching, 2D drawings, and 3D modelling in SketchUp. A 3D model for sun/shade analysis was built, modeled at solar noon (13h00 GMT+2) on the local longest day of the year (21st of June). Testing consisted of an expert judgment assessment, based on the seven criteria presented earlier. Seven experts from Wageningen University, Delft University of Technology, Chicago State University and Ain Shams University assessed the design according to their fields of expertise (Table 1). The experts rated the design prototypes on a five-point Likert scale, using an interactive online voting tool (Aha-slides). Per design alternative, experts were asked to answer the following question: *How would you rate the effectiveness/feasibility of sketch x?* The corresponding Likert scale was defined as: very low effectiveness/feasibility (1), low effectiveness/feasibility (2), effective/feasible (3), high effectiveness/feasibility (4) and very high effectiveness/feasibility (5). To understand what needed to improve in the next iteration, each assessment question was followed by an interdisciplinary discussion on the reasons behind the rating results.

Worldview

Within the RTD phase of this research, the study adopts a pragmatist research approach, as defined by Lenzholzer et al., (2013). A pragmatist approach combines different research methods to generate practical (design) knowledge for a complex problem (Lenzholzer et al., 2013; João Cortesão et al., 2019).

Table 1. Overview of the selected experts who assessed the effectiveness and feasibility of the proposed design interventions, prototypes, and site-specific design.

expertise	expert	institution	assessment criteria
climate-adaptive design	João Cortesão	Wageningen University & Research	climate regulation (SRQ1, SRQ2, SRQ3) and feasibility (SRQ1)
urban climate	Gert-Jan Steeneveld	Wageningen University & Research	climate regulation (SRQ1, SRQ2, SRQ3) and feasibility (SRQ1)
land use	Aynaz Lotfata	Chicago State University	feasibility (SRQ2)
genius loci	Samah El Khateeb	Ain Shams University	feasibility (SRQ2)
mobility	Wendy Tan	Wageningen University & Research	feasibility (SRQ2)
equity	Josephine van Zeben	Wageningen University & Research	feasibility (SRQ2)
affordibility	Zac Taylor	TU Delft	feasibility (SRQ2)

How to design streetscapes in unplanned urban areas in arid climates making use of climate-adaptive interventions to deal with urban heat stress?

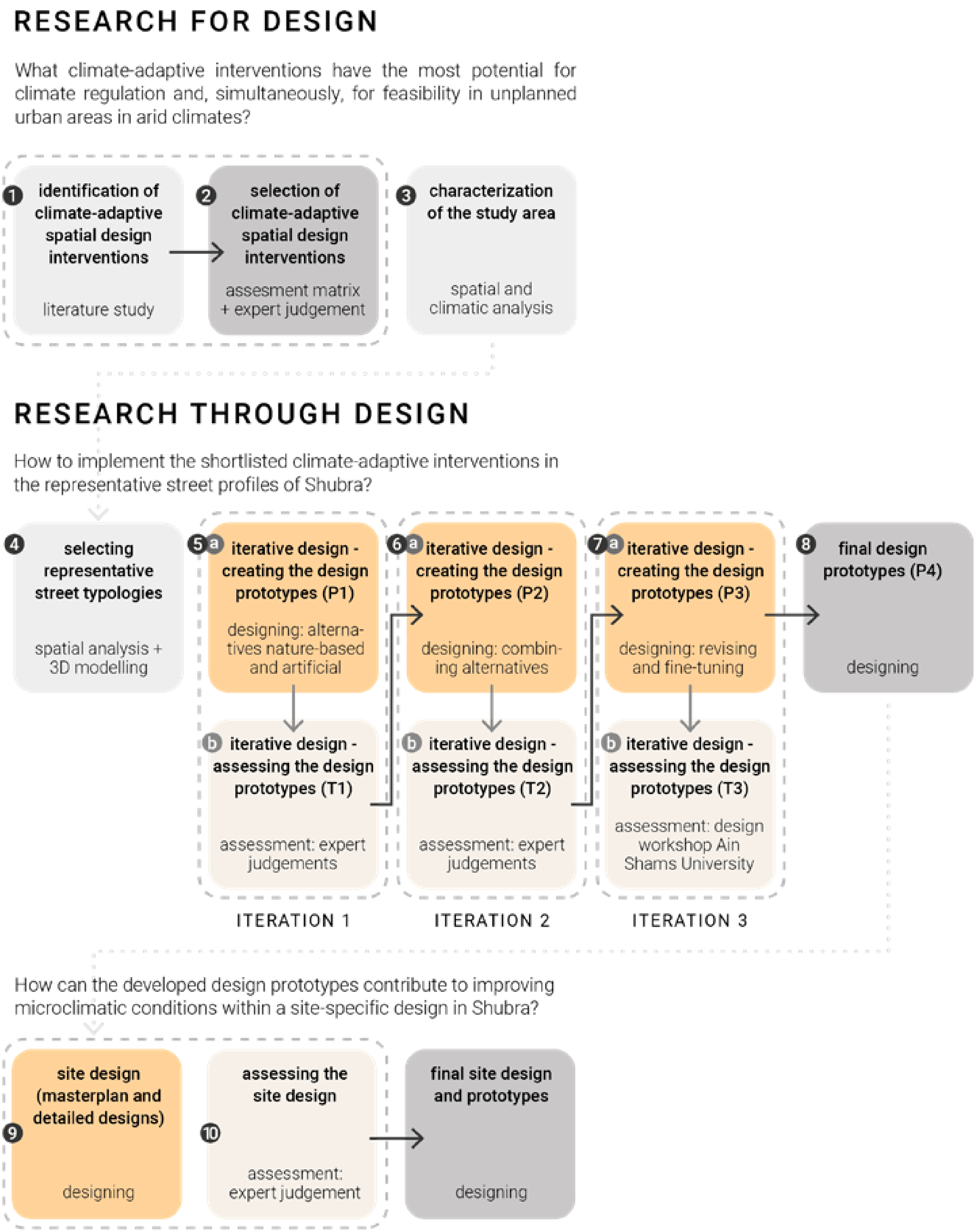


Fig. 6 Visual representation of the methodology structure, illustrating the various steps that were taken to answer the research question.

In particular, the pragmatist approach herewith presented employed post-positivist, constructivist and participatory methods targeted at different purposes (João Cortesão et al., 2019). For example, empirical observations were done by testing the designs on objective criteria (post-positive approach). The assessment of design alternatives included experts with different fields of expertise, aiming to understand cultural, aesthetic and ethical values in the specific context (as defined by Cortesão et al., (2019)) (constructivist and transformative/participatory approach).

3.2 RESEARCH FOR DESIGN

Research for design (RFD) describes the process of knowledge creation by designers to achieve a desired result in their project. It includes the development of new design tools, methods, and reliable predictions of end results to inform both the design process and product (Nijhuis & Bobbink, 2012). This first phase of the research was employed to gather all information needed to conduct the RTD phase. This involved identifying effective climate-adaptive interventions suitable for unplanned urban areas in arid climates, and a spatial and climatic analysis of the study area. To this end, steps 1-2 were guided by SRQ1: *What climate-adaptive interventions have the most potential for climate regulation and, simultaneously, for feasibility in unplanned urban areas in arid climates?* The steps followed during the RFD phase are presented below.

Step 1. Identifying climate-adaptive spatial design interventions

To identify climate-adaptive interventions suitable to arid climates, a literature review was conducted, making use of peer-reviewed scientific articles, reports, online toolboxes, and reference projects. To this end, the following search terms were entered in Google Scholar: (urban climate OR climate-adaptive design OR climate-responsive design OR climate-conscious design OR bioclimatic design); AND (arid climate); OR (temperate climate). Because data on climate-adaptive spatial design in arid climates is limited, the focus of this review had to be widened to include interventions in temperate climate. The resulting list of possible design interventions consequently is a conglomerate of many different sources.

Step 2. Selecting climate-adaptive spatial design interventions

The identified interventions were then assigned to different climate-adaptive strategies: adaptation of urban materials (changing heat-related properties of surface materials and/or increasing albedo values), implementation of shade (blocking incoming solar radiation by adding artificial shading structures), increasing evaporative cooling (adding interventions that increase evapotranspiration to provide cooling).
The interventions were then assessed by climate-adaptive design and urban climate experts from Wageningen University to evaluate their capacity to regulate microclimate in the streetscape. The experts rated the design interventions on a five-point Likert scale. The corresponding Likert scale was defined as: very low effectiveness (1), low effectiveness/ feasibility (2), effective/feasible (3), high effectiveness/ feasibility (4) and very high effectiveness/feasibility (5). The assessment criteria were the likeliness to reduce short- and longwave radiation and air temperature, regulate ventilation, and increase evaporative cooling. In addition, these interventions were assessed on their feasibility to be implemented in the local context based on their ease of construction, capacity for spontaneous maintenance and likelihood of low capital cost.

Step 3. Characterization of the study area

During this step, social, climatic, and spatial data were collected to characterize the study area (e.g., typical patterns for sun and shadow, street widths, building heights, etc.). Data from peer-reviewed articles, aerial and street-level photos, official climate data websites and cartographic material was used. Additionally, data from several field visits contributed to the analysis of the study area (field visits were done by the author and project partners).

3.3 RESEARCH FOR DESIGN

RTD describes a scientific approach to design studies within which the most suitable design propositions are selected based on an iterative process of development and testing of a set of design propositions. This process of design and evaluation continues until new relevant knowledge is collected (João Cortesão et al., 2019).

The first part of the RTD phase consisted of three iterations and focused on the development of design prototypes (steps 4-8), guided by SRQ2: *How to implement the shortlisted climate adaptive interventions in the representative street profiles of Shubra?* The development of the representative street profiles was rooted in the analysis done in the RFD phase (step 3). The second part of the RTD phase focused on the development of a site-specific design by applying the prototypes (steps 9-10), guided by SRQ3: *How can the developed design prototypes contribute to improving microclimatic conditions within a site-specific design in Shubra?* The following section describes the process that followed in more detail.

Step 4. Selection of representative street typologies

Based on the integrated analysis of the study area (step 3), representative street typologies were identified. The street typologies served as 'testbeds' during the design process and are nonspecific street profiles, based on the type of street occurring most frequently within the study site. Thus, ensuring the replicability of the design prototypes (João Cortesão et al., 2020).

During the selection of the representative street typologies, two main criteria were leading: height-to-width (H/W) ratio and street orientation (north-south and east-west). This resulted in four main street typologies. Additionally, the relevance of each typology was evaluated according to the type and condition of adjacent buildings, mobility, and predominant functions.

Steps 5a and 5b. Iteration 1: creating (P1) and assessing (T1) the prototypes

During this first design iteration (P1), two design prototypes were developed for each street typology: an artificial design alternative (applying only human-made elements) and a nature-based design alternative (only implementing vegetation). The first alternative represented a profile in which only human-made elements (e.g., shading structures) were implemented. The second alternative represented a profile where microclimatic conditions were aimed to be influenced through the implementation of different types of vegetation (e.g., trees, shrubs, etc.). The design alternatives of P1 were assessed and discussed according to the seven criteria and rating scale described above. This rating (T1) and feedback helped to identify aspects for improvement for the second iteration (P2).

Steps 6a and 6b. Iteration 2: creating (P2) and assessing (T2) the prototypes

Both the nature-based and artificial interventions that scored at least a 3 (effective/feasible) in T1 were used for the next design iteration. Interventions with a lower score were either refined or eliminated from the process. This resulted in one integrated design prototype per street typology (P2), which was assessed (T2) based on the same criteria and according to the same procedure as described in step 5. This was done to evaluate the validity of combinations of interventions.

Steps 7a and 7b. Iteration 3: creating (P3) and assessing (T3) the prototypes

Based on the assessment (T2), the design prototypes were further fine-tuned in terms of feasibility. In general, the results of T2 indicated high potential concerning the effectiveness of the prototypes to regulate microclimatic conditions within the streetscape. However, feasibility concerning affordability (e.g., high maintenance requirements) and mobility (e.g., impairment of car circulation) criteria scored low. The design prototypes were refined accordingly, designing shared space and substituting expensive interventions with lower-cost ones (P3). For the assessment of the P3 prototypes, a one-day workshop was organized at Ain Shams University (in Cairo). The workshop aimed to get more insight into the local context, by focusing on urban design, landscape architecture, architecture, and urbanism from students familiar with Egyptian culture. To this end, thirty students were asked to develop climate-adaptive design interventions on the identified street typologies, without having been presented the P3 Prototypes. This allowed for a comparison of the prototypes developed by local students to the P3

Table 2. Overview of the climate-adaptive interventions proposed in the third iteration and the ones added during design workshop; the final interventions that are considered in this thesis are presented in the first three columns.

confirmed	questioned	added	discarded
high albedo facade	green screening	rotational louvres	wind catcher
cool surface material		passive cooling system (qullah)	solar chimney
depaving			green roofs
vertical and horzontal shading elements (facade)			turfstone pavement
canopies (canvas, pergola, louvre, colonnades)			water elements
vertical shading structure			
vegetation (trees, shrubs, ground cover vegetation)			
planters (with vegetation)			
vegetated facade			

prototypes to assess the feasibility and local suitability of P3. This comparison was used to validate, eliminate and/or expand interventions.

Step 8. Definition of the final prototypes (P4)

During this step, insights of the previous iterations allowed to define the final prototypes. The results of the workshop were assessed, focusing on interventions that validated, contradicted, or added to the ones proposed in P3. Table 2 shows an overview of which of the interventions proposed by this author in P3 were confirmed or questioned during T3. It also shows the interventions that were proposed during the workshop, categorized into the ones that were added or discarded. The final interventions included in the final prototypes (P4) are presented in the first three columns (Table 2). Most of the interventions matched the ones of P3, sometimes having the same functionality but differing in for example material use (e.g., palm tree leaves for shading canopies). When an intervention contradicted or added to P3, the expert assessments of both rounds were used to make an informed decision. Climate-adaptive potential and feasibility in the local context were important criteria during this decision-making process. Interventions were rejected when they seemed cost-intensive, hard to implement, or to be posing a risk of compromising the structural stability of buildings. Ultimately, this process resulted into a set of final design prototypes (P4).

Step 9. Site-design

To test the applicability of the prototypes, the final prototypes were applied within a site-specific design. This resulted in a design consisting of a masterplan (1:1500) and three detailed designs (1:250), showing how the prototypes can be used to improve microclimatic conditions within the streetscapes of the study area. The design was further explained through 2D sections and artist impressions (i.e., visualizations). To inform the design, the climatic and spatial analysis of step 3 was extended, with a focus on a cohesive outline of the main problems and opportunities within the study area. Additionally, a short analysis of Islamic architecture and landscape architecture aimed to create a more comprehensive understanding of the site-specific context.

Step 10. Assessing the site-design

The site-specific effects on the microclimate were evaluated through an in-depth interview with two experts specialized in climate-adaptive design and urban climate from Wageningen University (Table 1). The two experts were asked to assess the different detailed site designs, based on a five-point Likert scale (using an interactive online voting tool). The corresponding Likert scale was defined as: very low effectiveness (1), low effectiveness (2), effective (3), high effectiveness (4) and very high effectiveness (5). First, the effectiveness of climate regulation was rated (likeliness to reduce short- and longwave radiation and air temperature, regulate ventilation, and increase evaporative cooling). This was followed by a discussion about the expected differences in daytime and nighttime effects, guided by the question: *What are the expected differences in effects of these interventions during the day and night?* Subsequently, the experts were asked to rate the overall effect of the interventions presented in the designs on improving microclimatic conditions within the streetscape (again on a five-point Likert scale). Lastly, the experts were asked to indicate what could be improved within the designs to increase the potential for climate regulation.

4. CLIMATE-ADAPTIVE INTERVENTIONS

This chapter presents a cohesive toolbox of climate-adaptive interventions that can be used in unplanned urban areas in arid climates. Each intervention is selected based on the criteria of maximum climate regulation and feasibility within the specific context.

The literature review, multi-criteria assessment, expert interviews, workshop at Ain Shams University and field visit resulted in the following spatial design interventions. The presented interventions have been identified to be the most effective in regulating microclimatic conditions in arid climates, while being feasible within the context of unplanned areas. The scores presented in Figures 8 – 23 represent the average assessment these interventions received from the experts (step 2 methodology) for climate regulation and feasibility. The detailed assessment table can be found in Appendix I. During the assessment process, further interventions were tested but not considered to be effective or feasible enough (e.g., wind catcher, solar chimney, extended eaves, or rubberized asphalt).

Based on the literature review, three cooling strategies for urban areas are distinguished: changing urban materials, introducing shade, and increasing evaporative cooling. The identified interventions were characterized according to the cooling strategy they contribute to (Figures 8 - 23). Interventions can contribute to a single strategy (e.g., high albedo facade) or contribute to several strategies simultaneously (e.g., pergola canopy). In case an intervention is contributing to several strategies, it is in the description below assigned to the strategy they have the most effect on. The colored circles in the top left corner of Figures 8 – 23 indicate to which strategies the specific intervention contribute to (Figure 7).

Fig. 7 Overview of the three cooling strategies, the different color assigned to each strategy indicates to which cooling strategy each design intervention contributes.

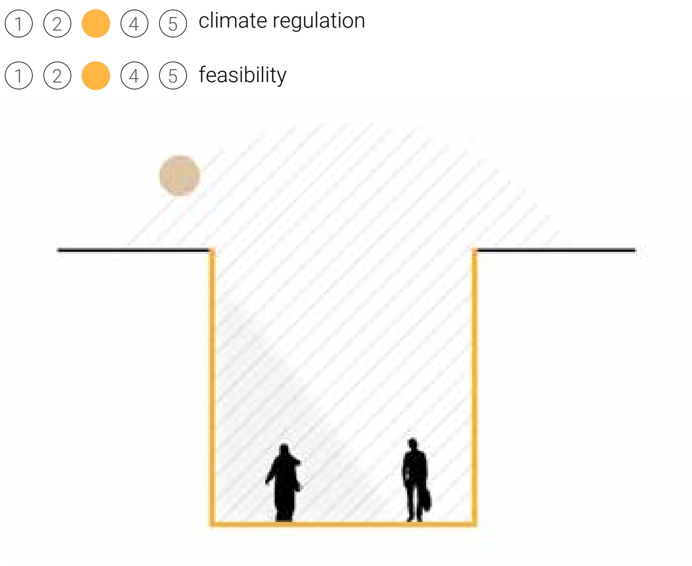


Fig. 8 Illustration of design intervention: high albedo surfaces.

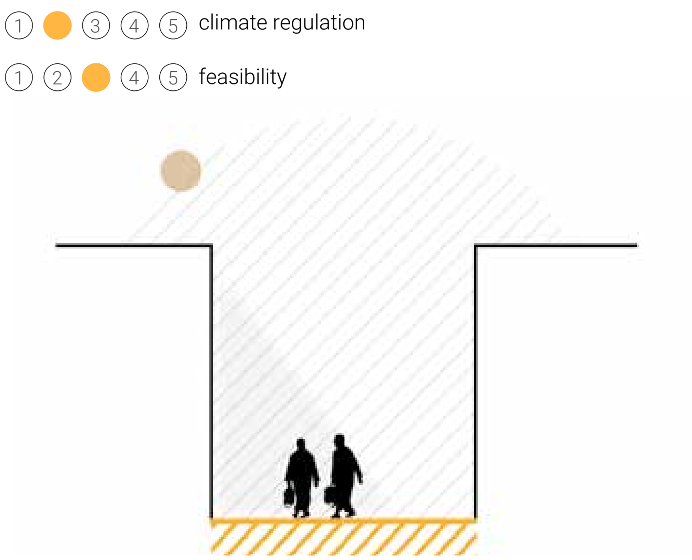


Fig. 9 Illustration of design intervention: cool surface material.

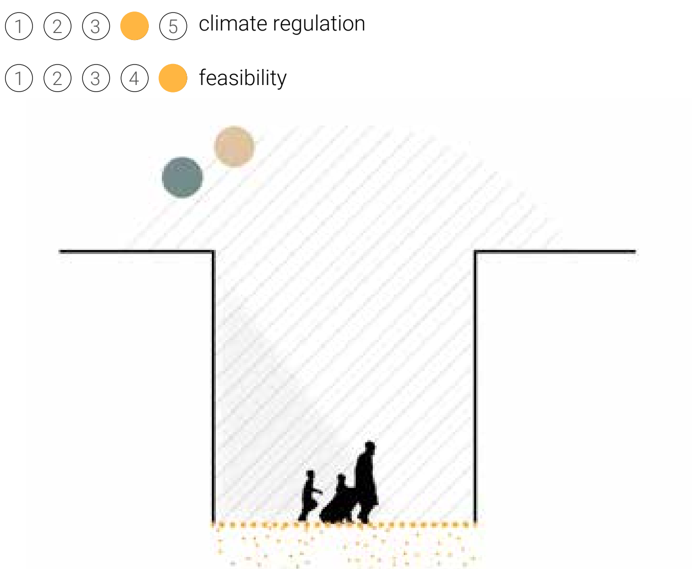


Fig. 10 Illustration of design intervention: depaving.

4.1 URBAN MATERIALS

Specific radiative and thermal properties define the heat absorption and emittance rate of urban materials (Rosenlund, 2000; Mills et al., 2021; Sharifi et al., 2021). Interventions that focus on increasing reflectivity and/or adapting specific heat properties of urban materials effectively decrease local ambient temperatures (Farhadi et al., 2019; Mills et al., 2021). To this end, three different interventions are presented.

High albedo facade/pavement

Increasing albedo values of urban surfaces, by changing the color of facades and pavements (i.e., repainting surfaces). To avoid glare and increased surface temperatures by reflected radiation, albedo values should be carefully selected. For facade surfaces, a medium albedo value of around 0,4 is recommended to balance these effects. For pavement surfaces, an albedo value of 0,7 or higher is recommended (Lopez-Cabeza et al., 2022). Examples of medium albedo values are different clay and sand colors, while high albedo colors typically vary between white or light beige. Recoloring surfaces is especially practical when it is not feasible to change the material itself (e.g., building facades).

Cool surface material

For surfaces where modifying the material is more feasible (e.g., sidewalks) cool surface materials can be applied, characterized by their decreased heat capacity, increased reflectivity, and permeability (Osmond & Sharifi, 2017). To compare different cool materials, the thermal mass expresses the capacity of the material to absorb, store and release heat. Materials with a high thermal mass are for example asphalt or concrete, while wood and mudbrick (i.e., adobe) have low thermal mass values. When changing pavement materials, it is important to avoid sealing the surface (e.g., pavers with non-pervious joints).

Depaving sealed surfaces

Depaving streets and sidewalks helps to lower daytime and nighttime temperatures. Since unpaved and pervious surfaces have higher albedo and lower specific heat capacity values compared to many paved surfaces (Mills et al., 2021). Depaving parts of the pavement which are less intensely used by local traffic, also increases albedo values and specific heat properties. This intervention is not recommended in streets with a high traffic flow, due to dust formation (Tamminga et al., 2020).

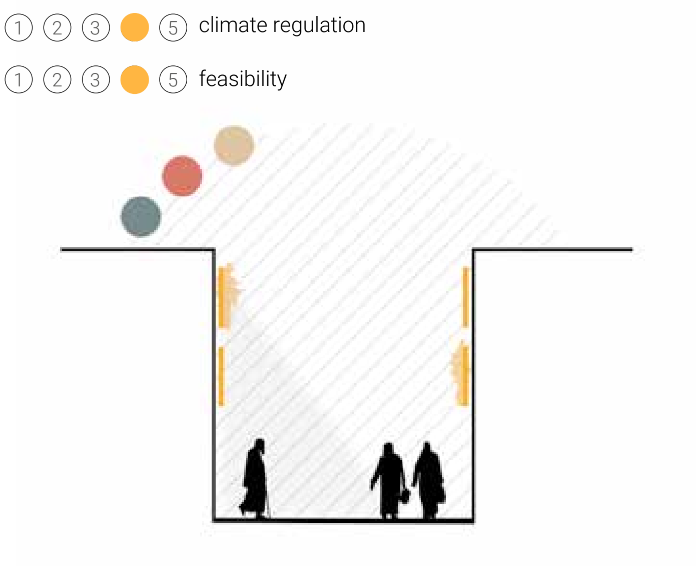


Fig. 11 Illustration of design intervention: vertical shading element.

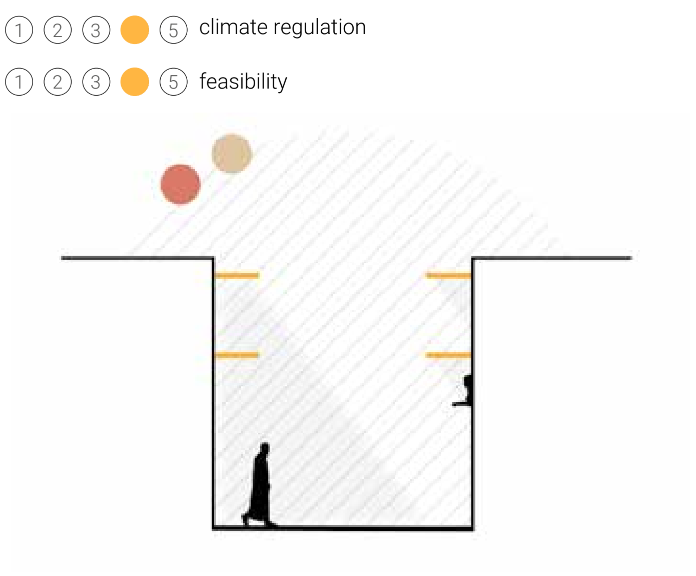


Fig. 12 Illustration of design intervention: horizontal shading element.

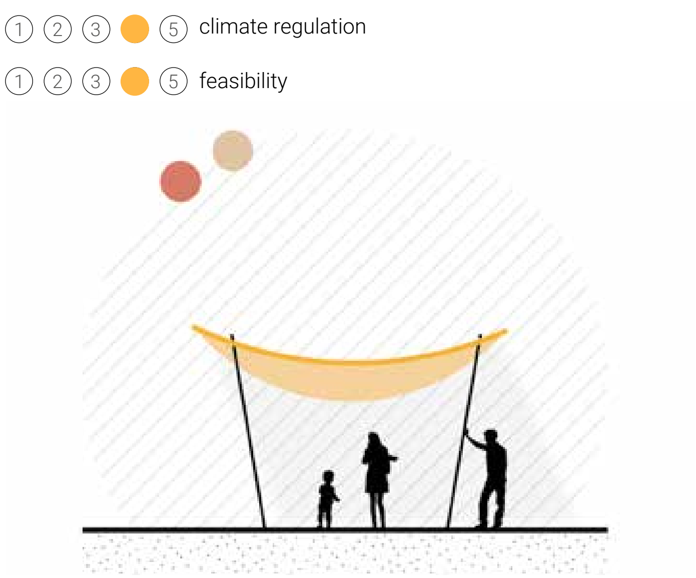


Fig. 13 Illustration of design intervention: canvas canopy.

4.2 SHADING

Shading as a cooling strategy describes the effect reached by blocking solar radiation from entering the urban canyon through the implementation of shading structures (La Roche et al., 2020). When implementing these interventions, solar gains are reduced by choosing cool materials.

Vertical and horizontal building elements

The first type of intervention focuses on shading vertical surfaces (i.e., building facades). The shading of building surfaces can be done in a multitude of ways. For example, attaching shading devices and vegetation on the facade, changing the shape of the building (e.g., colonnades) or adapting the urban geometry (e.g., shallow urban canyons) (City of Phoenix, 2008). However, considering the context of this study, only interventions that scored sufficient on both climate regulation potential and feasibility in unplanned areas are included. Therefore, more cost-intensive interventions such as adapting building shapes or urban geometry are excluded.

Vertical shading elements efficiently protect building facades from the low midday sun and are therefore especially important on east and west facades (City of Phoenix, 2008). For optimal efficiency, it is important that the screening elements are flexible and moveable along the building facades (e.g., windows and balconies). The materialization and design of such elements can be done in different ways, such as window shutters (e.g., wooden lattices), canvas screening (e.g., curtains) or green screening (e.g., vegetated panels). The latter allows for additional cooling through evapotranspiration.

Horizontal shading elements efficiently protect the north and south-facing facades from the high midday sun. Like the previous intervention, horizontal shading elements that are flexible and retractable can increase shading efficiency (City of Phoenix, 2008). Shading devices that are considered in this study are canvas or wooden awnings (e.g., wooden louvres).

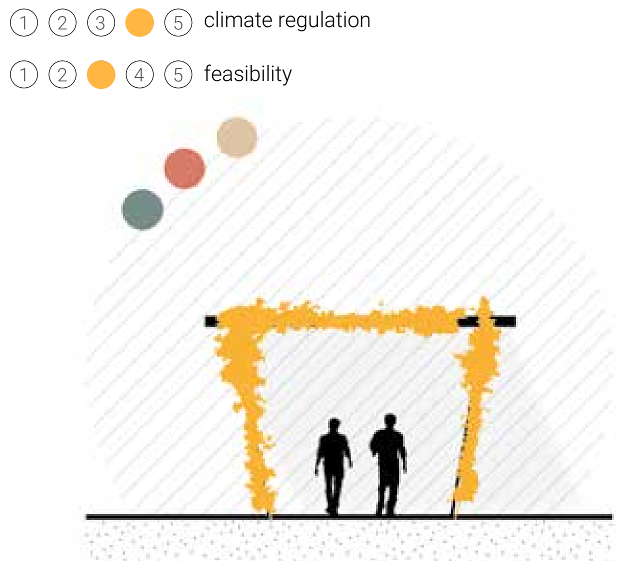


Fig. 14 Illustration of design intervention: pergola canopy.

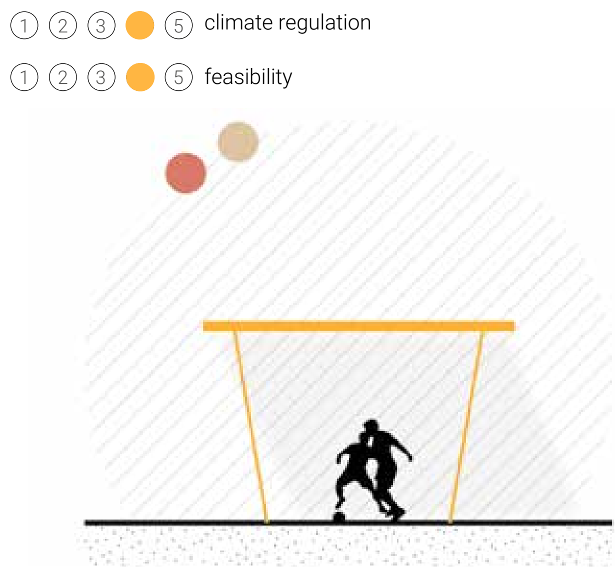


Fig. 15 Illustration of design intervention: louvre.

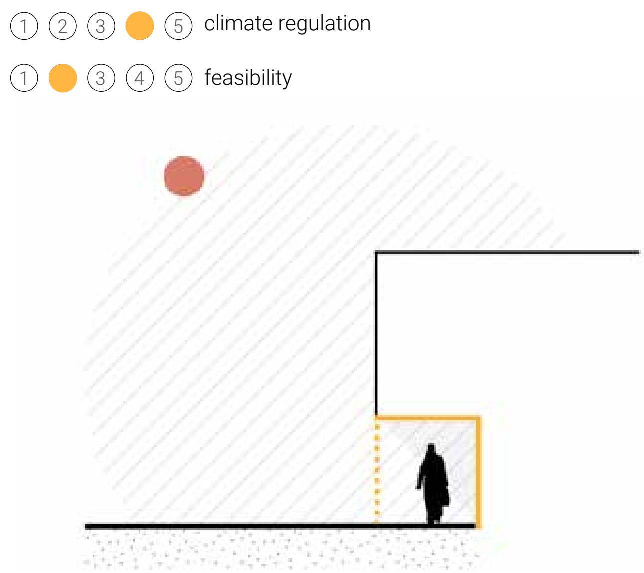


Fig. 16 Illustration of design intervention: colonnade.

Canopies (canvas canopies, pergola canopies, louvres and colonnades)

The second type of shading structures are canopies, which focus on shading horizontal surfaces (i.e., street surfaces). Canopies are located on street level and are either extended from building facades or free-standing. Materialization and design of such canopies vary greatly, however four subtypes can be distinguished: canvas canopies, pergola canopies, louvres, and colonnades.

Canvas canopies are flexible structures that can be opened and closed accordingly, allowing additional cooling during the night. Pergola canopies are fixed structures that provide both shade and evaporative cooling. Louvres are half-open structures, blocking direct solar radiation but allowing light and air to go through. The structure consists of multiple horizontal slats, with a specific distance and angle. When flexible, both the distance and angle can be adjusted to adapt to diurnal and seasonal changes. Colonnades are closed and often fixed structures, supported by an array of columns. Although colonnades can be free-standing structures, it is often part of a building (e.g., portico). When implementing this intervention, materialization and flexibility are important factors to consider. Since introducing a closed structure has the potential to trap heat, and this results in increased nighttime temperatures.

Vertical shading structure

Most canopy structures can be combined with vertical shading structures. These structures shade both street surfaces and building facades, while also decreasing wind nuisance (e.g., during sandstorms). This intervention is especially effective in wider streets when the solar angle is decreasing (i.e., morning and afternoon). Like with previous shading elements, flexibility and materialization are important factors to consider.

4.3 EVAPORATIVE COOLING

When daily outdoor temperatures are high, providing shade within the streetscape is not enough to improve thermal comfort and other strategies must be applied (La Roche et al., 2020). Aside from changing urban materials, more passive cooling strategies can be implemented, such as evaporative cooling. Due to water scarcity in arid climates, this is limited to increasing vegetation and the introduction of a passive evaporative cooling system within the streetscape.

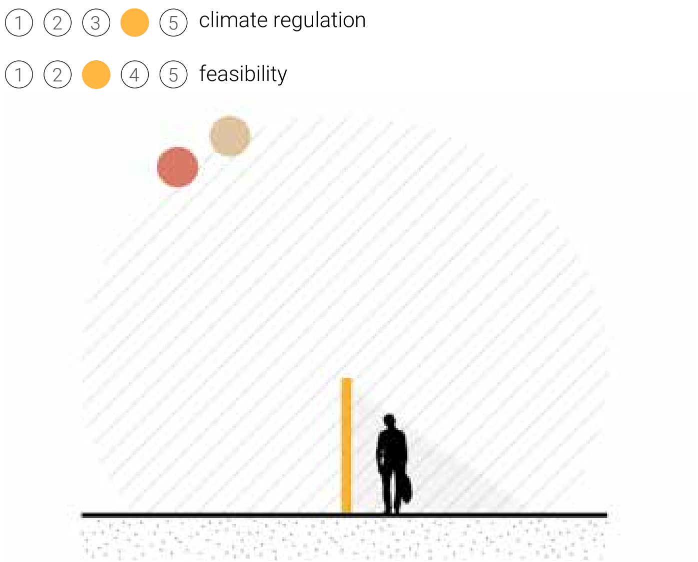


Fig. 17 Illustration of design intervention: vertical shading structure.

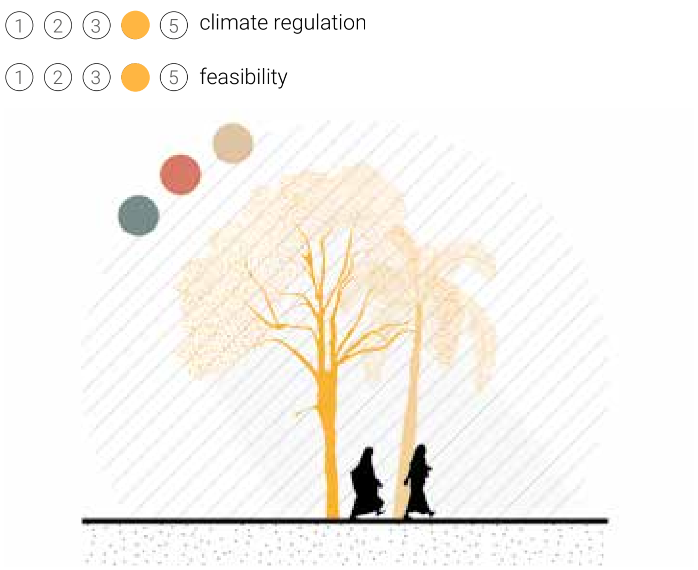


Fig. 18 Illustration of design intervention: trees.

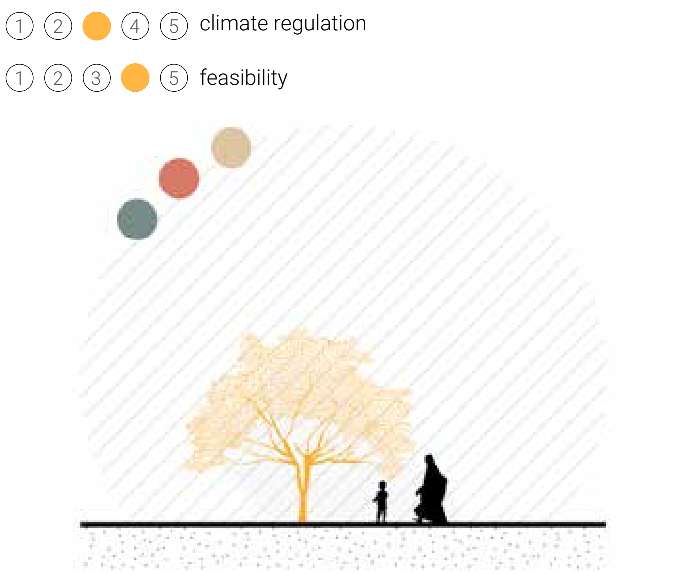


Fig. 19 Illustration of design intervention: shrubs.

Urban greenery (trees, shrubs, planters, ground cover vegetation, vegetated facades)

An increase in urban greenery improves thermal comfort and reduces PET values (Feyisa et al., 2014; Farhadi et al., 2019), through evaporative cooling and by protecting and shading urban surfaces (La Roche et al., 2020). The cooling effect depends largely on the selected species and the growing conditions, defined by site-specific factors such as sun, soil, water, and temperature (Dihkan et al., 2021). Species that are native to arid climates which have low water requirements and high drought tolerance are most suitable. However, it has to be considered, that the vegetation growing in arid climates shows a different cooling efficiency compared to vegetation in more temperate and humid climates. Due to high solar radiation and limited water availability, plants minimize the amount of moisture released throughout the day (i.e., evapotranspiration). Resulting in low evaporative cooling intensities during midday (Feyisa et al., 2014).

Within this study, five different urban greenery interventions are presented: trees, shrubs, planters, ground cover vegetation and vegetated facade. Trees are widely recognized as an effective cooling intervention. However, the cooling effect is determined by the spatial arrangement of trees (Wu & Chen, 2017), size and shape of the urban space and plant-specific properties (e.g., tree species, canopy cover and age of trees) (Feyisa et al., 2014). Like trees, shrubs have the potential to cool down surfaces (Dihkan et al., 2021). However, as shrubs are often smaller in size, both shading and evapotranspiration potentials are lower. When planting trees or shrubs in the open ground is not possible, planters can be used to introduce vegetation into the streetscape. In addition, ground cover vegetation has the potential, like other unpaved surfaces, to lower air temperature and PET (Aboelata & Sodoudi, 2019). When combined with other vegetation, the cooling effect will increase (Dihkan et al., 2021).

Lastly, to effectively protect and shade vertical urban surfaces (i.e., exterior walls of buildings), facades can be vegetated. Resulting in decreased heat gain by building facades (Dihkan et al., 2021). Climbing and trailing plants are used to vegetate the facade, either in the open ground or with the help of low-tech planter systems along the wall.

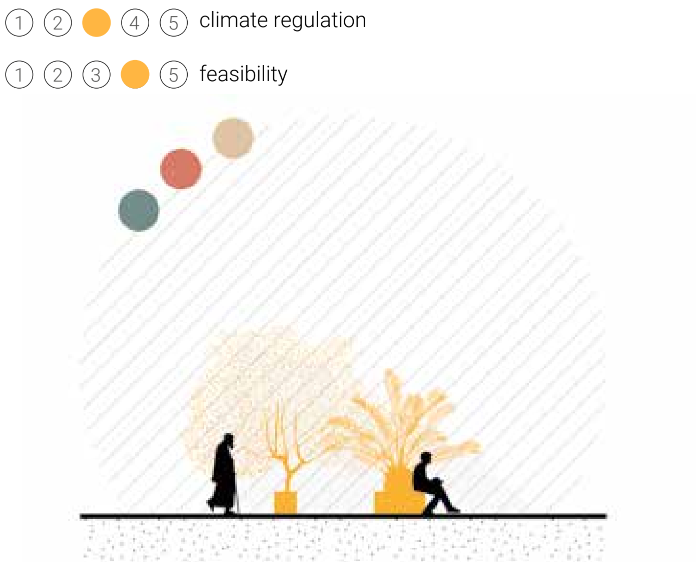


Fig. 20 Illustration of design intervention: planters with vegetation.

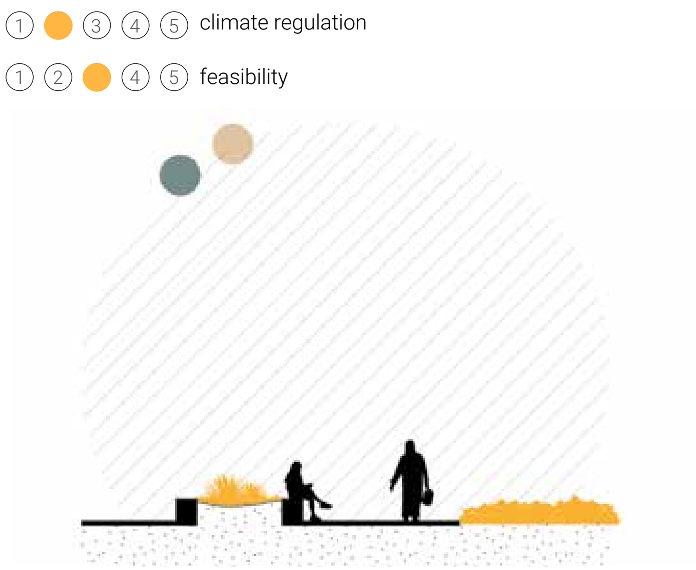


Fig. 21 Illustration of design intervention: ground cover vegetation.

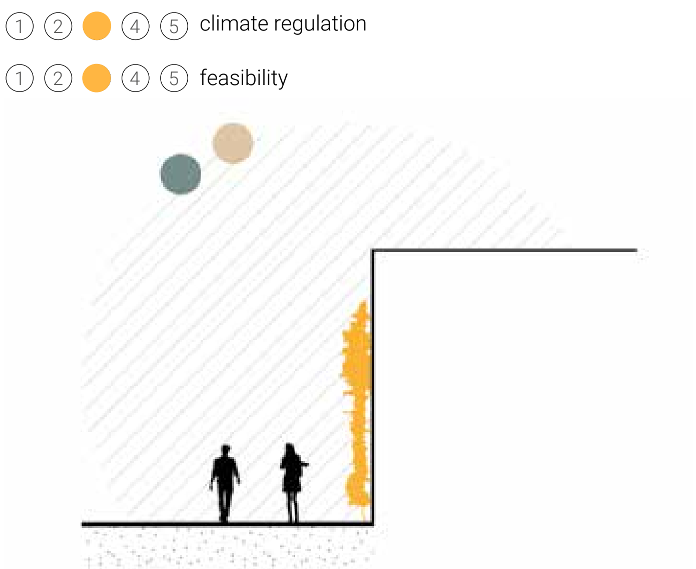


Fig. 22 Illustration of design intervention: green facade.

Artificial evaporative cooling systems

For climates with a low relative humidity value (70% or lower), implementation of a passive evaporative cooling system can decrease air temperatures. When evaporating water in a hot and dry environment, sensible heat from the air is exchanged for the latent heat within water vapor or wetted surfaces. Since no energy is used or lost during this process, evaporation can be categorized as a passive cooling intervention (La Roche et al., 2020). In Egypt, a traditional way to cool down air is through a porous pot (made of clay or ceramic), sometimes covered by a wet cloth. The wetted surface of the clay and the cloth functions as an evaporative cooling system. More contemporary methods of this system are for example water filled bricks or outdoor passive evaporative cooling walls (Tejero-González et al., 2021).

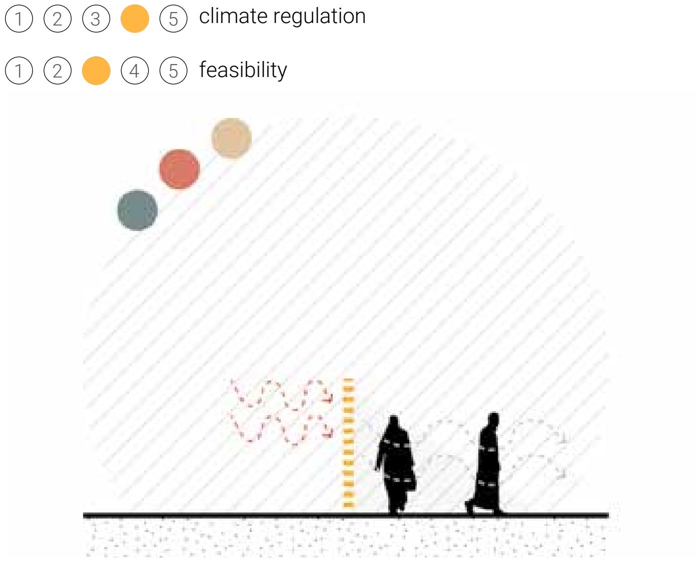


Fig. 23 Illustration of design intervention: passive evaporative cooling system (cooling wall or Egyptian qullah).

5. STREET TYPOLOGIES

This chapter presents the representative street typologies, which were used as testbeds to develop the design prototypes. Based on the literature review, spatial and climatic analysis of the study site and its context, and observations during the field visit, four main street typologies were identified. The findings of this analysis are presented below, followed by a description of the street typologies.

5.1 CONTEXT ANALYSIS

5.1.1 Greater Cairo Region

Cairo is the densely populated capital of Egypt, and with an urban population of more than 22 million inhabitants it is the 6th largest metropolitan area in the world (United Nations, 2019; Badwi et al., 2021). Cairo consists of several administrative districts, together defined as the Greater Cairo Region (GCR) (Figure 24), in which around 20% of the population of Egypt resides (Khalifa, 2015).

The built-up area within the GCR increased gradually from 466 km2 in 2001 to nearly 1000 km2 in 2017 (Badwi et al., 2021). The rapid annual growth rate of the population of more than 2% (United Nations, 2019) can be explained by the fact that the GCR is where Egypt's economic, political and cultural life is concentrated (El-Magd et al., 2016; Badwi et al., 2021).

Climate

The city, like most of Egypt, is situated within a hot-arid climate (classified as BWh within the Köppen-Geiger classification). The climate is characterized by large diurnal temperature variations, limited rainfall and hot winds (Table 3) (Elnabawi et al., 2013; Robaa, 2013). Spring (March to May) and autumn (September to November) are characterized by dust and sandstorms, with extreme conditions during spring months due to the hot desert depressions typical for the region. In winter (December to February) the climate is characterized by cold temperatures and humid and rainy conditions. Unlike the summers, where temperatures are extremely high and a dry and rainless climate is common (Robaa, 2003).

The predominant wind direction during the year is northerly (ranging from NW to NE), with strong enough windspeeds to penetrate the urban canopy layer (Robaa, 2003). Since the city is situated within

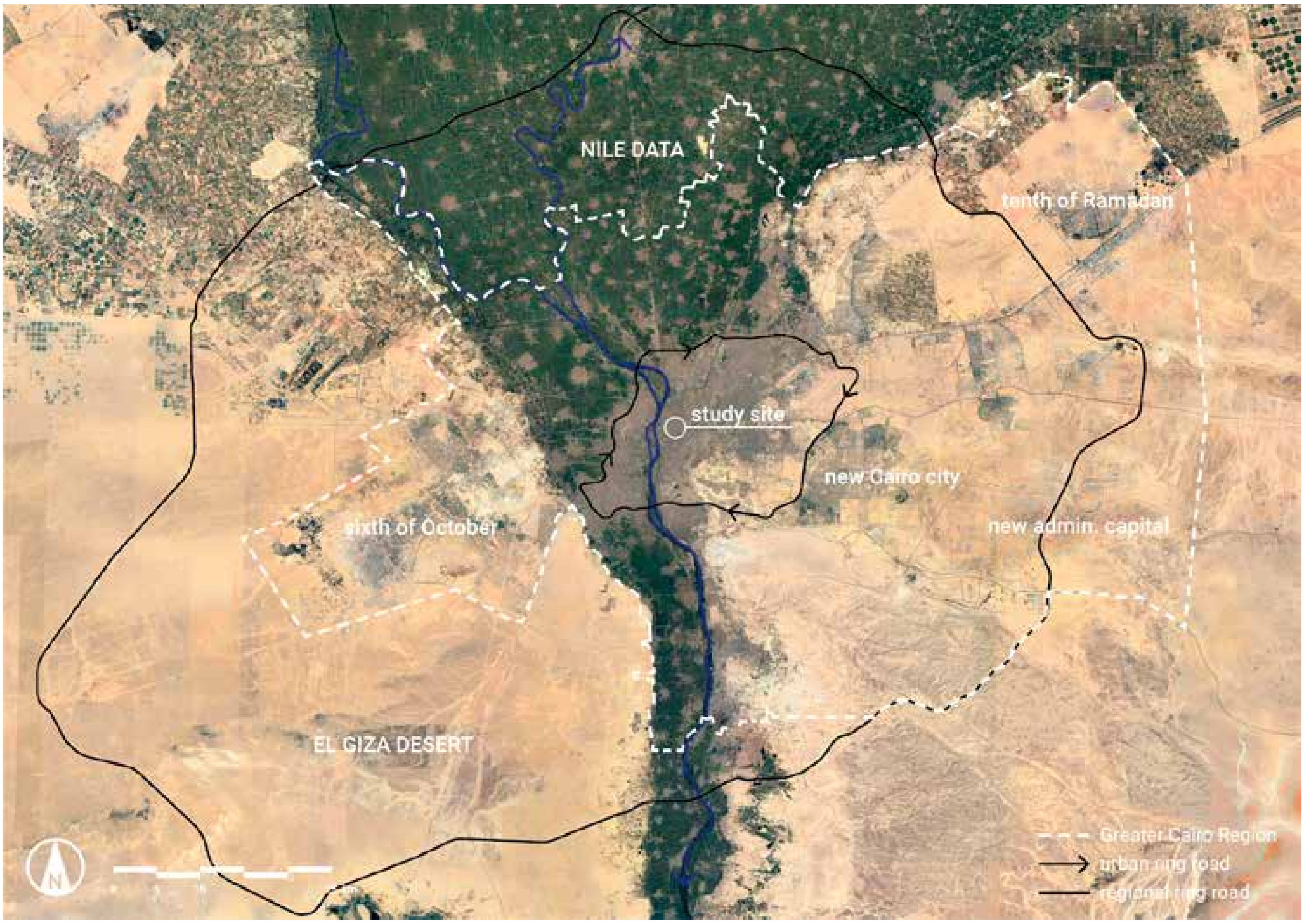


Fig. 24 True color satellite image illustrating the landscape in the greater Cairo region and the Nile delta. Image taken on date 30-08-2022.

the Nile delta, most of the topography is relatively flat. Combined with the surrounding mountain ranges and desert on the east and west, Cairo has a high vulnerability to shortwave radiation, elevated air-, and surface temperatures. Microclimatic conditions are further worsened due to high levels of anthropogenic heat, caused by for example AC systems and high car dependency.

Unplanned urban areas within GCR

Due to the fast urbanization, informal areas increasingly became the rule and not the exception within the GCR (Badwi et al., 2021). The saturation and limitation of formal housing within the city contributed to the development of densely populated informal areas. Statistics show that around 64% of the urban population lived in informal areas in 2009, only taking up 40% of the urban mass of the GCR (El-Shahat & El Khateeb, 2013). Within the GCR, informal areas have been developing since the 1960s, converting desert or agricultural lands into built-up areas (Hereher, 2017; Badwi et al., 2021). The shift from an agriculture-based economy to an industrial- and service-based economy was one of the main drivers of change. This led to a sudden population increase and combined with inadequate housing policies middle and low-income families had to resort to informal housing. After 1975, privatization and new regulations provided another input for change. Since 1980, almost no new informal areas have been constructed within the GCR, due to new legislations and a decrease in population growth rates. However, the growth within existing informal areas in the GCR did not slow down. From 1992 onwards, the government started several national programs, aiming to 'upgrade' informal areas through the provision of services and infrastructures. However, this resulted in an accelerated growth of informal areas. In response to this, new national programs and strategies were launched by the government to restrict further growth of informal areas (El-Shahat & El Khateeb, 2013).

5.1.2 Study site

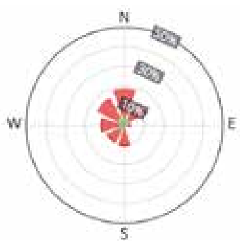
The selected study site is located within the district of Shubra (30°06'93"10N, 31°24'97"55E). The district consists of both planned and unplanned areas, has a total population of approximately 81.000 residents (CAPMAS, 2018) and covers an area of around 140 ha. The study site is situated in the South of the district and has a total area of around 20 ha. Bordered on the East by the Emtedad Ahmed Helmi road and the national train line, on the West by the El Teraa Al Bolakia street, on the South by the Ahmed Badawi street and on the North by the Samoaeel Morkos street (Figure 25).

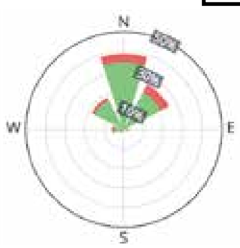
Located at the heart of Cairo's surface skin urban heat island (Figure 26) and within a heat accumulation zone (Figure 27), the study site has a high climatic vulnerability. The irregular urban geometry, narrow streets, high buildings, limited amount of vegetation or open spaces, lack of porous materials and/or moisture-trapping surfaces, and the prevalence of sealed surfaces are all factors contributing to this vulnerability.

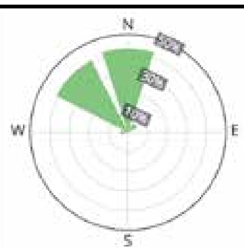
Table 3. Overview of yearly weather conditions in Cairo - data presented are averages based on ECMWF Data (1991 - 2021) and satellite data (adapted from climate-data.org, weatherspark.com and predesign.sketchup.com)

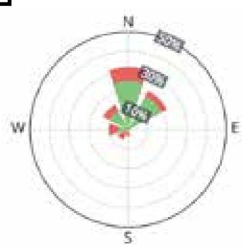
	WINTER		SPRING			SUMMER				AUTUMN		
	January	February	March	April	May	June	July	August	September	October	November	December
avg. temperature (°C)	13,4	14,8	17,9	21,4	25,3	27,9	29,1	29,2	27,4	24	19,4	15,1
min. temperature (°C)	7,8	8,7	10,8	13,6	17,1	19,7	21,3	21,8	20,3	17,7	13,7	9,8
max. temperature (°C)	19,2	21,1	24,9	29	33,1	35,8	36,8	36,6	34,5	30,4	25,5	20,8
precipitation (mm)	5	4	3	1	0	0	0	0	0	1	2	2
humidity (%)	54%	47%	42%	37%	36%	40%	45%	47%	48%	52%	54%	55%
rainy days (d)	1	1	0	0	0	0	0	0	0	0	0	0
avg. sun hours (h)	7,9	8,8	10,0	11,1	11,9	12,1	11,6	10,9	10,3	9,6	8,6	7,9
avg. wind speed (m/s)	3,7	3,8	4,1	4,3	4,4	4,5	4,1	3,9	4,0	3,8	3,6	3,6

wind direction









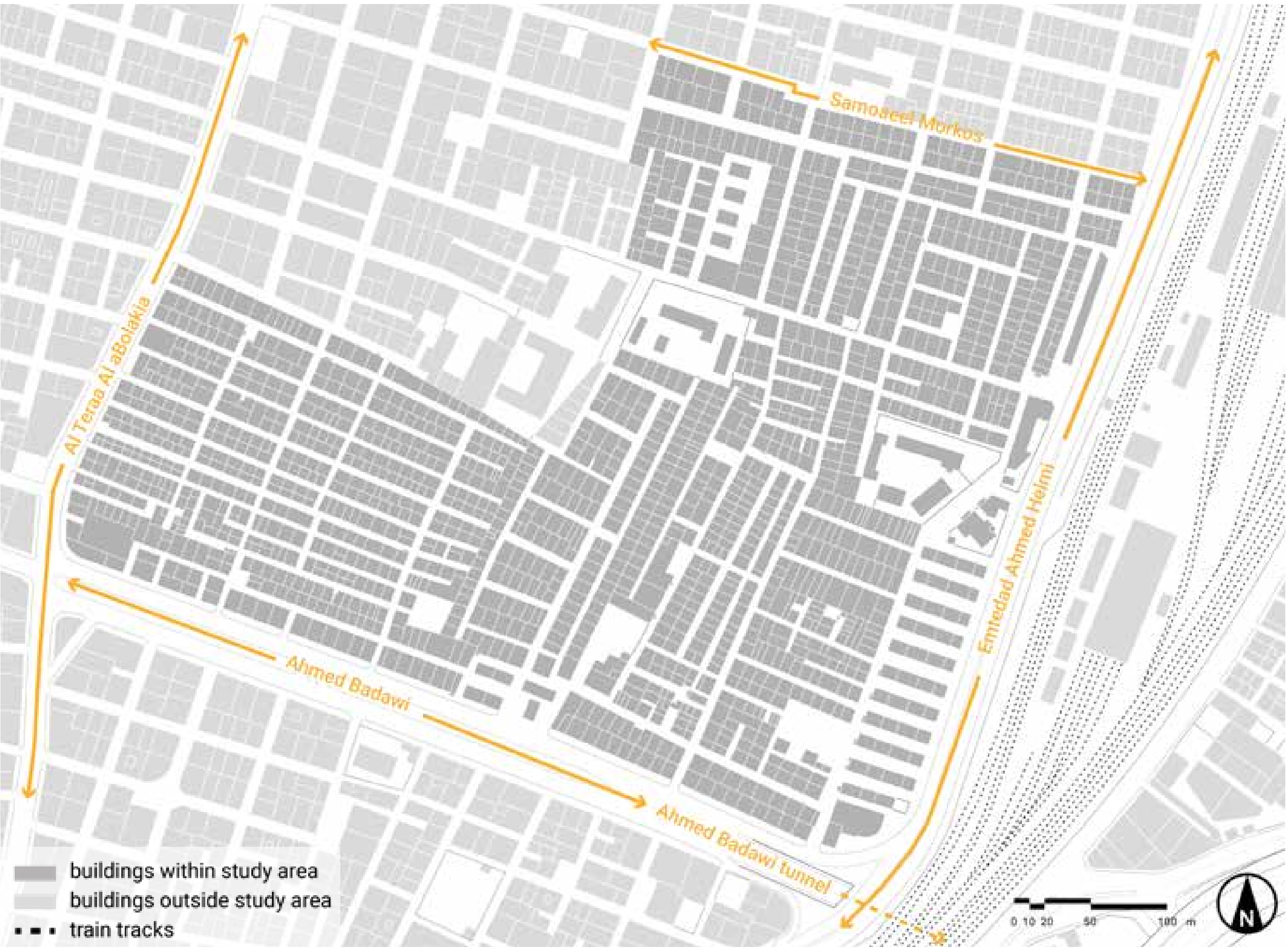


Fig. 25 Map of spatial location and situation of the study area, bordered by three major roads in the East, South and West and by the national train line in the East.

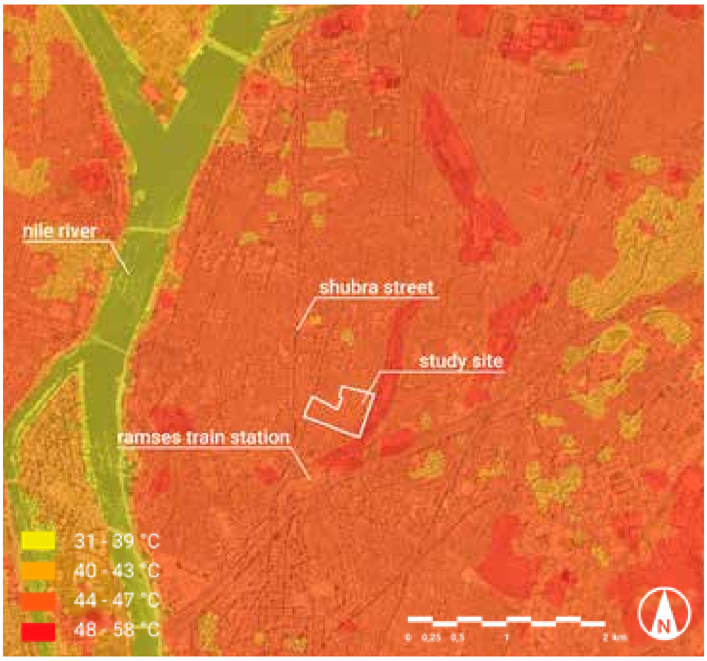


Fig. 26 Map of observed land surface temperature (LST), projecting the spatial distribution of the surface heat island for the study area. Mapped using Google Earth Engine Open-Source Code for LST estimation from the Landsat series and calculated for 1st-15th July 2022.

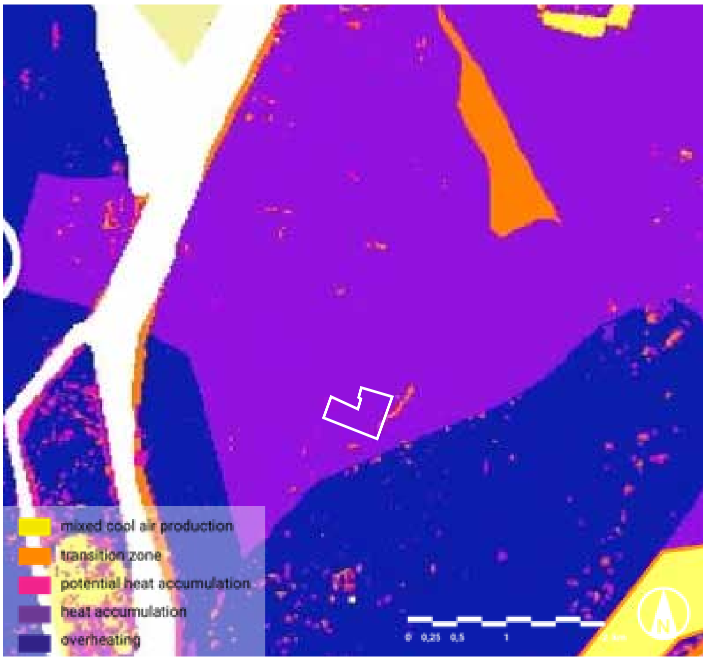


Fig. 27 Map of heat accumulation zones for the study area, based on a GIS analysis (adapted from Khalil et al., 2018)

Examples of these characteristics are illustrated in Figures 28-30. Additionally, since common building materials within the neighborhood consist of concrete and bricks, high amounts of solar radiation are absorbed and retained within the area (Wonorahardjo et al., 2020). There is also a distinctive lack of plastering or painting, which results in low thermal resistance of the building facades (Mohammad & Shea, 2013). High dependency on motorized traffic increases anthropogenic heat and pollution levels. Which in turn reduces air transparency and trap heat within the streetscape, ultimately preventing the cooling by re-radiation during night-time (Bek et al., 2018).

MICROCLIMATIC PATTERNS WITHIN AN URBAN CANYON

Microclimate within an urban canyon is mainly impacted by the height-to-width (H/W) ratio and the street orientation. H/W ratio is defined by the building's height versus the width of the street. Street orientation is defined as the axis orientation of the canyon (e.g., north-south or east-west). These two criteria affect how much solar radiation is entering the urban canyon, thus, defining microclimatic conditions within the streetscape. Ambient temperatures during the day increase with decreasing H/W ratios (Bakarman & Chang, 2015). In other words, horizontal and vertical surfaces in wide or shallow urban canyons are more exposed to solar radiation, as opposed to deep and narrow urban canyons. Bakarman & Chang (2015) found that "*The exposure of urban surfaces to the sun in an urban profile decreases as the profile becomes deep. The more solar radiation is received by the surface, the larger the net radiation is left at the surface and the greater sensible heat is added into the ambient air, leading to a significant increase in its temperature*" (p. 107). The same study found that ambient temperatures in urban canyons are peaking between noon and 13:00 when solar radiation is the strongest. During the night, both shallow and deep canyons experience increased temperatures (i.e., nocturnal heat island effect). An opposite pattern can be detected comparing shallow and deep urban canyons. Deeper canyons (higher H/W ratios) experience higher ambient temperatures during the night, compared to shallow canyons (lower H/W ratios). This can be explained by the fact that canyons with higher H/W ratios tend to trap heat within the profile (i.e., low SVF) and canyons with lower H/W ratios have increased potential for cooling through natural ventilation (i.e., wind is more likely to enter the streetscape) (Bakarman & Chang, 2015).

Fig. 28 Photo illustrating the streetscape of one of the many narrow streets within the study area.

Fig. 29 Photo illustrating the lack of porous materials and prevalence of sealed surfaces within the streets of the study area.

Fig. 30 Photo illustrating the high building geometry which influence shadow patterns within the study area.

5.2 STREET TYPOLOGIES

The identification of the street typologies is based on two main criteria: height-to-width (H/W) ratio and street orientation. Based on their H/W ratio, the four main typologies are: narrow street, medium street, wide street, and open spaces (Figures 31-34). Each typology has two subcategories, to cover the north-south (N/S) and east-west (E/W) orientation, resulting in a total of eight typologies.

The presented street typologies are described in the following section based on these two criteria. Additionally, the relevance of each typology is described based on predominant functions (streets and adjacent buildings), urban materials, occurrence of vegetation and mobility. Figure 35 shows an overview of the four main street typologies and where they are located within the study area.

5.2.1 Typology T1 | narrow street (N/S and E/W)

Narrow streets have an average width of 5 m and range from 1,5 to 10 m wide. The height of the buildings along this street profile varies tremendously, which is typical for the whole neighborhood. Building heights of 6, 9 and 12 m occur most, resulting in a representative height-to-width ratio of 2:1 and 1:1. This type of street gives access to residential areas, and serves as public space. Small-scale shops and local cafés or restaurants use the streetscape for their commercial businesses. Furthermore, schools and mosques can also be located within this street typology, which influence the use of the streetscape accordingly (e.g., people gathering for prayer). Although space is limited, some of the wider streets and street junctions comprise vegetation (e.g., trees or planters). The surface is often unpaved, and the street is typically without a sidewalk or other ways of spatial separation of functions and users (i.e., people, vehicles and sometimes animals share the street). The predominant functions are residential, small-scale informal activities (e.g., street vendors or markets), motorized and pedestrian traffic, car parking, and social meeting.

5.2.2 Typology T2 | medium street (N/S and E/W)

Medium streets have an average width of 20 m and range from 15 to 25 m wide. Predominant building heights are 9, 12, 15 and 18 m, resulting in a representative height-to-width ratio of 1:2 and 1:1. This street type can be characterized as a secondary road, fully paved, and one that connects different neighborhoods. Buildings are mainly residential, with some small local businesses on the ground floor. Like narrow streets, building functionality is not limited by commercial purposes, but ranges from public services to leisure, and religious functions. Vegetation is planted

NARROW STREET (T1)

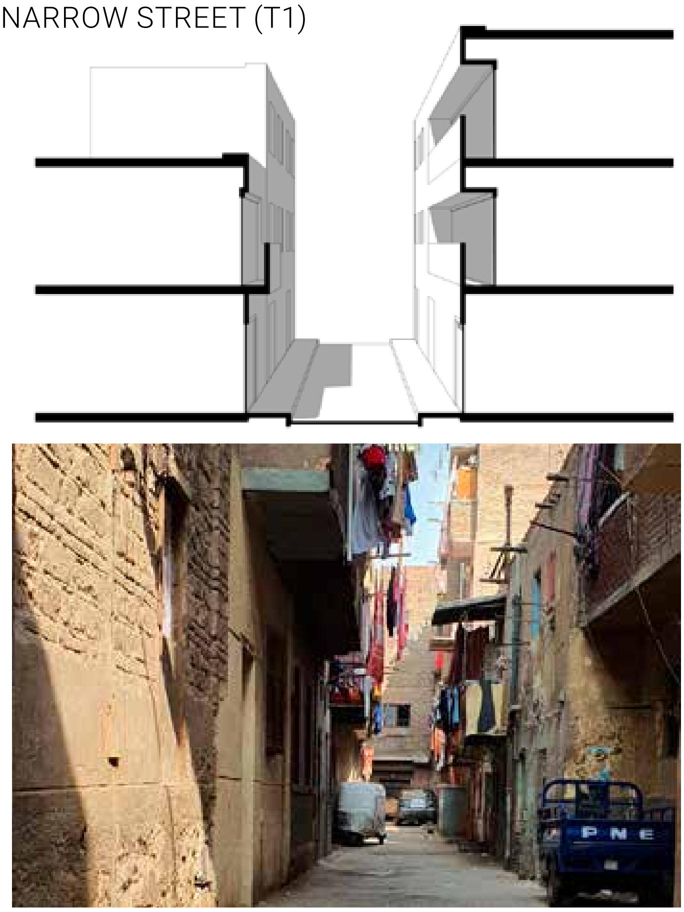


Fig. 31 Schematic representation of narrow street typology (T1) (above) and reference picture from study area (below).

MEDIUM STREET (T2)

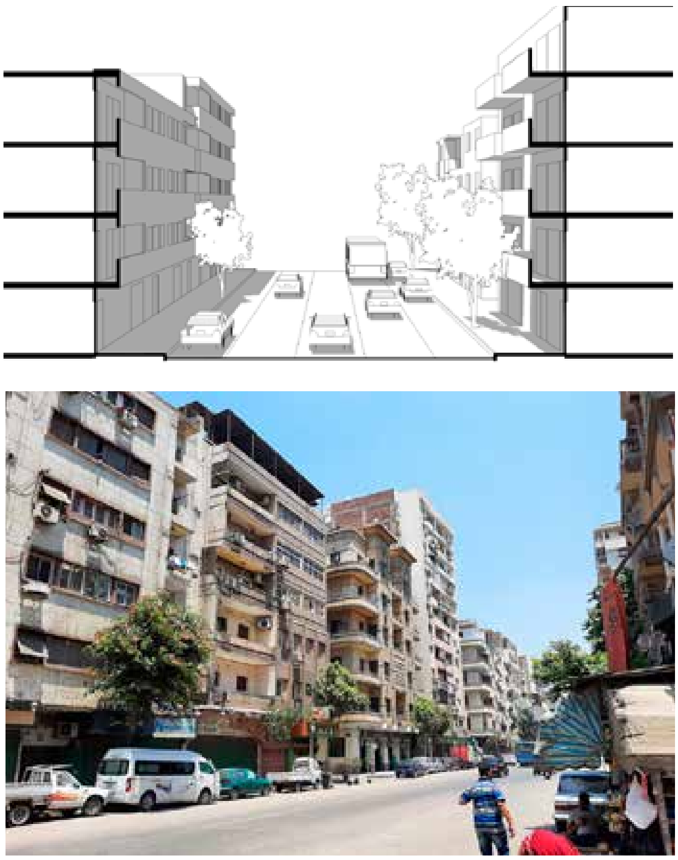


Fig. 32 Schematic representation of medium street typology (T2) (above) and reference picture from study area (below).

alongside the edges of the profile, ranging from older full-grown trees to smaller younger trees, shrubs, and creepers. Sidewalks are minimal, and the streetscape is dominated by motorized traffic. Along the sides of the road, small street vendors, bus stops and parking spots are located. The predominant functions of this typology are residential, small local business, street vendors, motorized and pedestrian traffic, and car parking.

5.2.3 Typology T3 | wide street (N/S and E/W)

Wide streets have an average width of 38 m and range from 30 to 45 m wide. Predominant building heights are 12, 15, and 18 m resulting in a representative height-to-width ratio of 1:3 and 1:2. This street type can be characterized as a primary road, fully paved, and connects neighborhoods and districts. Heavy traffic flowing in both directions dominates the streetscape. Sidewalks tend to be a little bit wider compared to medium streets. Vegetation is planted in planting pits on sidewalks, ranging from full-grown trees, young trees, and shrubs. The road is in most cases split by a traffic island, varying in size and material (e.g., fully paved or with vegetation). While most of the horizontal surface within this profile is dedicated to infrastructural functions, building fronts are mainly used for commercial functions. Local businesses (e.g., retail, restaurants, workshops) are located on the ground floor, while the rest of the building often has a residential function. While commercial activities dominate the streetscape, other functionalities such as mosques, offices and event locations are also present. The predominant functions at street level are residential, local businesses, motorized and pedestrian traffic, and car parking.

5.2.4 Typology T4 | (semi-) open space (N/S and E/W)

The shape and size of the semi-open and open outdoor spaces vary considerably throughout the study area (ranging from 120 to 25.000 m2). The average areas for the two subtypes are respectively 369 m2 (semi-open) and 1905 m2 (open). For the sake of simplicity, the profile of this typology uses an average width of 25 m and abstracts the area to a squared space. Open spaces have different functionalities, such as parking spots, markets, and schoolyards. They are often located within the residential area; however adjacent buildings can fulfil other functions (e.g., schools or mosques) and can be accessed via narrow streets (T1). Depending on their size and function of the space, vegetation is limited. Generally, open spaces within the study area are privately owned, and often fenced off from the public. These spaces are typically owned by either local governments (e.g., car parking places), schools or mosques.

MEDIUM STREET (T3)

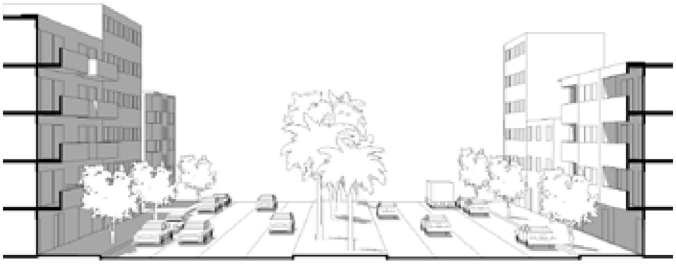


Fig. 33 Schematic representation of wide street typology (T3) (above) and reference picture from study area (below).

OPEN SPACE (T4)

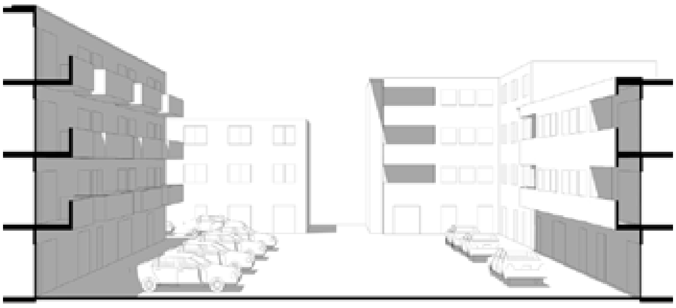


Fig. 34 Schematic representation of open space street typology (T4) (above) and reference picture from study area (below).

Fig. 35 Spatial overview of the representative street typologies T1-T4 and their distribution at the Shubra district.

6. DESIGN PROTOTYPES

The prototypes presented in this chapter are identified as the most effective way of bringing together the identified interventions within the defined street profiles. The design prototypes are based on three iterations of design and testing. According to the described methodology, the selected seven experts were asked to grade the effectiveness or feasibility of the presented interventions within the different street typologies. The outcomes of the assessment rounds and final design prototypes are described in the following section.

Each intervention serves different cooling strategies, and thus, optimal cooling effects can be achieved by combining them. The cooling strategies are focused on changing radiative and thermal properties of urban materials, blocking solar radiation by providing shade, increasing passive cooling through evaporation, and introducing vegetation within the streetscape. The street profiles are typically lined with tall buildings on both sides, so part of the streetscape is protected from direct solar radiation in the morning and late afternoon hours (depending on the specific H/W ratio). However, when the sun is reaching solar noon, local ambient temperatures increase tremendously. As the prototypes are modeled for extreme climatic conditions, diurnal and seasonal patterns were considered. The prototypes are modeled around solar noon on the longest day of the year (21/06/21 13:00 GMT+2) for a cloud-free atmosphere.

Since not all eight typologies occur within the study area (i.e., medium street E/W is not present), and two street typologies resulted in no detectable difference between design interventions for both orientations (i.e., wide street and open spaces E/W and N/S), the number of typologies is reduced from eight to five (Figure 36).

Fig. 36 Schematic overview of the different street typologies identified, the ones used as testbeds during the prototype development are marked and numbered.

6.1 PROTOTYPE 1 | 1A NARROW STREET N/S AND 1B NARROW STREET E/W

6.1.1 Characterization of prototype

Although space is limited within narrow street profiles, multiple design interventions can be implemented to improve outdoor comfort (Figures 37 and 38). The small-scale climate-adaptive design interventions that design prototype 1 combines, are presented below.

Adapting urban materials

To decrease heat storage within urban surfaces and increase reflectivity, the albedo of building facades and ground surfaces is increased, and cool surface materials are used where possible. This can be done by repainting building facades with light-colored paint or by paving horizontal surfaces with cool surface materials (e.g., light-colored clay bricks). For parts of the street which are less intensely used by local traffic, interventions such as depaving and/or use of loose permeable ground covers (e.g., gravel or bare soil) are effective to minimize heat gains.

Implementing shade

The street surface is shaded by flexible canvas canopies, while the building facades are shaded by vertical and horizontal shading elements. The narrow width of this street type allows the canopy to stretch over the entire width of the urban canyon. To allow additional cooling during the night, the canopy structure is retractable and can be adjusted accordingly. The position of these canopy structures is different in prototype 1a and 1b, due to the street orientation and prevailing wind direction. With a predominant wind direction from the North, natural ventilation can occur in prototype 1a, whereas in prototype 1b the wind will be skimming over the canyon. To allow natural ventilation in 1a, the position of the canopies is lower and varies more over the profile length. This also allows adjustments to varying wind speeds during summer and winter. Other canopy structures were graded as unsuitable since fixed canopy structures would trap heat and increase nighttime temperatures.

Increasing evaporative cooling

Trees, shrubs, and ground covers were also graded as unsuitable for narrow street profiles. Trees may trap longwave radiation and block wind. Moreover, as the street profile is very narrow, other vegetation types (i.e., shrubs and ground cover) may impair the transit of people and vehicles. Alternatively, building facades can be vegetated by climbing vegetation to help shade the building's exterior and add evaporative cooling. Finally, low-tech passive evaporative cooling systems (e.g., Egyptian qullah) are introduced in front of windows or balconies.

6.1.2 Assessment of the prototype

The results of the expert judgement assessment of prototype 1a and 1b are presented in Tables 4 and 5. Between the two different assessment rounds (P1 and P2), the effectiveness and feasibility scores are improved for all seven criteria. During the first iteration (P1), the nature-based and artificial alternatives scored generally similar grades: 3 (effective/feasible) or 4 (high effectiveness/feasibility). However, both prototypes 1a and 1b scored lower during this round for mobility and equity criteria. Finally, the integrated versions (P2) of both prototypes received approximately the same scores, both prototype 1a and 1b scored either 4 (high effectiveness/feasibility) or 5 (very high effectiveness/feasibility). The lowest score was for equity: 3 (effective/feasible). During the last iteration (P3), the match of design interventions with the ones proposed during the workshop (Table 2) confirms the adequacy of the interventions selected for prototype 1a and 1b.

Table 4. Results of the assessment of prototype 1a | narrow street N/S based on the score ranges from 1-5

	climate-responsive design	urban climate	land use	genius loci	mobility	equity	affordibility
P1 nature based	4	3	3	3	4	3	3
P1 artificial	4	4	3	4	2	4	3
P2 integrated	5	4	5	5	4	3	4

Table 5. Results of the assessment of prototype 1b | narrow street E/W based on the score ranges from 1-5

	climate-responsive design	urban climate	land use	genius loci	mobility	equity	affordibility
P1 nature based	4	3	3	3	3	4	4
P1 artificial	4	3	3	4	2	2	4
P2 integrated	5	4	5	5	4	3	4

DESIGN PROTOTYPE 1A | NARROW STREET N/S

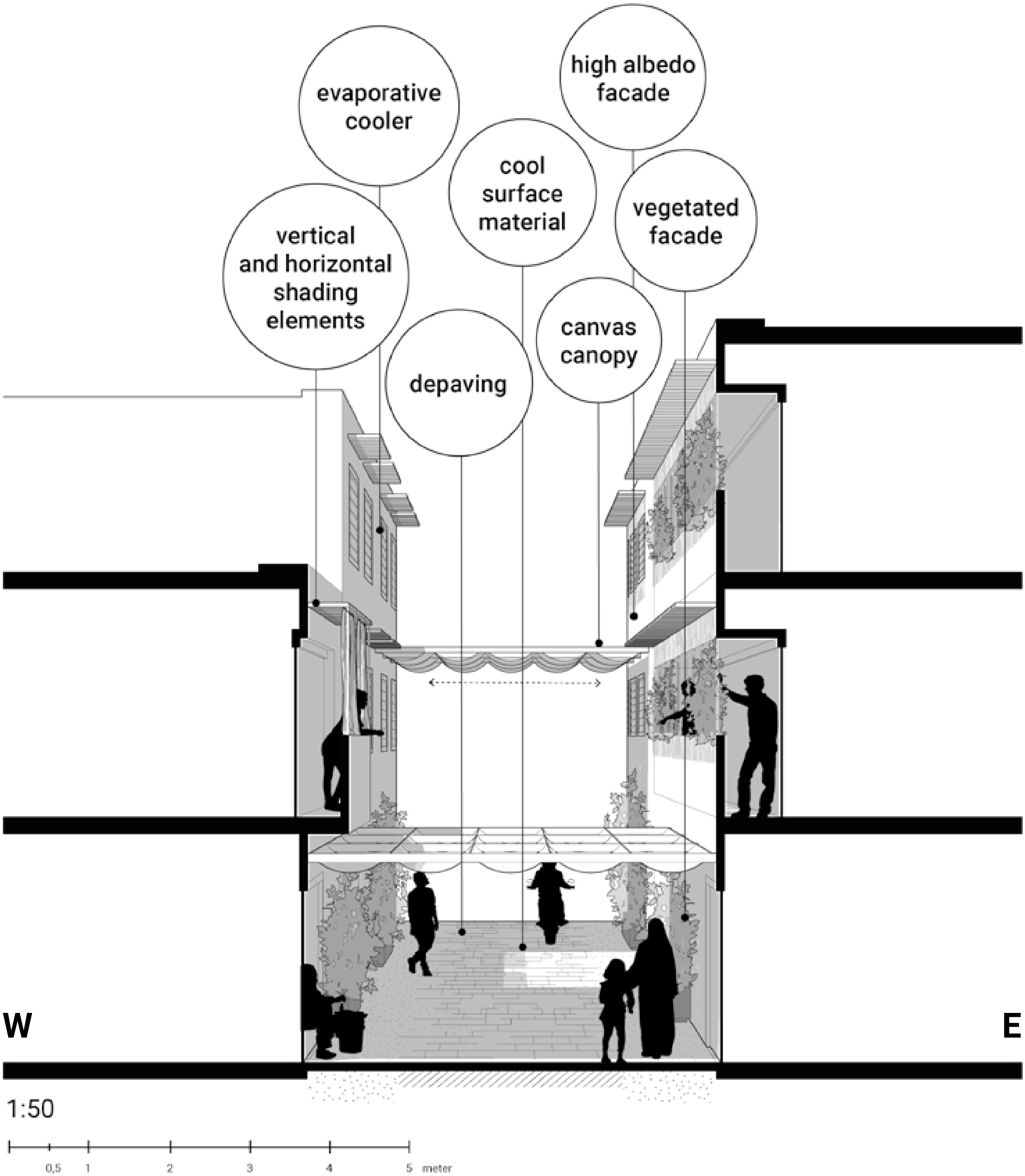


Fig. 37 Illustration of design prototype 1a | narrow street N/S

DESIGN PROTOTYPE 1B | NARROW STREET E/W

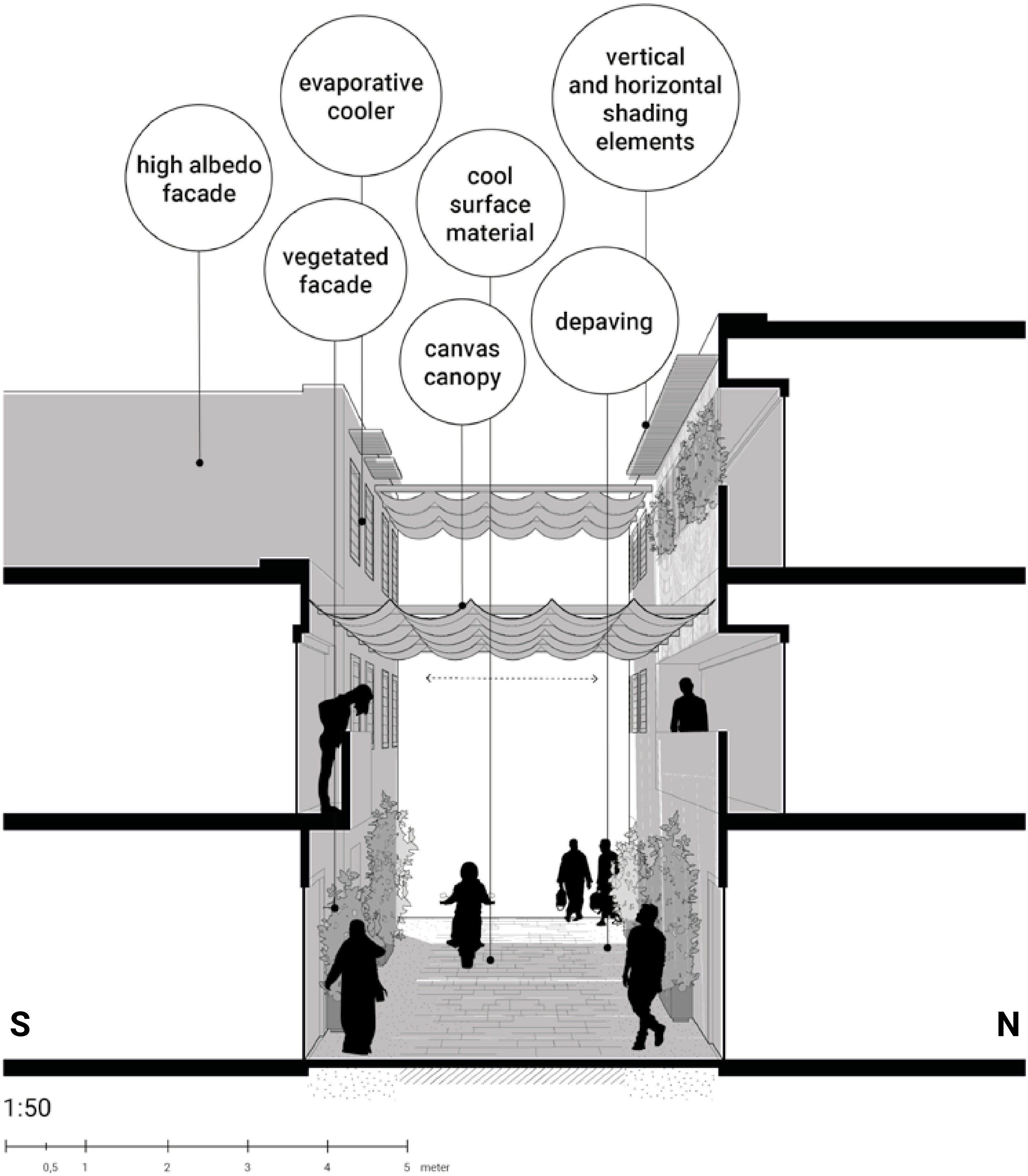


Fig. 38 Illustration of design prototype 1b | narrow street E/W

6.2 PROTOTYPE 2 | MEDIUM STREET N/S

6.2.1 Characterization of prototype

Prototype 2 combines small- and large-scale climate-adaptive spatial design interventions within the streetscape of medium streets. Since the street profile is wider compared to the previous prototype, more interventions per climate-adaptive strategy can be implemented (Figure 39).

Adapting urban materials

The albedo of the building facades, ground surfaces and roads is increased by applying light-colored paint and/or new cool surface materials within the profile. For example, road surfaces can be painted to decrease heat storage and increase reflexivity. Since it is more feasible to change surface materials along sidewalks, pedestrian areas are paved with cool surface materials (e.g., light-colored clay bricks). To further decrease paved surfaces, depaving should occur as much as possible without obstructing car circulation. Between the road and sidewalks, depaved strips can create space for vegetation and protect pedestrians from car traffic.

Implementing shade

Building facades are protected from incoming solar radiation by implementing vertical and horizontal shading elements (e.g., window shutters, rotational louvres, or curtains). The vertical shading elements protect east and west facades from low midday sun, while horizontal shading elements protect north and south facades from high midday sun. Applying green screening interventions (e.g., vegetated panels along balconies), results in additional cooling through evaporation. Finally, sidewalks and parking spots can be shaded by implementing different types of canopies. Flexible structures, like canvas canopies, allow nocturnal cooling and are thus the preferred option.

Increasing evaporative cooling

Trees, shrubs, and ground cover vegetation are planted in the depaved strip between the sidewalk and road, providing both evaporative cooling and shade. To avoid an increase in temperatures, trees and higher shrubs are planted in an alternating spatial arrangement. This is important because vegetation has the potential to block wind when the prevailing wind direction is parallel to the street's orientation. To reduce the vulnerability of trees and shrubs to damage (e.g., stepping or car parking), ground cover vegetation can be planted within the same area. The pockets with vegetation are alternated with parking spots, to minimize negative effects on mobility (car circulation) and functionality (e.g., space for freight and service operators). Alongside the sidewalk, climbing plants can vegetate parts of the building's facade, planted in the ground, raised planters or pots.

6.2.2 Assessment of the prototype

The results of the expert judgement assessment of prototype 2 are presented in Table 6. During the second iteration, in most cases, the prototypes scored either higher than or the same as in the first assessment round (P1). This indicates that the final prototype managed to effectively integrate the best-scoring interventions, generally scoring either 4 (high effectiveness/feasibility) or 5 (very high effectiveness/feasibility). The assessment of affordability had the lowest score: 3 (effective/feasible). This can be explained by the high maintenance costs of implementing urban greenery and its related cost of irrigation. Although these costs can be initially high, more matured vegetation will have a lower water demand once the root network is developed. During the last iteration (P3), the match of design interventions with the ones proposed during the workshop (Table 2) confirms the adequacy of the interventions selected for prototype 2.

Table 6. Results of the assessment of prototype 2 | medium street N/S based on scores ranges from 1-5

	climate-responsive design	urban climate	land use	genius loci	mobility	equity	affordibility
P1 nature based	4	4	3	3	3	4	3
P1 artificial	4	5	5	4	3	3	5
P2 integrated	5	4	5	4	4	4	3

DESIGN PROTOTYPE 2 | MEDIUM STREET N/S

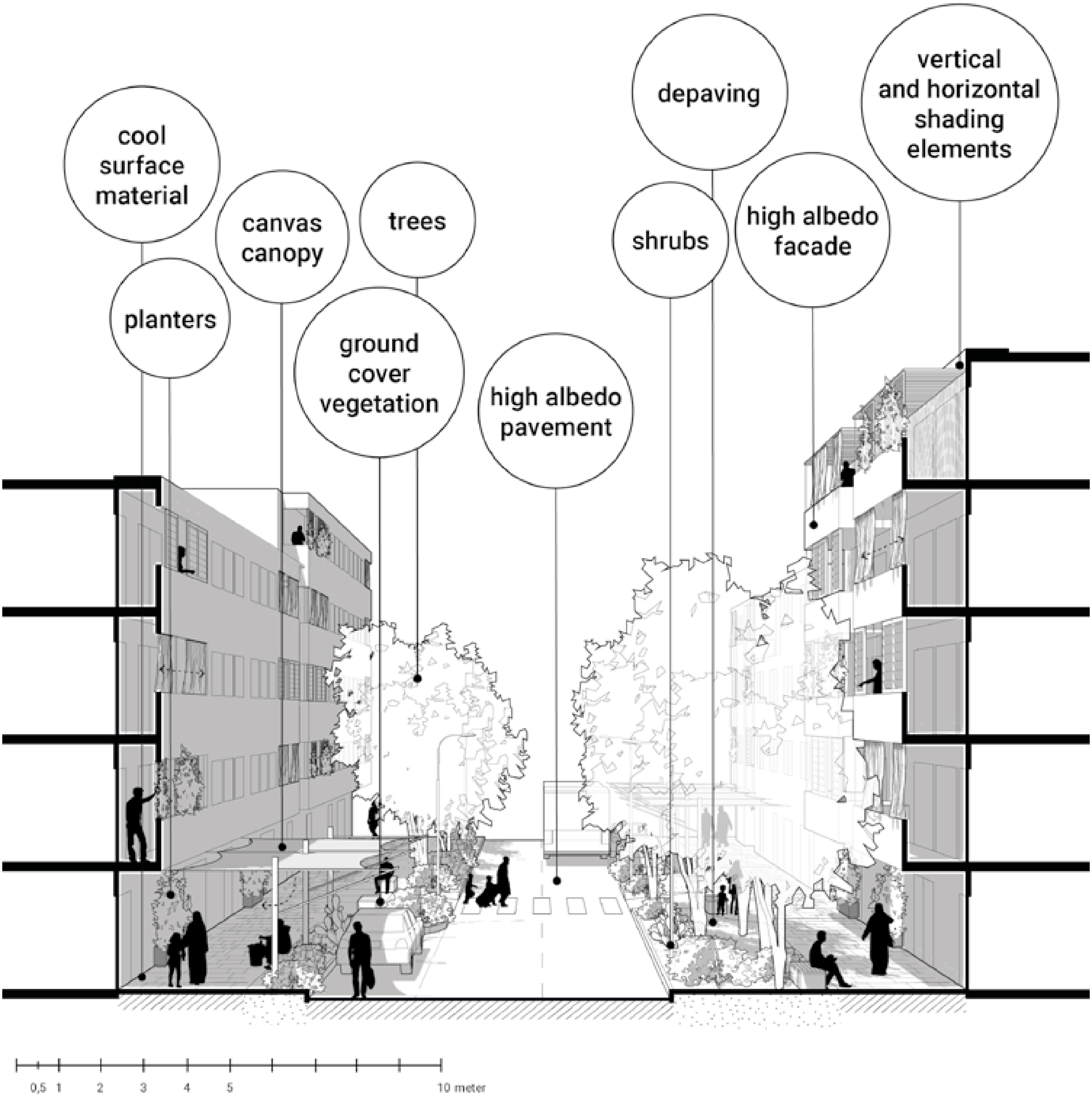


Fig. 39 Illustration of design prototype 2 | medium street N/S

6.3 PROTOTYPE 3 | WIDE STREET N/S AND E/W

6.3.1 Characterization of prototype

Prototype 3 presents a combination of interventions which are suitable for both N/S and E/W street orientations (Figure 40). This is based on the extensive shadow analysis of the wide street typology (Appendix II), which did not show a substantial difference between the two orientations (due to the low H/W ratio). The difference in diurnal solar patterns in both street orientations is considered during the development of this prototype. Similarly, as wind patterns are different for both orientations, this is another factor to consider when placing trees and other interventions that can obstruct ventilation. This prototype includes the same interventions as prototype 2. However, due to the increased space within the profile the interventions are more large-scale.

Adapting urban materials

Like previous prototypes, the albedo of the building facades, ground surfaces and roads is increased by applying light-colored paint and/or new cool surface materials (e.g., light-colored clay bricks). Depaving should occur as much as possible without obstructing car circulation. To further decrease the area of paved surfaces, the traffic island in the middle of the profile can be widened and depaved. This simultaneously results in extended space for vegetation and additional public space to foster social interaction.

Implementing shade

To allow natural ventilation and avoid trapping of night-time longwave radiation and exhaustion fumes under tree canopies, vegetation is interchanged with flexible canvas canopies. These structures provide additional shade and are retractable during nighttime to allow nocturnal cooling. Along the sidewalks, urban greenery is interchanged with canvas canopies, louvres, and pergola canopies. Due to low H/W ratios, wide street profiles typically receive more direct solar radiation, particularly during lower solar angles. To this end, vertical shading structures are combined with these canopy structures, to shade sidewalks during morning and afternoon hours. Like previous prototypes, building facades are protected through vertical and horizontal shading elements (e.g., window shutters, awnings).

Increasing evaporative cooling

Trees, shrubs, and ground cover vegetation can be planted in the depaved areas (e.g., depaved strip along sidewalks or traffic island). Bare building facades exposed to intense solar radiation (e.g., side facades of buildings) can be vegetated with climbing plants in pots or raised planters. When structural stability of buildings allows, roofs can be protected by pergola canopies and planters with vegetation.

6.3.2 Assessment of the prototype

The results of the expert judgement assessment of prototype 3 are presented in Table 7. During the first iteration (P1), the artificial design alternative scored generally lower compared to the nature-based alternative, except on affordability (as green interventions are generally more costly). The overall score of the prototype during the second iteration (P2) increased substantially, most expert scored the effectiveness or feasibility of the interventions high (4) and very high (5). However, both affordability and urban climate scored only moderate (3) values. Reasons for a low score were motivated by the high costs of most urban greenery interventions and the indivertible large area of paved surface due to car circulation requirements. This is slightly decreased by removing two car lanes, but changing the functionality entirely is currently not possible, as the city's infrastructure depends almost completely on motorized traffic. During the last iteration (P3), the match of design interventions with the ones proposed during the workshop (Table 2) confirms the adequacy of the interventions selected for prototype 3.

Table 7. Results of the assessment of prototype 3 | wide street N/S-E/W based on scores ranges from 1-5

	climate-responsive design	urban climate	land use	genius loci	mobility	equity	affordibility
P1 nature based	4	2	3	3	3	3	3
P1 artificial	3	2	2	3	2	2	4
P2 integrated	5	3	5	5	4	4	3

6.4 PROTOTYPE 4 | OPEN SPACE N/S AND E/W

6.4.1 Characterization of prototype

Prototype 3 comprises the same interventions as in prototypes 2 and 3 (Figure 41). However, the shape and width of this generic open space and the absence of motorized traffic allow for more large-scale interventions. The description below will discuss mainly the implementation of interventions that differ from prototypes 2 and 3.

Adapting urban materials

Albedo of the building facades, ground surfaces and roads are increased by applying light-colored paint and/ or new cool surface materials (e.g., light-colored clay bricks). Since open spaces are characterized by limited to no car circulation (e.g., car parks or school yards), a large amount of the total surface area can be depaved.

Implementing shade

The same shading interventions as in prototypes 2 and 3 are used to shade building facades and ground surfaces (e.g., shutters, canopies, louvres, etc.). To allow for night-time cooling, it is important that shading structures are retractable. The use of these spaces should be flexible, to promote social interaction during daytime and night-time.

Increasing evaporative cooling

Trees, shrubs and ground cover vegetation can be planted in depaved areas. However, special attention should be paid to the spatial arrangement to enable natural ventilation. Where feasible, buildings' facades are vegetated with climbing plants (planted in the ground, planters, or pots). Low-tech evaporative cooling systems can be combined with urban furniture to add extra cooling (e.g., benches).

6.4.2 Assessment of the prototype

The results of the expert judgement assessment of prototype 4 are presented in Table 8. Like previous prototypes, the interventions of P2 integrated scored high: 4 (high effectiveness/feasibility) or 5 (very high effectiveness/feasibility). Only the assessment of affordability scored lower: 3 (effective/feasible). During the last iteration (P3), the match of design interventions with the ones proposed during the workshop (Table 2) confirms the adequacy of the interventions selected for prototype 3.

Table 8. Results of the assessment of prototype 4 | open space N/S-E/W based on scores ranges from 1-5

	climate-responsive design	urban climate	land use	genius loci	mobility	equity	affordibility
P1 nature based	5	3	3	3	4	3	4
P1 artificial	3	3	1	3	2	4	4
P2 integrated	5	5	5	5	5	4	3

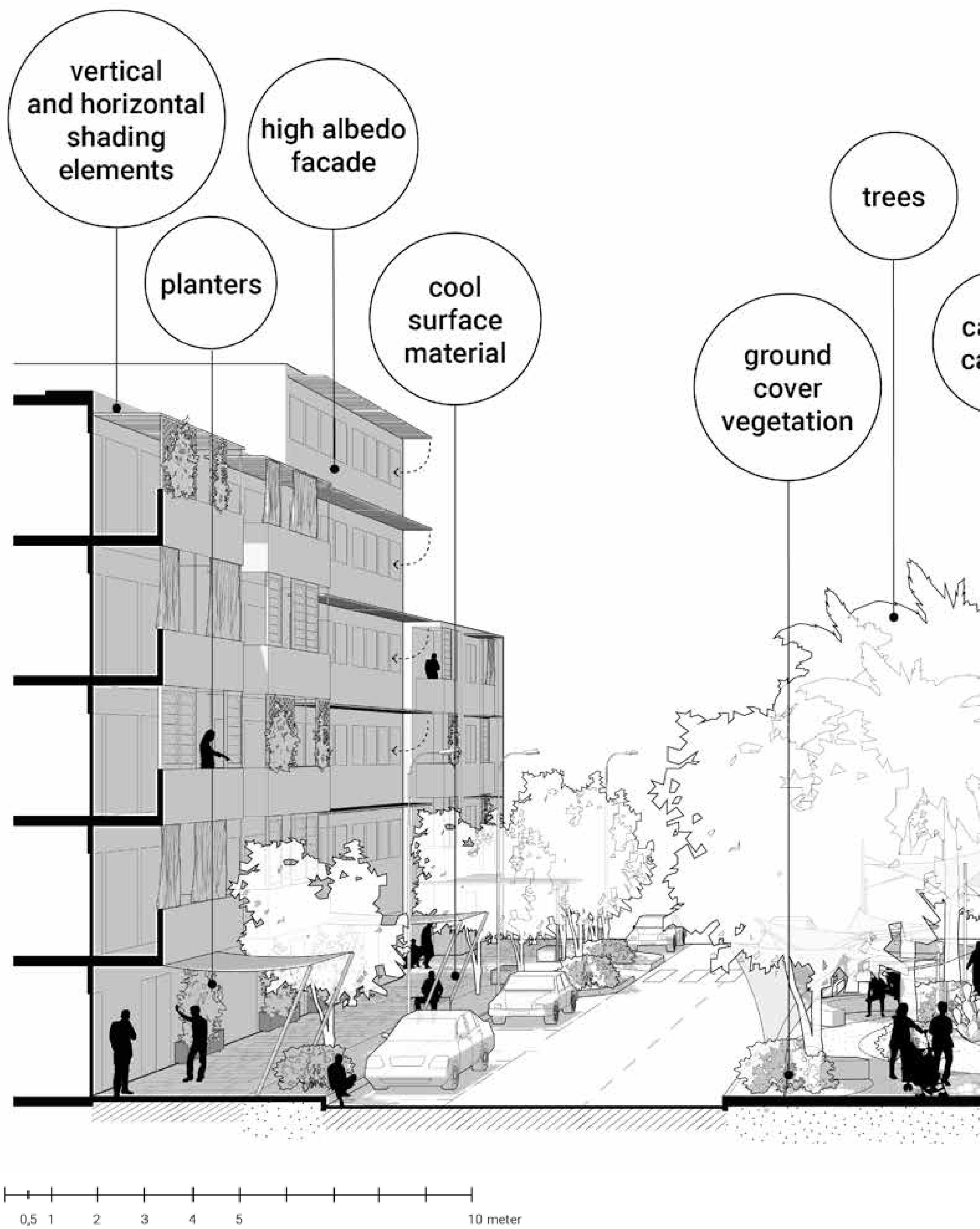
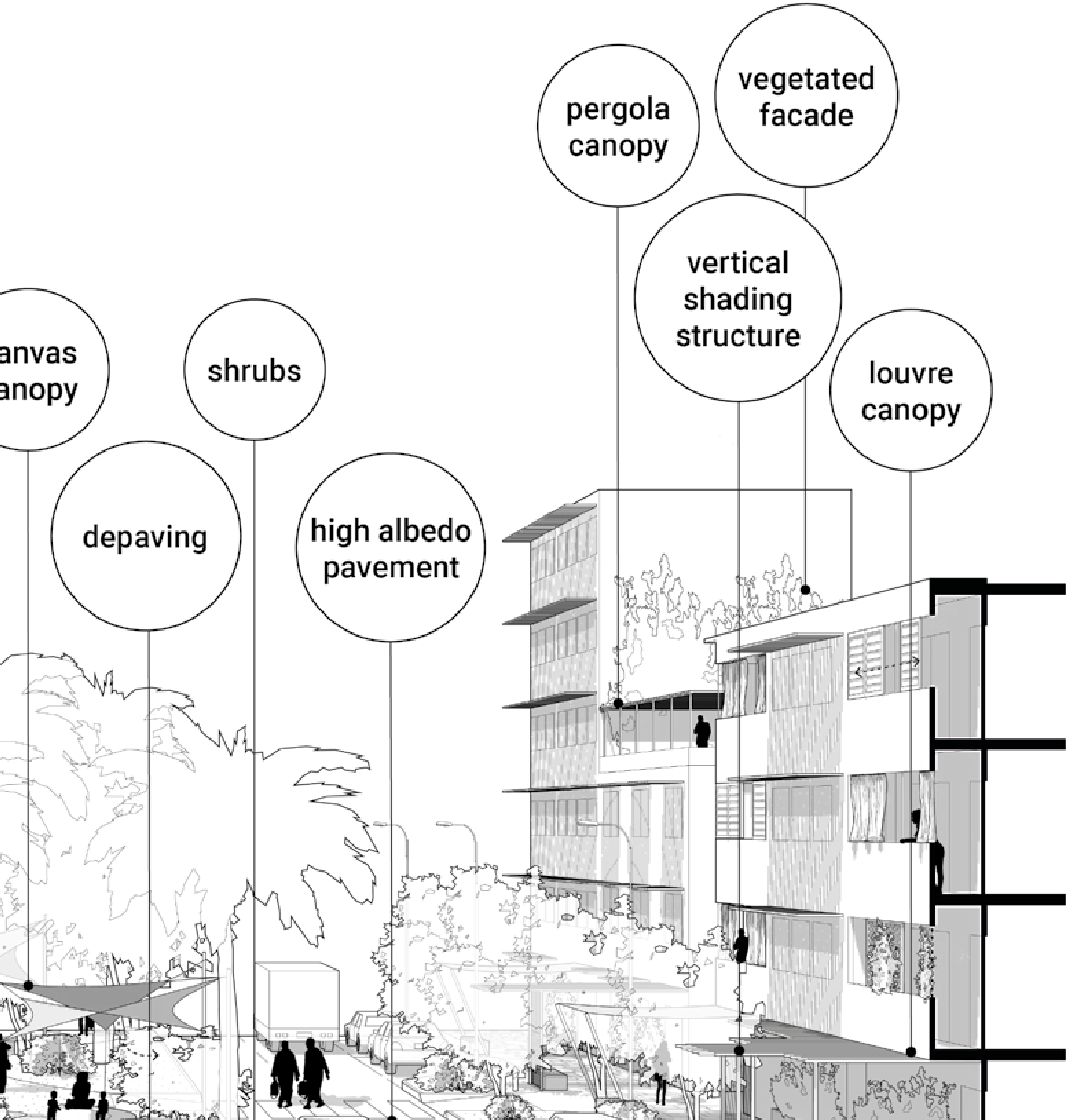


Fig. 40 Illustration of design prototype 3 | wide street N/S-E/W.



vegetated facade
pergola canopy
vertical shading structure
anvas anopy
shrubs
louvre canopy
depaving
high albedo pavement

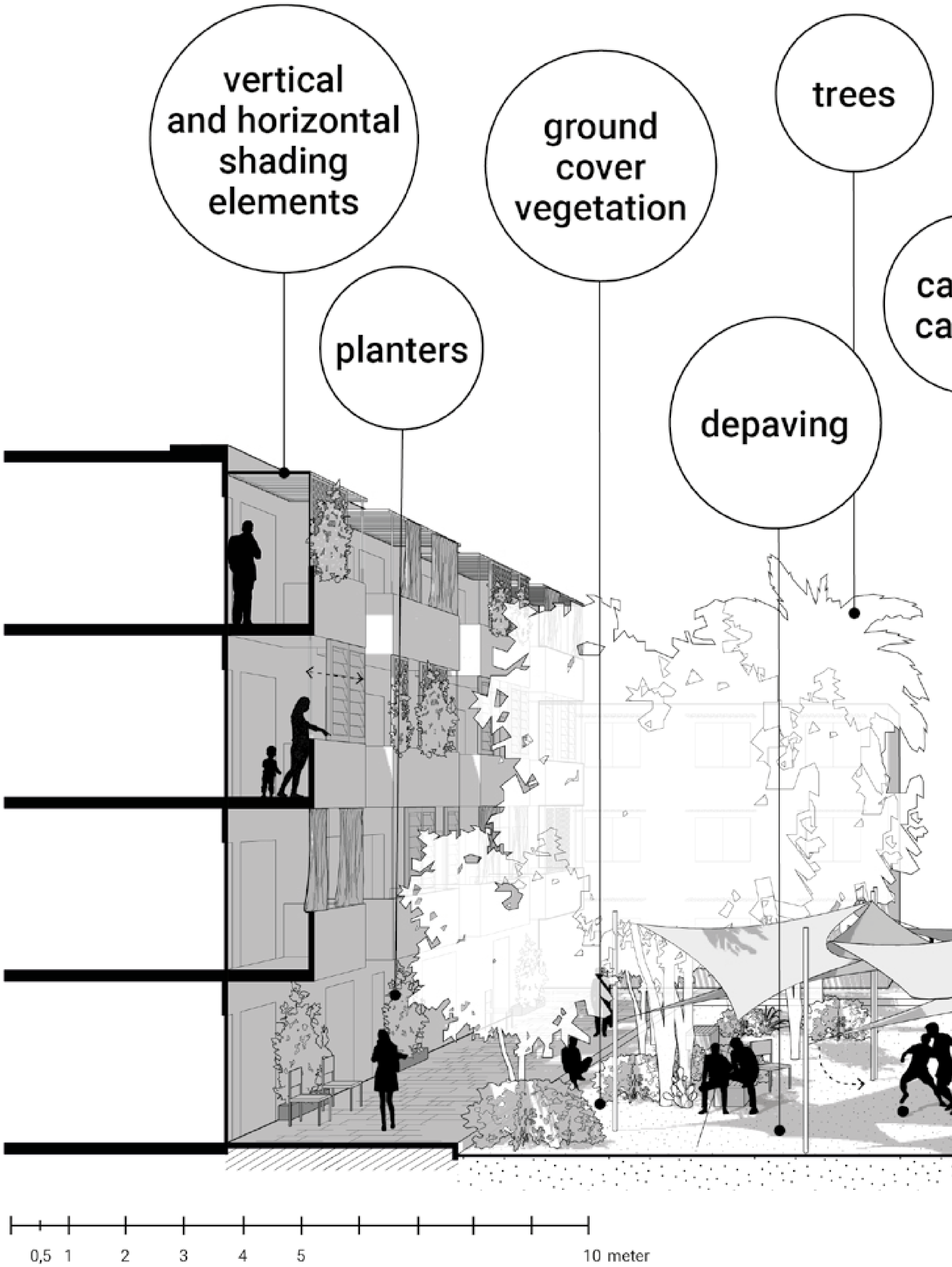
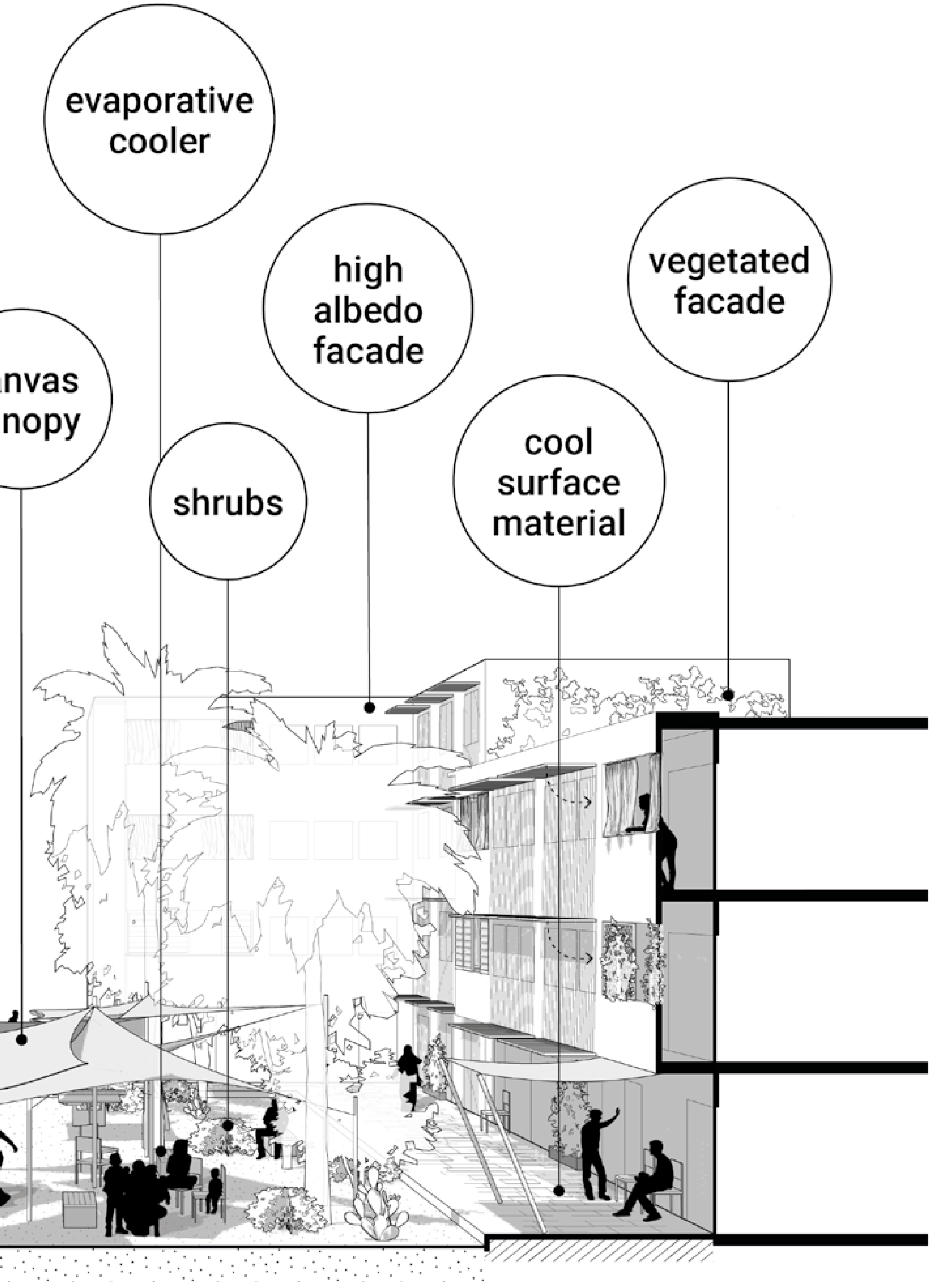


Fig. 41 Illustration of design prototype 4 | open space N/S-E/W


evaporative cooler
high albedo facade
vegetated facade
nvas
nopy
shrubs
cool surface material

7. SITE DESIGN

This chapter presents a site design of the selected study site within an unplanned urban area of Shubra. The design aims to improve microclimatic conditions by implementing the prototypes, considering site-specific conditions. A design at masterplan scale (1:1500) and three detailed designs (1:250) show how the prototypes can be used within the design process. In addition, each detailed design will discuss shortly the effects of the interventions on the microclimate. To ground the design within its context, an extensive site analysis is presented preparatory to the design.

7.1 SITE ANALYSIS

Adding to the analysis done in chapter 5, the following section describes an analysis of the background of the site (e.g., history, demography, religion), a spatial analysis (e.g., mobility, green infrastructure, amenities) and a climatic analysis (e.g., solar radiation, wind).

7.1.1 Background analysis

History

The district of Shubra can be described as a densely populated district, where planned and unplanned urban areas exist side by side. However, this was not always the case when reviewing Shubra's history, which dates over 200 years back in time. The district was for a long period an area for the middle classes and Egyptian bourgeoisie, with wealthy palaces and lush gardens. When Cairo expanded to north and north-west directions at the beginning of the 19th century, the agricultural lands and small villages surrounding the city were converted into new suburbs. It was Muhammad 'Ali, the de facto ruler of Egypt from 1805 to 1848, who selected the area of Shubra as a location for his new palace. The construction of this countryside palace and extended gardens is understood as a defining factor of the subsequent urban development of the area. Muhammad 'Ali was also responsible for the construction of the historical road connecting Shubra to downtown Cairo. The road was designed carefully, under the watchful eye of Muhammad 'Ali, who envisioned the street to be an area of relaxation and recreation. With a wide profile and flanked by a single lane of Albizia and Sycamore trees, the street provided the elite with the opportunity to escape the busy city. Due to this development, Shubra became the area of Cairo where influential families resided, and wealthy citizens went for recreation and exercise within one of the several extravagant gardens (Figure 42).

When around the end of the 19th century the influential families moved and abandoned their properties, several palaces and gardens within the district got deserted. The vacant palaces received a new purpose around the beginning of the 20th century: the large buildings turned out to be very suitable as factories (e.g., cigarettes, clothes). Combined with the development of the first train station on Ramses Street and the proximity to the primary port of Cairo, migrants from surrounding villages started to settle in Shubra. This spurred the development of affordable housing within the area, resolved by dividing former garden grounds into building plots. By 1987, the population of Shubra had doubled to 300.000, increasing the development of unplanned areas (Tadamun, 2016).

Demography

With a population of around 81.000 people, spread over an area of 140 ha, the population density of Shubra is high (57,2/km2). Around 16% of the population can be categorized as rural migrants, responsible for part of the annual population growth within the district (CAPMAS, 2018). Concerning religion, the district has a high demographic diversity. Both Muslims and Christians reside within the area, resulting in a wide variety of churches and mosques as cultural landmarks. Moreover, Shubra hosts the largest concentration of Copts in Cairo (Tadamun, 2016).

Fig. 42 Distribution of gardens in the urban fabric of Shubra in 1896 (adapted from Tadamun, 2016)

7.1.2 Spatial analysis

Buildings

Building heights within the study area vary tremendously, ranging from 3 to 30 meters (Figure 43], resulting in an irregular spatial pattern and a high surface roughness. Buildings are constructed with basic materials, including concrete, bricks and clay, often lacking any cladding along the building facade. Based on an appraisal made by Egypt's Ministry of Planning and Economic Development, the structural condition of buildings can be analyzed. Figure 44 shows the buildings which are currently under demolition and buildings that are beyond repair and need to be demolished in the near future.

Infrastructure

The study site is bordered by secondary and primary roads (Figure 45), connecting the area to both other neighborhoods within Shubra and other districts within Cairo. Smaller residential streets branch out into the dense urban fabric of the neighborhood. In addition, the area is connected to a public transport system through multiple bus lines. All roads (primary, secondary and residential) are used by mixed types of traffic. Pedestrians, cyclists, and motorized traffic share space within the different street profiles.

The current green infrastructure within the study site is shown in Figure 45. Most of the vegetation is concentrated in wider streets and open spaces, resulting in a limited amount of vegetation within the study area. Along the streets bordering the study area (Al Teraa Al Bolakia, Ahmed Badawi and Emtedad Ahmed Helmi) some tree lane structures can be identified. Furthermore, green areas with a variety of vegetation are located in some of the fenced-off open spaces and on the traffic island along the Ahmed Badawi street.

Amenities

Figure 46 shows where different types of main amenities are located, in which street people move along, and where people stay. The one-way street of Al Teraa Bolakia is one of the main arteries of the district, characterized by a lively mix of street vendors, shops, restaurants on street level and apartments from the first floor and up. Similarly, the two-way street of Ahmed Badawi is also characterized by a mixed use of residential and commercial amenities. Despite this commercial character, Shubra is first and foremost a

Fig. 43 Map of building heights in the study area (ranging from 3 to 30 meters), showing an irregular pattern with a high surface roughness (based on a GIS analysis; data received from Ain Shams University).

Fig. 44 Map of building conditions in the study area, showing buildings currently under demolition and ones that are to be demolished in the future. Based on a GIS analysis; data received from Ain Shams University.

Fig. 45 Map of mobility and green infrastructure in the study area, showing street hierarchy, public transport, trees (clustered and scattered) and green spaces. Based on a GIS (Ain Shams University) and satellite (Google Earth) analysis.

lively residential area (Tadamun, 2016). At the center of the neighborhood, three major school complexes are located. Other main landmarks are the several mosques, where people gather multiple times a day. Based on the location of these different amenities, an educated guess was made as to which streets are used as main walking routes. Additionally, places where people stay and gather during day- and nighttime. These are mainly schools, mosques, shops and markets during the day, and restaurants and cafes during the evening and night.

7.1.3 Climatic analysis

Solar radiation

Building further on the analysis presented in chapter 5, Figure 47 shows the amount of solar radiation the area receives on the 21st of July, from 7:00 to 17:00 o'clock. This map is based on a shadow analysis done in Sketchup, measuring the amount of shading time (h) the area received on the selected date. Some conclusions can be drawn based on this analysis. Open spaces and wider streets receive more solar radiation and will heat up accordingly during daytimes. However, low H/W ratios and high SVF in these areas will allow for some night-time cooling. The cooling potential is likely to be low, depending on which urban materials are used within the urban canyon (Khalil et al., 2018). The opposite can be expected of the narrow streets. Due to high H/W ratios and low SVF, these streets will receive less solar radiation during the day (Figure 47). Accordingly, nighttime cooling is likely to be obstructed due to narrow and deep street profiles.

Wind flow

Windspeeds do not exceed 13.9 m/s, and they are strong enough to penetrate the streetscape (Robaa, 2003). However, depending on the street orientation and H/W ratio, wind patterns will be different (Figure 48). With a northerly predominant wind direction (Table 3), streets with N/S orientation have the highest potential for ventilation. Additionally, wide streets tend to have a higher potential for ventilation than narrow streets due to less physical obstruction interfering with wind flows. Streets perpendicular to the wind direction (i.e., E/W streets) have a low potential for ventilation due to a skimming flow. Wide streets and open spaces with an E/W orientation tend to be affected by a wake interference flow, resulting into wind blockage areas.

Fig. 46 Map of amenities, main walking routes and zones were people spent time outdoor (e.g., in front of mosques and on school yards) in the study area. Based on a GIS (Ain Shams University) and satellite (Google Earth) analysis.

Fig. 47 Map of solar radiation that the study area receives, expressed in amount of shading hours per day. Based on the Shadow Analysis plugin in Sketchup 2021.

Fig. 48 Map of wind flow patterns in the study area and ventilation zones, based on wind regimes as explained by Lenzholzer (2015).

7.1.4 Problems and opportunities

The above presented analysis results into the following problem and opportunities map (Figure 49).

Narrow streets in a N/S orientation can be categorized within the lowest accumulated stress level, due to the low amount of solar radiation and the potential for wind ventilation. Narrow streets in an E/W orientation are, depending on their width, assigned to the medium or high accumulated risk category. However, as mentioned above, heat accumulated during the day tends to get trapped within the urban canyon leading to increased nighttime temperatures within narrow streets.

Since open spaces receive high amounts of solar radiation and have a limited potential for ventilation, they are generally assigned to the high and extremely high-risk category. In the few open spaces with vegetation (e.g., schoolyards), the risk of heat stress is locally lowered. The risk of heat stress in open spaces is especially problematic since these are areas where people gather.

Like open spaces, medium and wide streets receive high amounts of solar radiation but in contrast to closed-off open spaces have the potential for wind ventilation. Due to mobility needs, the implementation of cooling interventions in these streets is limited.

The predominant wind direction creates the opportunity for N/S oriented streets to operate as a ventilation zone. Open spaces which are currently underused (e.g., car parks), have the potential to be turned into green areas. Since many buildings have been identified to have structural issues or are in the process of being demolished, there is a potential to increase the amount of green open spaces. An even distribution of these vegetated open spaces has the potential to form a cooling network affecting the local microclimate (Wu & Chen, 2017). Last but not least, interventions in areas that are most frequented by pedestrians have the highest potential to reduce the effects of heat stress on local residents.

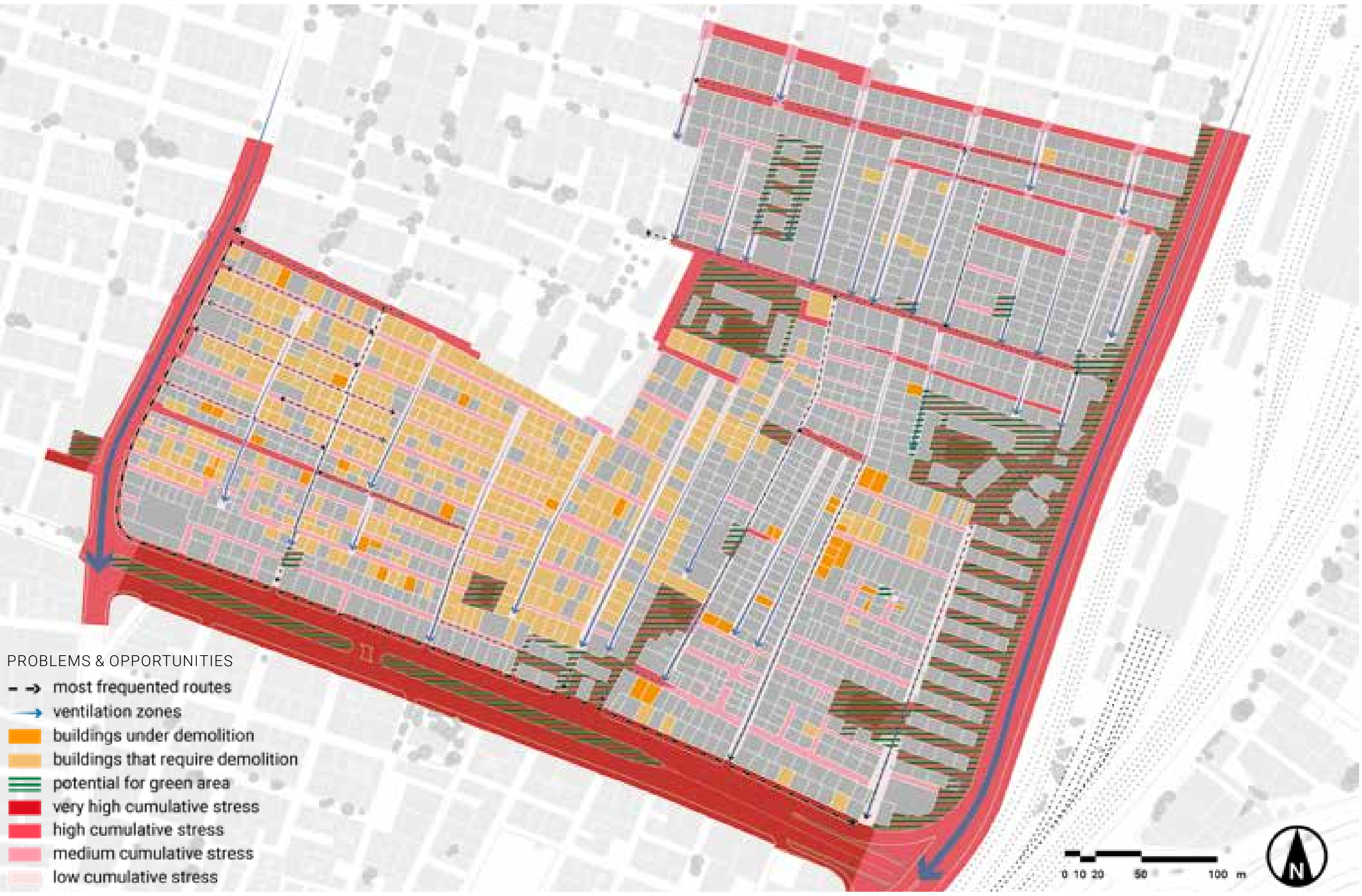


Fig. 49 Map of main problems and opportunities for the study area, synthesis of spatial and climatic analysis presented above.

7.2 DESIGN

Rooted in the multi-scaled analysis, the following section presents a design for the selected study area within the district of Shubra. The design aims to improve microclimatic conditions, by applying the knowledge gained by answering the first two sub-research questions. While designing to improve climate-resilience in a feasible manner for the neighborhood is the first and foremost goal, the design also aims to preserve and enhance the spatial quality of the neighborhood. Focusing for example on sense of place, preservation of cultural landmarks, functionality, and landscape aesthetics.

7.2.1 Design concept

To guide the design process of an integrated masterplan and detailed designs, a leading spatial concept was developed. Based on the findings of Wu & Chen (2017), and inspired by the rich history of Shubra, the design proposes to implement a cool network (Figure 50): a network of cool streets connecting multiple small-scale pocket parks to each other.

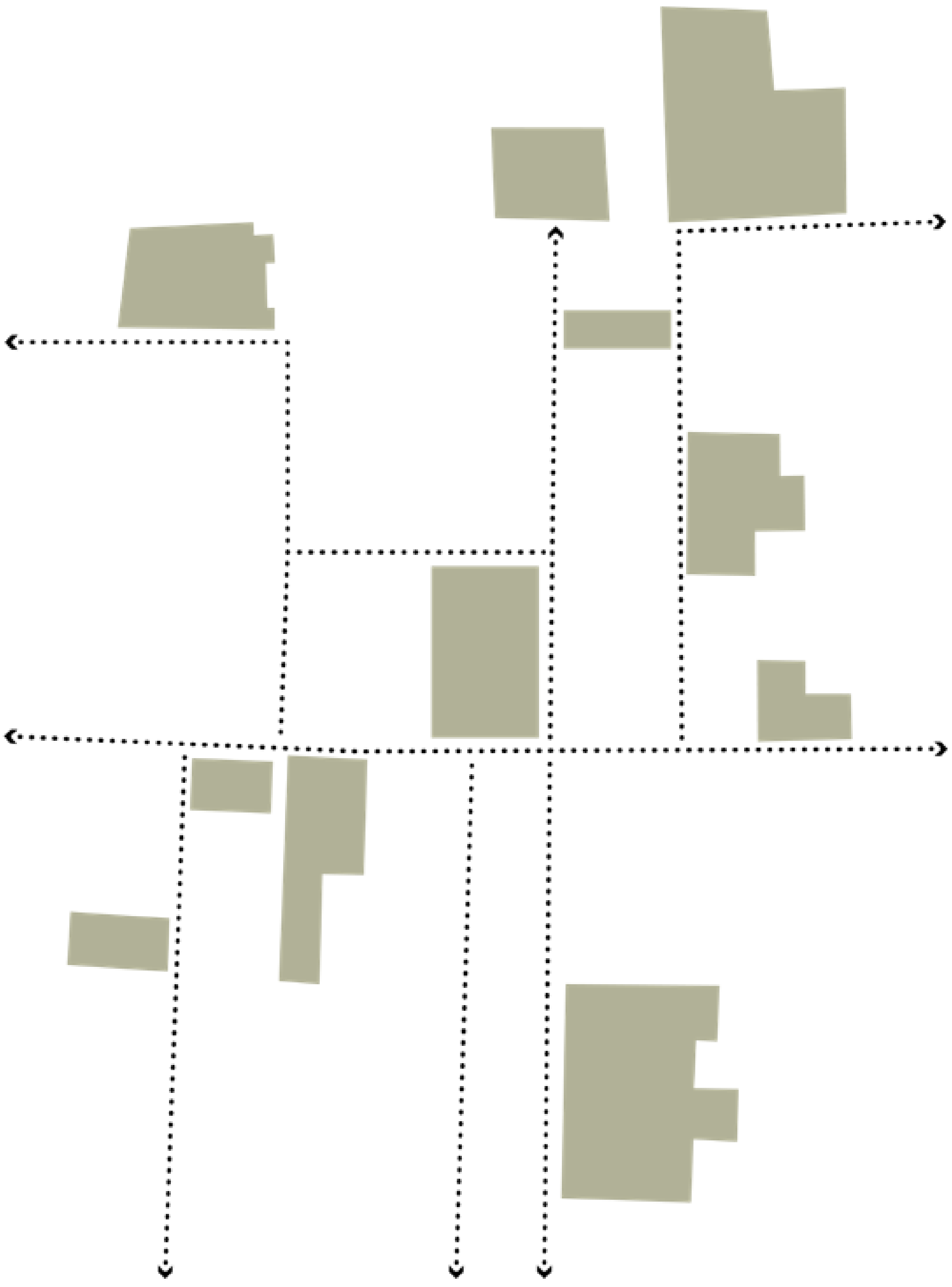


Fig. 50 Diagram of concept used to guide and structure the design process, illustrating a network of cool streets connecting green areas with each other. Within the cool network and green spaces, different design prototypes are applied according to their street typology.

Intermezzo: Islamic aesthetics in garden design and architecture

To ensure the sense of place and landscape aesthetics fitting to the culture of Egypt, the following section presents a short analysis of Islamic aesthetics in garden design and architecture. This analysis served as a source of inspiration during the design process. For example, the design of green areas is inspired by key elements of traditional garden design and ornamental geometric patterns occurring in Islamic architecture.

Within traditional Islamic Garden design, different spatial elements aim to reflect and symbolize the gardens of Eden as described within the Qur'an (Mahdy, 2019). This signifies the importance of gardens within Islamic culture. Furthermore, as gardens were intended for rest and reflection, they are often designed in enclosed spaces (e.g., courtyards) that offer privacy and protection from the harsh desert environment (Ansari, 2011; Mahdy, 2019). The layout of the garden traditionally follows the concept of the Char-bagh design. Mahdy (2019) described the Char-bagh concept as follows: "*The layout usually consists of a central pool with a fountain and four channels at right angles to each other enclosing flower beds, while shrubs, shady trees and fruit trees line the paths to provide the essential shade" (p. 5).* This concept served as inspiration during the design process of the green pocket parks within the three detailed designs. More specifically, it influenced the general spatial layout and distribution of shapes and forms. To break up elongated linear lines within the traditional Char-bagh concept, the orientation of the axis is turned (Figure 51). In this way, it is a reference to the Char-bagh concept, interpreted freely by the author.

Water and trees are key elements within Islamic gardens, due to the cooling effect and shade they provide. Water features such as fountains and small water bodies symbolize purity and reflectance within Islamic culture. Due to water scarcity in the GCR, water was not included in the developed designs. To cope with this water scarcity, trees are traditionally planted within small ditches or wadis where run-off water is collected (Bodeker, 1996). Different types of vegetation were used, characterized by Bodeker (1996) as follows: "*Vine leaves often shaded entire courts and small gardens. Trees were set out in pots or planted at intervals. Flower beds, ponds, and canals were narrowly bordered. Next to the paths were pleasant flowers and plants and shrubbery. To create order in the multicolored and multiform park, palms and other trees were regularly planted. They also formed a shaded area, which made possible a pleasant visit in the hot seasons.*" (p.89).

Within Islamic architecture, intricate geometric patterns are used as decorative elements on building surfaces (e.g., walls, ceilings, and doors). As the geometric shape of a star has a special religious value within Islam, these complex patterns are often based on a 6-, 8- or 10-point star pattern (Abdullahi & Embi, 2013). For this thesis, one of these patterns was selected to inspire spatial form used in the designs (Figure 52).

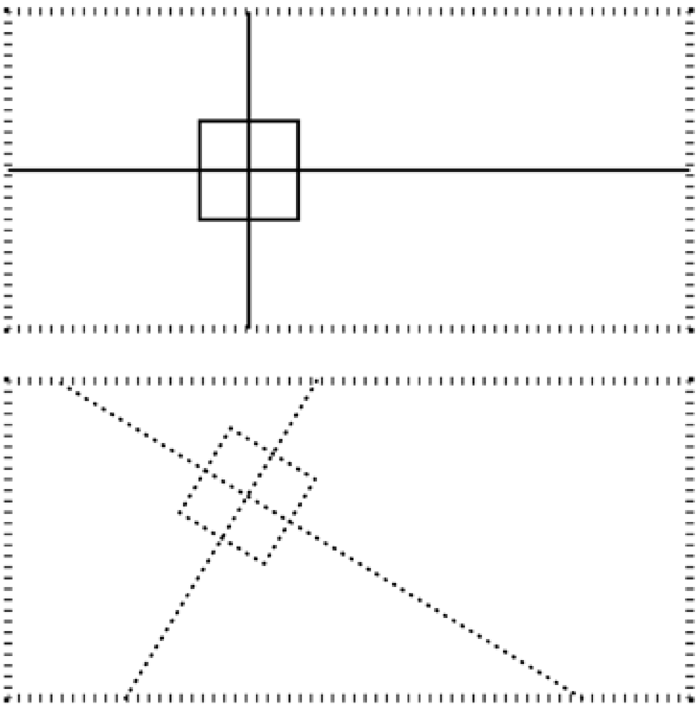


Fig. 51 Diagram of the Char-bagh concept within a garden (above) and the interpretation of this concept by the author (below).

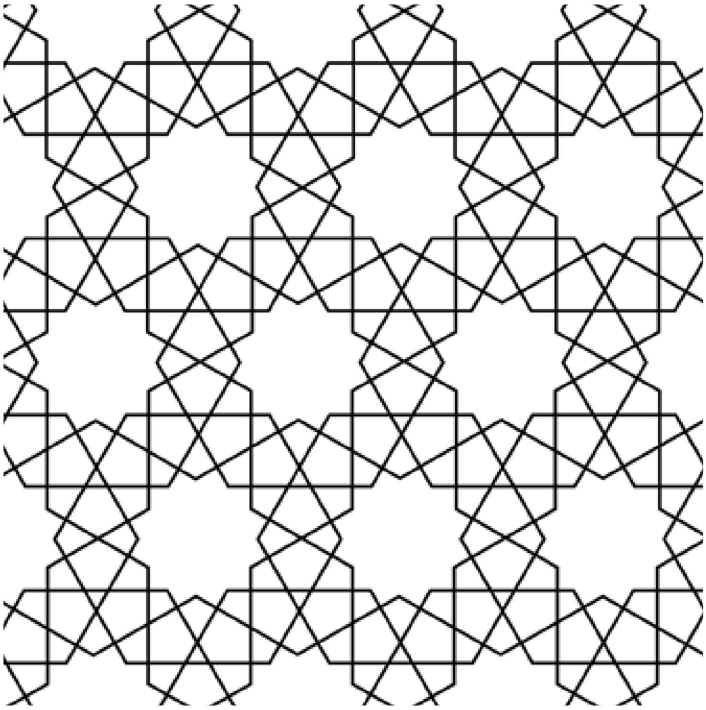


Fig. 52 Geometric pattern of a 12-point star used in Islamic architecture, art, and design.

7.2.2 Masterplan

Based on the above-presented problems and opportunities and proposed concept, the masterplan (Figure 56) consists of the following key elements.

Pocket parks

Existing open spaces are designed as small-scale pocket parks, which are publicly accessible (except for school yards, which stay partially private). To enhance cooling effects of these areas, additional green spaces are created, strategically positioned in areas where buildings are registered to be demolished (as described above). These green areas have a mixed-use functionality, depending on the function of the adjacent buildings. For example, green areas surrounding mosques have a different character as opposed to areas that are surrounded by residential and commercial buildings. The design of these areas aims to implement elements and general landscape aesthetics of local Egyptian culture, to secure a sense of place.

Network of cool streets

Based on frequently used routes and the most direct way to connect the pocket parks, a network of cool streets is designed. Within these cool streets, different climate-adaptive interventions are implemented as presented in prototype 1. Inside the network, pedestrians are prioritized and no parking is allowed. The network aims to be continuous and accessible at several locations from the surrounding wider streets.

Street modifications

To reduce the fully paved surface and create space for the implementation of interventions, the number of lanes is reduced in medium and wide streets. Through an improved hierarchy within the street network, traffic flows are maintained. Along the medium and wide streets bike paths and parking are situated. Along the Al Teraa Al Bolakia street, different climate-adaptive interventions are implemented as presented in prototype 2. Similarly, the Ahmed Badawi street and Emtedad Ahmed Helmi street are also redesigned using climate-adaptive interventions according to prototype 3. Although the functionality of all the above-presented streets is focused on car circulation, space for pedestrians is increased by extended pavement. Furthermore, new pedestrian crossings improve safety and general hierarchy within the streetscape.

Street orientation

Depending on the orientation of the street, interventions are adapted due to the potential of natural ventilation in N/S streets and the accumulated risk of heat stress on south-facing facades in E/W streets.

Fig. 53 Reference image of vegetation strategy: planting trees in wadis (source: Bodeker, 1996).

Fig. 54 Reference image of vegetation strategy: use of stones (source: trademarklandscapeaz.com).

Fig. 55 Reference image of wooden louvre design within Cairo, Egypt (source: author).

Focus on frequented areas

To maximize the impact of the interventions, their implementation focuses on the places which are most frequented by residents (e.g., mosques, schools, cafes, and restaurants). Streetscapes around cultural landmarks, such as mosques, are improved and accentuated. As mosques are of great cultural significance, adjacent to these buildings green spaces are added or extended where possible. The design of these small-scale vegetated areas aims to implement elements of Islamic Garden design and Egyptian architecture (freely interpreted in a contemporary way by the author).

Flexibility

To increase climate regulation potential, the interventions are designed in the most flexible manner considering the context of an unplanned urban area. For example, retractable canopies protect street surfaces from direct solar radiation during the day, while allowing for night-time cooling during the night by opening the canopies. Special attention is given to the usage pattern of the streetscape throughout the day and night. Due to the increased temperatures from late morning hours till the afternoon, outdoor activity of people is concentrated during the morning and evening hours (as was observed during the field visit). This affects for example how and when shops and restaurants are used, which influences the use of the streetscape accordingly.

Vegetation strategy

As water is a scarce resource within the arid climate of Egypt, vegetation species are carefully selected. To increase the sustainability of the added vegetation, species native to arid climates are proposed. Selection criteria were water requirement, drought tolerance and shade potential. To ensure a variety of heights, shapes and colors, different types of vegetation are included within this selection (i.e., trees, shrubs, ground cover vegetation and climbing plants). These species include for example Olea Europea, Plumeria Alba or Hyphaene Thebaica. A list of other appropriate species can be found in Appendix III. Following the planting strategy common for arid environments, vegetation is planted in wadis. This not only helps to collect runoff water (and potentially some rainwater during winter months), but additionally creates organically shaped higher and lower areas (Figure 53). Another design feature that breaks up the straight lines of the urban surroundings and are typical of arid climates are the use of stones. Furthermore, they help to protect the vegetation from trampling and create a demarcation along some of the planting beds (Figure 54).

MASTERPLAN LEGEND

- pocket parks
- cool street network
- bike path
- pedestrian crossing
- green area
- mosque
- market place
- existing trees
- new trees
- buildings within study area
- buildings outside study area
- tunnel
- depaved area
- fences
- train tracks
- busstop

Fig. 56 Map of the masterplan for the study area - applying the prototypes in a site-specific design (next page).

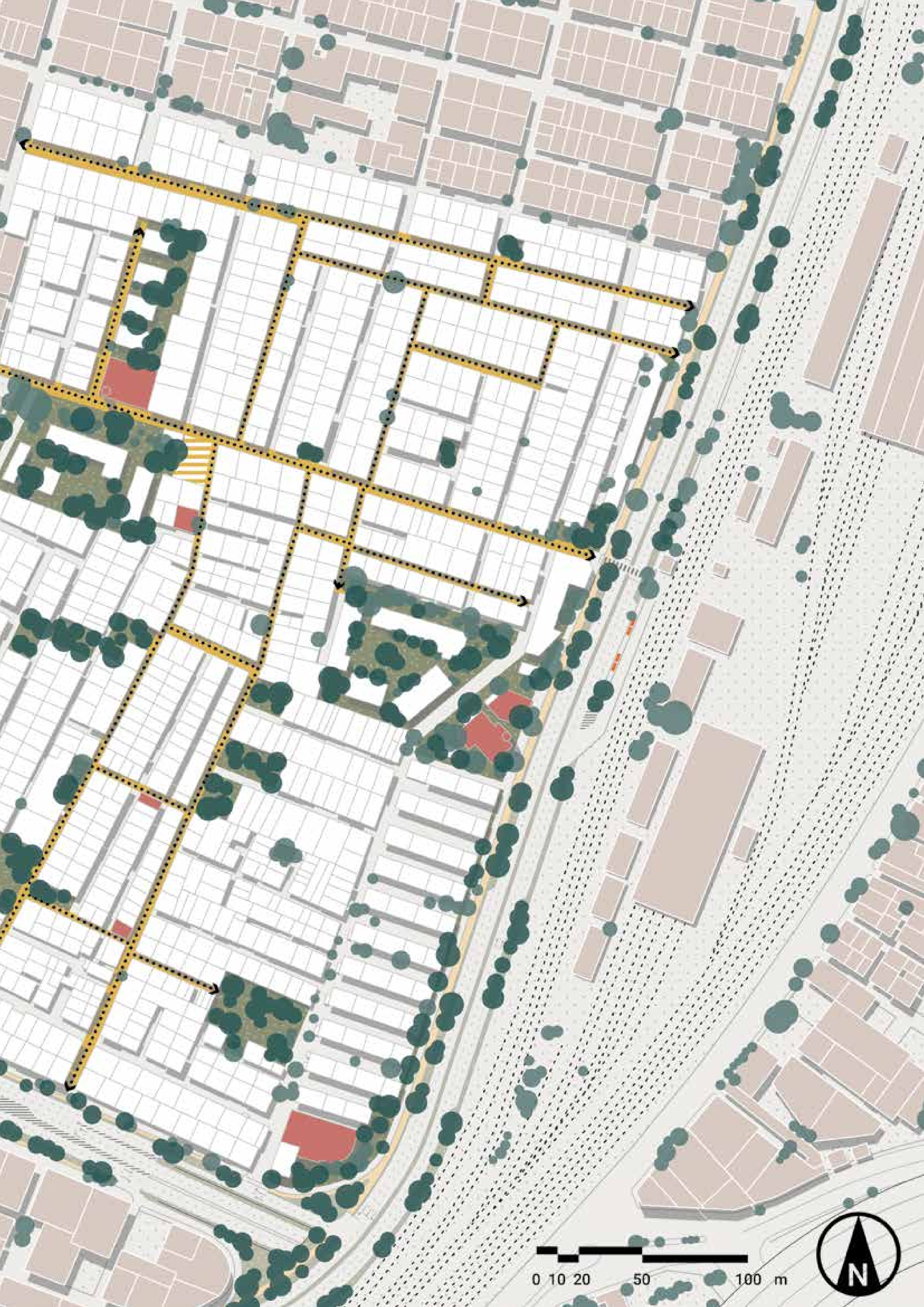

0 10 20 50 100 m
N

Fig. 57 Map of the specific locations of the three detailed designs within the study area.

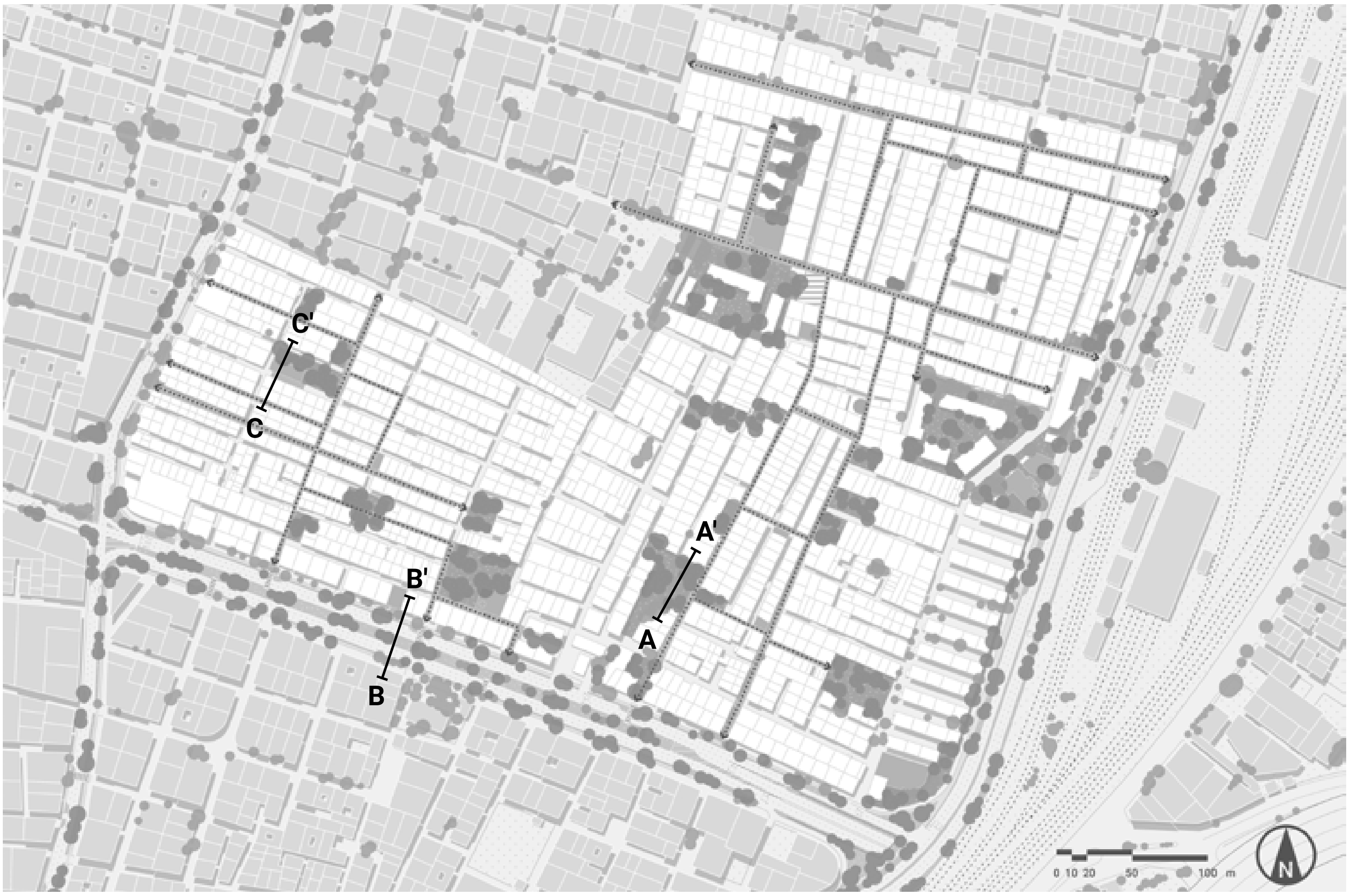


Fig. 58 Map indicating the location of the illustrated sections within the corresponding detailed design context.

7.2.3 Detailed design 1

The following detailed design is focused on the redesign of an open space and the surrounding narrow streets which are part of the cool network. The existing open space is currently used as a parking lot and storage space for local authorities. It is fenced off and guarded by district officials. Some sparsely planted trees are located along the north facade of the public building. The ground surface is unpaved, and the surrounding buildings have minimal or no cladding material. The entrances of the surrounding buildings are faced away from the open space, connecting to the adjacent narrow streets. Along the narrow streets, local commercial activity takes place.

To improve microclimatic conditions within the area, the following interventions are implemented: high albedo facade/pavement, cool surface material, depaving, vertical and horizontal shading elements along building facades, canopies (canvas, pergola and louvre), vertical shading structure, trees, shrubs, planters, ground cover vegetation and a passive evaporative cooling system (Figure 59).

Based on the knowledge gained from answering the sub-research questions and the intended design goals, the following design decisions were made:

- To increase the cooling potential of pocket parks, additional space for green areas is created (according to the spatial building analysis). This also improves the accessibility of the area by connecting Mohammed Gad Lane to the Ahmed Badawi street.
- The ground surface of the open space is depaved, and gravel (i.e., fine dolomite) is used to prevent dust from forming during sandstorms. This is combined with light-colored pavement. The design of the paving is inspired by a 12-point star Islamic pattern (as presented above).
- Raised planting beds allow for extra seating area but also prevent cars from parking/accessing the area. The geometrical shapes of the planting beds and shading structures are also inspired by the 12-point star pattern. Different trees, shrubs and ground cover vegetation are planted within these planting beds.
- The layout of the space is inspired by some of the elements of the Char-bagh concept. Instead of a water feature in the center of the area, three accentuating trees (representing water in a different form) are placed. This area is enclosed by a semi-permeable cooling wall, to offer increased evaporative cooling and a space for rest and reflection (Figure 60).
- At the several places throughout the area, (free-standing) shading structures (i.e., pergola canopies and louvres) provide additional shading during the day without obstructing nighttime cooling. The materialization and design of these louvres are inspired by local wooden louvres shading streetscapes (Figure 55). Flexible canvas canopies are combined with these structures and provide additional cooling during the day.
- Along the cool network, moveable canopies allow for adaptation to daytime and nighttime situations (reducing solar radiation gain during the day and improved nighttime cooling). Other interventions implemented along the cool network are also according to prototypes 1a and 1b.

Effect on microclimate

Based on the interview with climate-adaptive design and urban climate experts, the following assessment of the effects of the design on the microclimate was made (Table 9). All climate regulation criteria scored relatively well, which resulted in a high overall score. Only the effectiveness of evaporative cooling scored relatively low. This can be explained by raised PET temperatures due to the locally increased humidity rates related to increased evaporation.

Table 9. Results of the assessment of detailed design 1, based on scores ranges from 1-5

	effectiveness to reduce shortwave radiation	effectiveness to reduce longwave radiation	effectiveness to reduce air temperature	effectiveness to regulate ventilation	effectiveness to increase evaporative cooling	overall effect on microclimate
climate adaptive design	5	5	5	5	5	5
urban climate	5	4	5	4	3	4

INTERVENTIONS OVERVIEW

01 high albedo surface (facade/pavement)

02 cool surface material

03 depaving

04 vertical shading elements

05 horizontal shading elements

06 canvas canopy

07 pergola canopy

08 louvre

09 colonnade

10 vertical shading structure

11 trees

12 shrubs

13 planters with trees or shrubs

14 ground cover vegetation

15 green facade

16 passive evaporative cooling system

LEGEND DETAILED DESIGN 1

- sandstone pavers (accent paving)
- light-colored clay brick pavers
- fine dolomite gravel
- wooden awnings
- flexible canvas canopy
- wooden louvre structures
- pergola with climbing plants
- evaporative cooling wall
- existing trees
- trees
- shrubs
- ground cover vegetation
- planters with vegetation
- chairs
- tables
- bike path
- raised planting bed
- benches
- ping pong table

Fig. 59 Map of site design for the first detailed area, applying different climate-adaptive interventions according to prototypes 1a, 1b, 3 and 4 (right-hand side).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SECTION A | DETAILED DESIGN 1

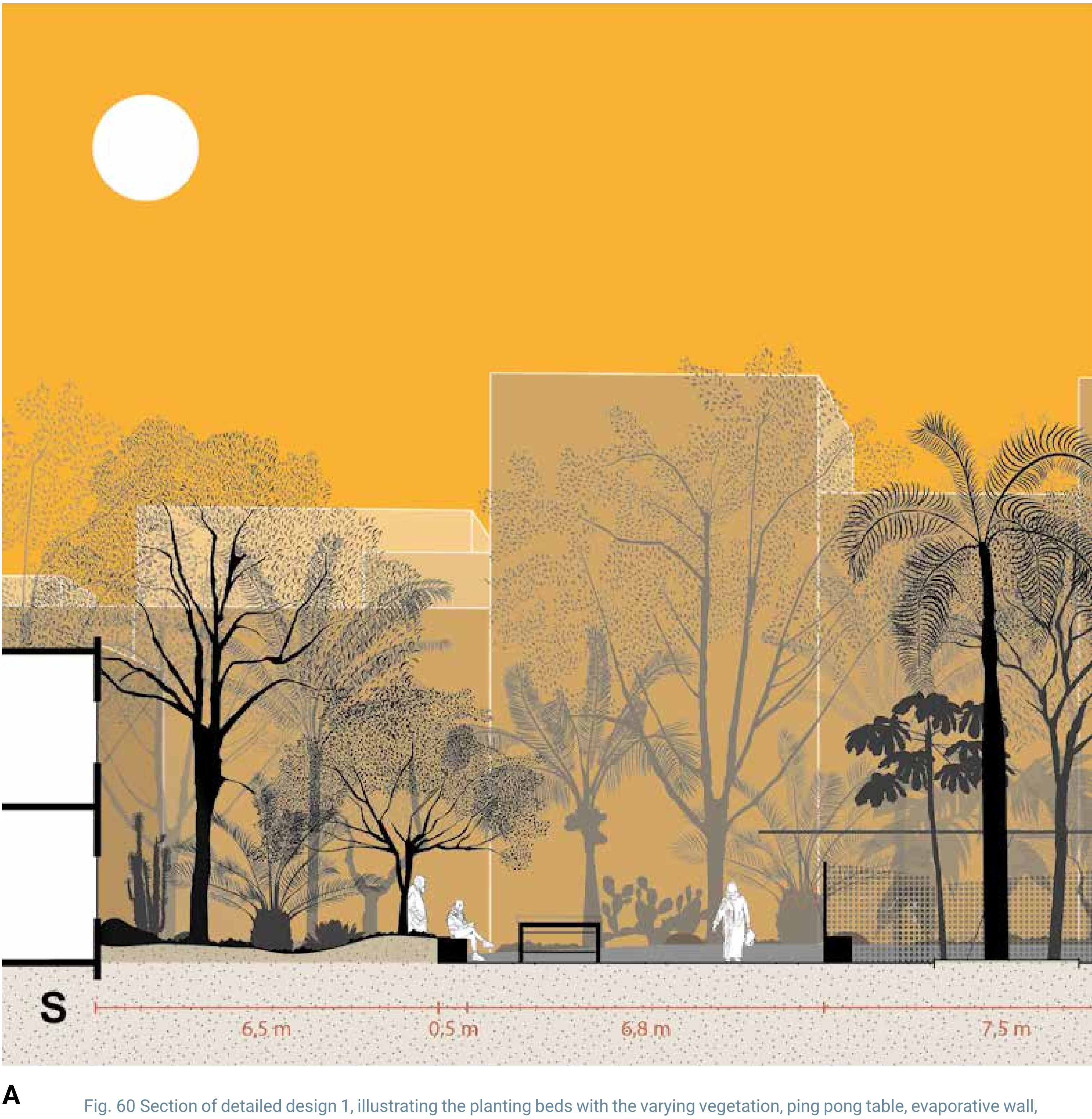

Fig. 60 Section of detailed design 1, illustrating the planting beds with the varying vegetation, ping pong table, evaporative wall, and free-standing louvres with canvas canopies.

A'

7.2.4 Detailed design 2

The following detailed design includes the redesign of a wide street, open space, and some narrow streets within the cool network. Since the Ahmed Badawi street is one of the main roads connecting two districts, motorized traffic dominates the streetscape of this wide street profile. While opposite roads are already split by a traffic island and some small-scale shading structures aim to implement shade, this area is mostly characterized as a bare and exposed space. The pedestrian area is limited and safe passage to and from the traffic island is missing. Some trees are planted along the pavement and on the traffic island, providing local shade. Shops and restaurants occasionally have some shading devices (e.g., canvas awnings). The open space in the north is smaller in the current situation and used as a parking lot. No vegetation is planted within this space, making it very sensitive to heat stress.

To improve microclimatic conditions within the area, the following interventions are implemented: high albedo facade/pavement, cool surface material, depaving, vertical and horizontal shading elements along building facades, canopies (canvas, pergola and louvre), vertical shading structure, trees, shrubs, planters, ground cover vegetation and a passive evaporative cooling system (Figure 61).

Based on the knowledge gained from answering the previous sub-research questions and the intended design goals, the following design decisions were made:

- Within the wide street all climate-adaptive interventions were implemented according to prototype 3. Pavements are widened, bike paths are added and on both sides of the street the road is decreased by one traffic lane.
- Because of the social and commercial activities during morning and evening hours (e.g., grocery shopping, drinking a juice, gathering with friends), building fronts are important in the design. In front of cafes, restaurants or mosques shading structures are built (i.e., louvres and pergola canopies). As these shading structures are half-open, they can be combined with canvas canopies during the day (Figure 62). In addition, a semi-permeable evaporative cooling wall provides evaporative cooling and additional shading for people residing under these structures. In front of shops, flexible canvas canopies are implemented.
- In the depaved strips along the sidewalk and the bike path, there is space for vegetation and integrated seating areas. During the evening, chairs and tables can be placed along these seating areas to function as an outdoor terrace for cafes and restaurants.
- Along the traffic island, similar design decisions are made. The island comprises depaved areas, raised planting beds with diverse vegetation, integrated seating areas, shading structures, and canvas canopies. Safe pedestrian crossing give access to and from the traffic island.
- The open space in the north of Figure 61, comprises the same design decisions as in detailed design 1. However, since a mosque is adjacent to the area, special attention is given to the connection between the mosque and the green area around it. An extended louvre aims to guide people towards the entrance and provides additional shade for the people gathering in front of the mosque for prayer.
- Along the cool network, climate-adaptive interventions are implemented according to prototypes 1a and 1b.

Effect on microclimate

Based on the interview with climate-adaptive design and urban climate experts, the following assessment of the effects of the design on the microclimate was made (Table 10). Like the previous design, all climate regulation criteria scored relatively well, which resulted in a high overall score. Only the effectiveness of the interventions to reduce shortwave radiation and regulate ventilation scored low. Due to the large area of paved surfaces and high amount of traffic, interventions to shade the road without obstructing car circulation were not possible within this design. This results in a high amount of direct solar radiation which enters the street profile and heats up urban surfaces during the day. Additionally, car-induced turbulence affects ventilation potentials.

Table 10. Results of the assessment of detailed design 2, based on scores ranges from 1-5

	effectiveness to reduce shortwave radiation	effectiveness to reduce longwave radiation	effectiveness to reduce air temperature	effectiveness to regulate ventilation	effectiveness to increase evaporative cooling	overall effect on microclimate
climate-adaptive design	5	4	5	5	5	5
urban climate	3	4	5	3	4	4

INTERVENTIONS OVERVIEW

01 high albedo surface (facade/pavement)
02 cool surface material
03 depaving
04 vertical shading elements
05 horizontal shading elements
06 canvas canopy
07 pergola canopy
08 louvre
09 colonnade
10 vertical shading structure
11 trees
12 shrubs
13 planters with trees or shrubs
14 ground cover vegetation
15 green facade
16 passive evaporative cooling system

LEGEND DETAILED DESIGN 2

- sandstone pavers (accent paving)
- light-colored clay brick pavers
- fine dolomite gravel
- wooden awnings
- flexible canvas canopy
- wooden louvre structures
- pergola with climbing plants
- louvre structure w/ evaporative cooling wall
- existing trees
- trees
- shrubs
- ground cover vegetation
- planters with vegetation
- chairs
- tables
- bike path
- raised planting bed
- benches

Fig. 61 Map of site design for the second detailed area, applying different climate-adaptive interventions according to prototypes 1a, 1b, 3 and 4 (next page).


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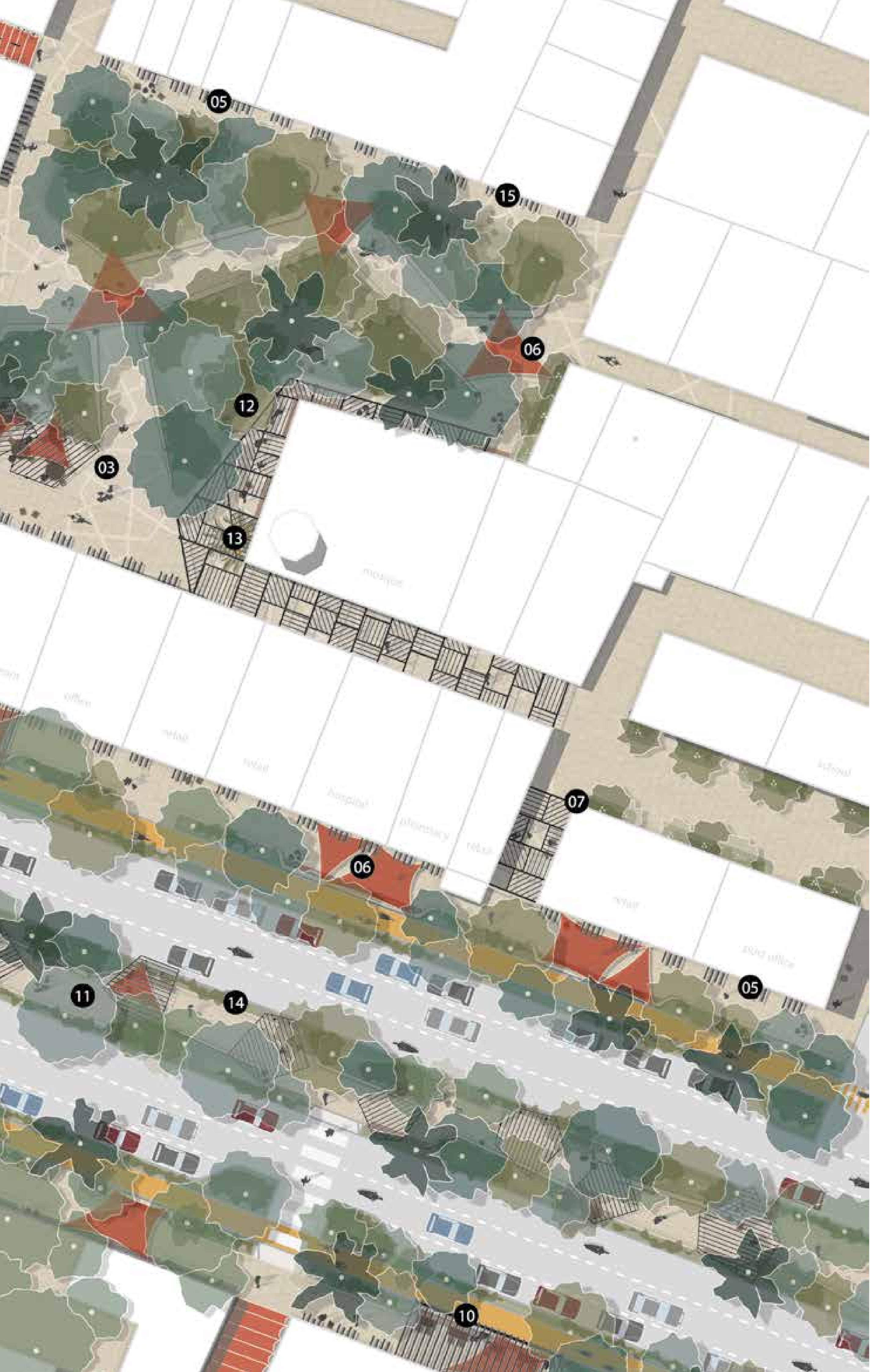
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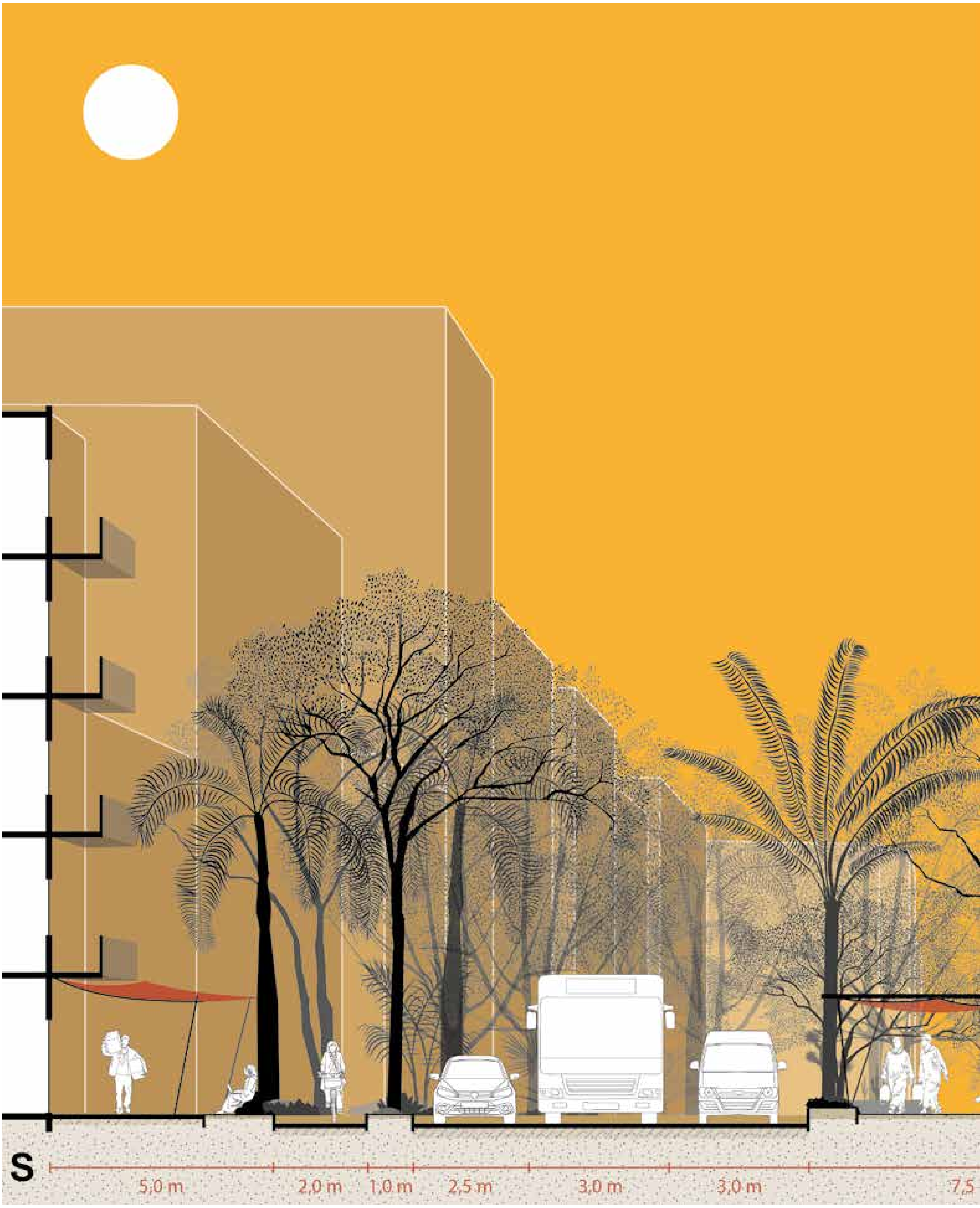


B

Fig. 62 Section of detailed design 2, illustrating the several shading methods applied to shade pedestrian areas as effectively as possible.

B'

7.2.5 Detailed design 3

The following detailed design includes the redesign of a medium street, narrow streets (E/W and N/S orientations), and some small-scale open spaces. As the Al Teraa Al Bolakia street can be categorized as a medium street, the profile has similar functionalities as the wide street. Buildings have mixed functions, with commercial functions on the ground floor and residential functions from the first floor and up. Trees are planted on the east side of the street.

To improve microclimatic conditions within the area, the following interventions are implemented: high albedo facade/pavement, cool surface material, depaving, vertical and horizontal shading elements along building facades, canopies (canvas, pergola and louvre), vertical shading structure, trees, shrubs, planters, ground cover vegetation and a passive evaporative cooling system (Figure 63).

Based on the knowledge gained from answering the previous sub-research questions and the intended design goals, the following design decisions were made:

- Within the medium street, all climate-adaptive interventions were implemented according to prototype 2. Pavements are widened, a bike path is added, and pockets of green are located on both sides of the street in an alternating pattern to allow natural ventilation through the street.
- Similar to the previous design, social and commercial activities are taking place within the streetscape during morning and evening hours. The same design elements are placed in front of shops, cafes and restaurants (e.g., louvres, pergolas and canvas canopies).
- Under most shading structures, integrated or informal seating areas are located. Integrated seating areas consist of wooden benches along raised planting beds, while informal ones consist of areas where residents can place their own chairs (according to the customs common in Cairo, as observed during the site visit).
- On the car parking areas located on both side of the profile, street vendors can set up their stalls.
- Along the cool network, climate-adaptive interventions are implemented according to prototype 1a and 1b. Additional louvres and canvas canopies provide extra shading, where the same design decisions were taken as described in chapters 7.2.3 and 7.2.4. This also applies to the design decision taken for the small-scale open spaces in the east of Figure 64.

Effect on microclimate

Based on the interview with climate-adaptive design and urban climate experts, the following assessment of the effects of the design on the microclimate was made (Table 11). All climate regulation criteria scored relatively well, which resulted in a high overall score. Only the effectiveness to reduce air temperatures scored low. This is explained by the high amount of unprotected area, especially on the west side of the medium street, which results in increased air temperatures due to direct solar radiation. Due to car circulation and need for car parking areas, interventions to shade this part of the road without impairing functionality were not possible. Additionally, placing shading structures or trees on both sides of the street would impair natural ventilation.

Table 11. Results of the assessment of detailed design 3, based on scores ranges from 1-5

	effectiveness to reduce shortwave radiation	effectiveness to reduce longwave radiation	effectiveness to reduce air temperature	effectiveness to regulate ventilation	effectiveness to increase evaporative cooling	overall effect on microclimate
climate-adaptive design	5	4	4	5	4	4
urban climate	4	5	3	5	4	4

INTERVENTIONS OVERVIEW

01 high albedo surface (facade/pavement)

02 cool surface material

03 depaving

04 vertical shading elements

05 horizontal shading elements

06 canvas canopy

07 pergola canopy

08 louvre

09 colonnade

10 vertical shading structure

11 trees

12 shrubs

13 planters with trees or shrubs

14 ground cover vegetation

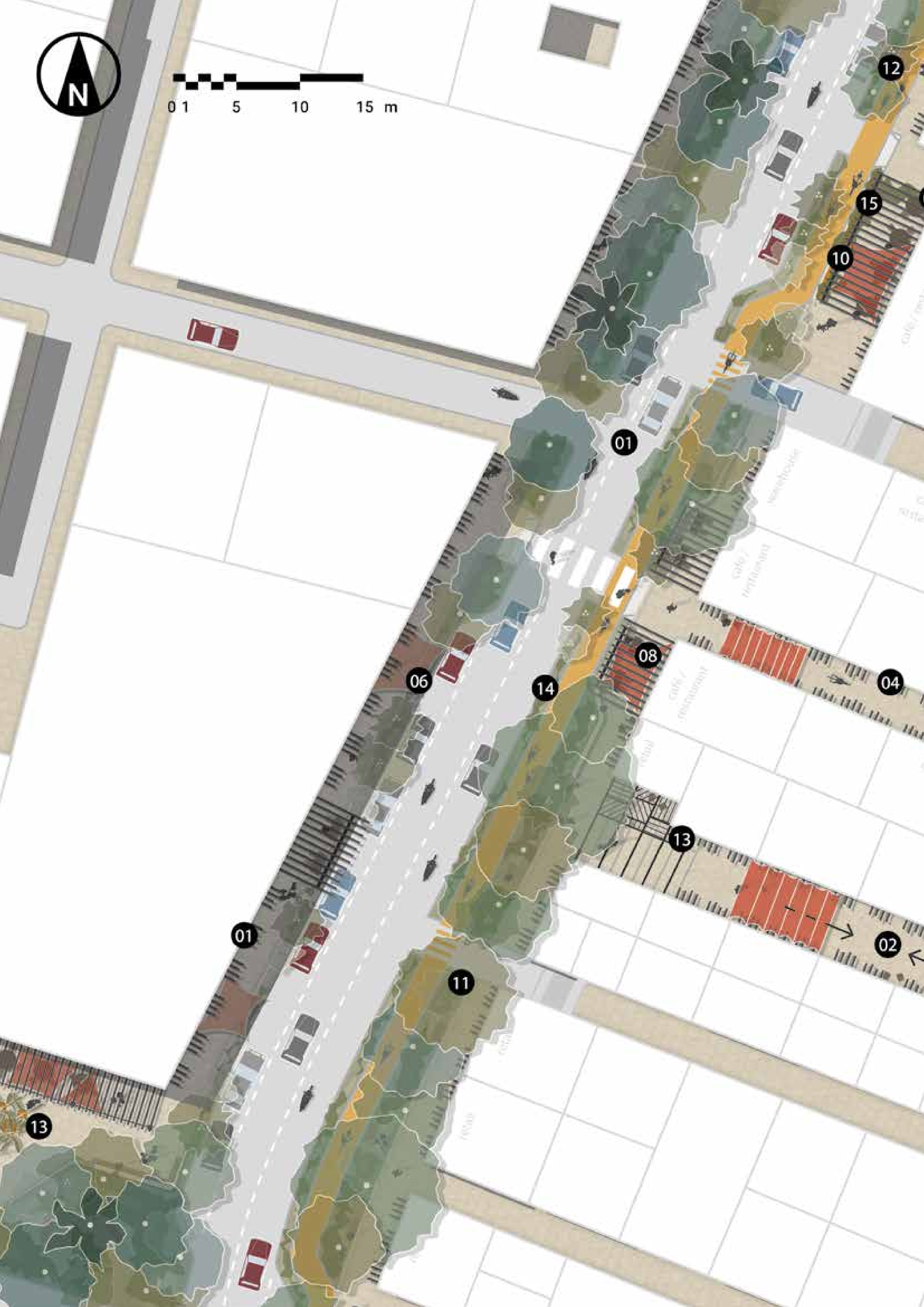
15 green facade

16 passive evaporative cooling system

LEGEND DETAILED DESIGN 3

- sandstone pavers (accent paving)
- light-colored clay brick pavers
- fine dolomite gravel
- wooden awnings
- flexible canvas canopy
- wooden louvre structures
- pergola with climbing plants
- louvre structure w/ evaporative cooling wall
- existing trees
- trees
- shrubs
- ground cover vegetation
- planters with vegetation
- chairs
- tables
- bike path
- raised planting bed
- benches

Fig. 63 Map of site design for the third detailed area, applying different climate-adaptive interventions according to prototypes 1b, 2 and 4 (next page).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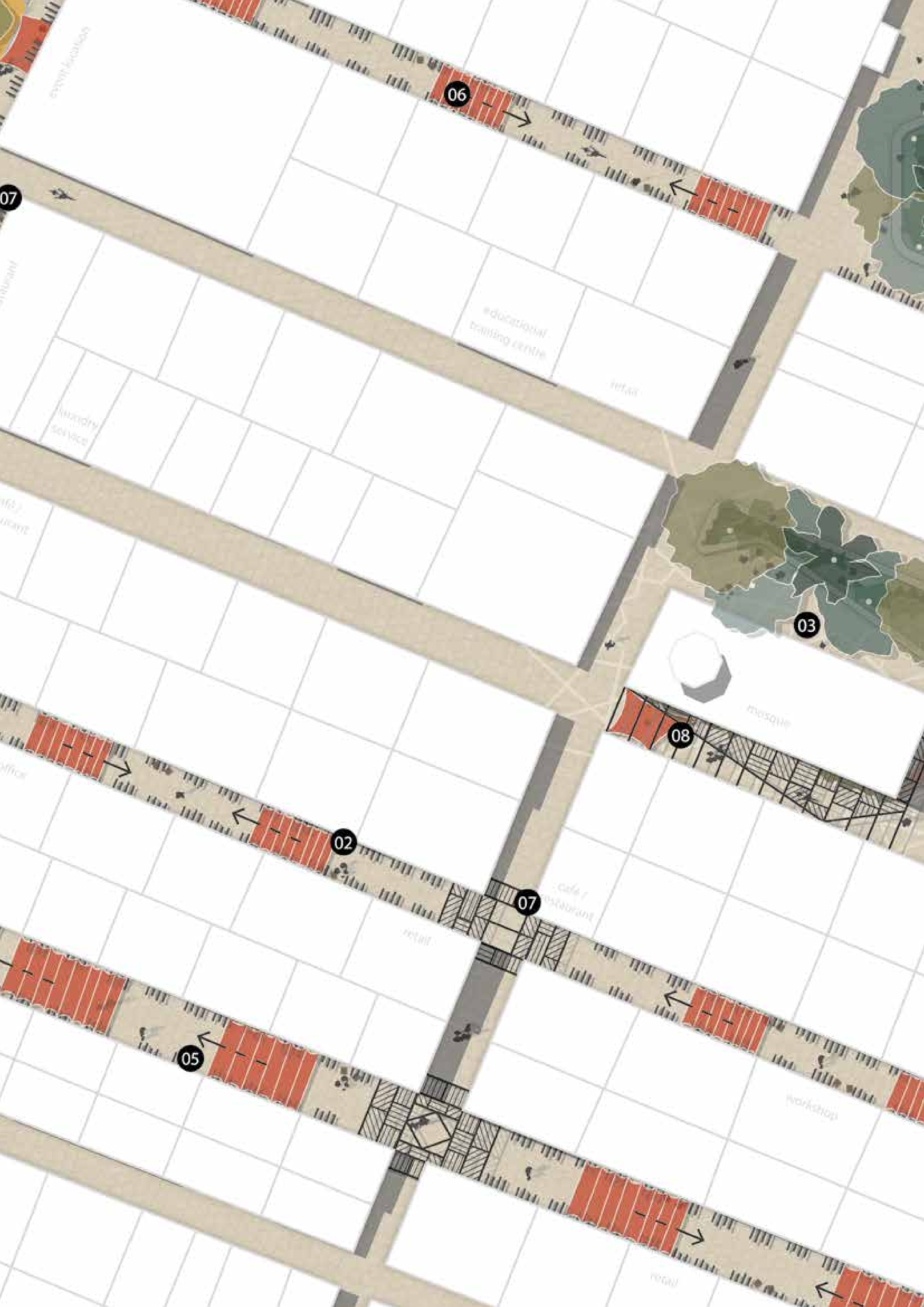
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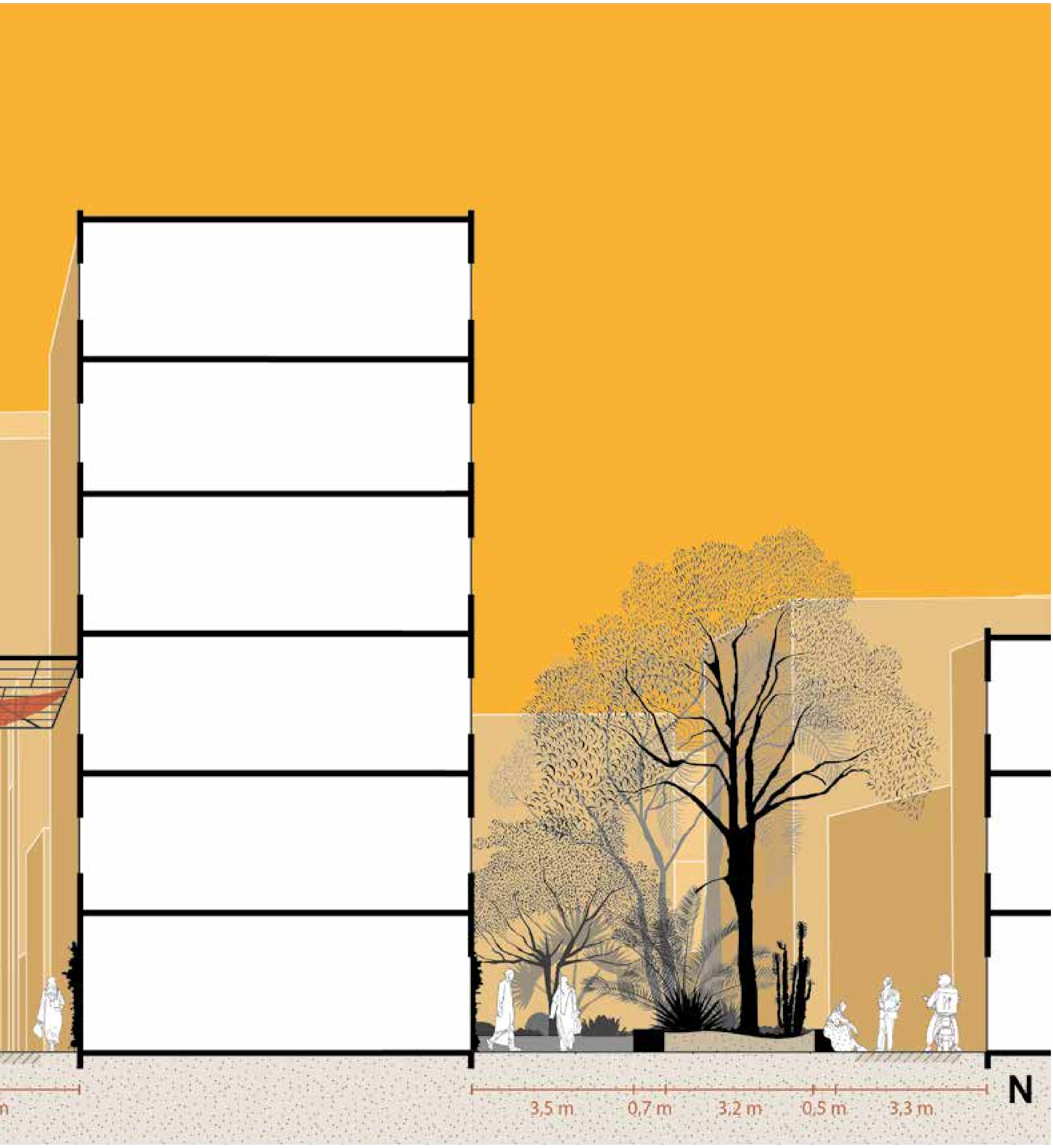
C

Fig. 64 Section of detailed design 3, illustrating two narrow street profiles within the cool network and a small-scale pocket park connected to a mosque.



C'

Fig. 65 Artist impression of a narrow street within the cool network.

Fig. 66 Artist impression of a pocket park embedded in the existing urban fabric.

8. DISCUSSION

This chapter discusses the implications of the results, how they relate to existing knowledge and how they provide new insights for current knowledge and/or practice. It further elaborates on the identified opportunities and challenges and discusses the limitations of this research.

There is a wide consensus within the literature about the effectiveness of the climate-adaptive design interventions applied in the prototypes to regulate urban microclimates (e.g., Lenzholzer, 2015; Marando et al., 2022). Since the focus of this thesis is on unplanned urban areas, it is key to not only discuss the effectiveness of the prototypes, but also the challenges and opportunities they may face in the specific context of unplanned urban areas.

Effectiveness of climate regulation in arid climates

The adaptation of urban materials to increase albedo and/or adapt specific heat properties was applied in all prototypes and designs. Such interventions can decrease local ambient temperatures by increasing permeability and reflectivity, and can reduce heat storage (Osmond & Sharifi, 2017; Farhadi et al., 2019; Mills et al., 2021). Re-coloring outdoor surfaces is a low-cost measure to increase albedo and can potentially be implemented by local residence and local authorities. More structural interventions, such as the installation of cool surfaces on the other hand are more costly and therefore request substantial outside investments. Furthermore, interventions are limited by the function of a street. To illustrate this, in prototype 3 large parts of the profile consists of fully paved surfaces due to mobility needs, which results in a relatively low score on urban climate.

To decrease air temperature and radiant heat, all prototypes include shading by artificial vertical and horizontal structures (La Roche et al., 2020). These shading elements are designed in a manner, that residents can adjust them to cater for changing thermal heat requirements during the day and seasons (Nikolopoulou & Steemers, 2003). The importance to be able to adjust shading devices during night-time to prevent heat-trapping was also raised during the microclimatic assessment of the site design. The proposed shading interventions are inspired by local building practices and/or existing initiatives by residents and therefore strengthen the sense of place in an affordable and easy to implement manner. Colonnades were, despite the initial plan, not included in the designs because of their potential to interfere with mobility needs and wind flows in narrow streets and their assumed high cost.

The cooling effects of vegetation are widely described in literature (Klemm, 2018; Schlaepfer et al., 2020; Dihkan et al., 2021), but their introduction in unplanned urban areas is complex. First, the limitation of space in narrow street profiles reduces the locations where trees and shrubs could be planted. Secondly, plant health can be negatively affected by the high density of motorized traffic. Thirdly, the feasibility of healthy vegetation is further influenced by high acquisition and maintenance costs, mainly caused by irrigation needs. This resulted in lower affordability ratings in prototypes 2 and 3. The application of species with a low water requirement and a high drought tolerance such as Olea Europea, Plumeria Alba or Hyphaene Thebaica is key to reduce maintenance costs and sustainability. Although such vegetation species can cope with high solar radiation and limited water availability, plants adapted to arid climates reduce their moisture release during the day. Thus, decreasing the evaporative cooling potential, when compared to vegetation growing in for example temperate climates (Feyisa et al., 2014).

Challenges and opportunities within the context of unplanned urban areas

To integrate the above-described cooling interventions in an unplanned area, the main challenge is to avoid the negative effects of the interventions on the access to basic needs of residents (e.g., mobility needs, livability, and sense of place). Investments in climate resilience can significantly improve livability, well-being, and health in the long term. However, many residents will, due to their socio-economic situation, prefer to focus on immediate concerns and tangible results related to social mobility, safety, and economic development. In a situation of resource scarcity, one would therefore expect the implementation of such interventions to be delayed. The field visit to the study site has shown, that many of the proposed interventions have already been implemented by residents in an ad hoc way. This proves that there is potential for a more coordinated and systematic implementation of the presented interventions if these challenges are recognized and addressed.

The first main challenge for the implementation of interventions within a densely populated unplanned area is related to their effect on mobility. In informal areas, there is often no clear hierarchy of streets and traffic speed. This means that vehicular traffic, scooters, and delivery trucks compromise the usage of space by pedestrians. This leads to unnecessary congestion and a reduced feeling of safety (Hidayati et al., 2020). To address this, the prototypes and designs assign the types of traffic to a more explicit hierarchy of streets. This can for example be seen in prototype

1, where paving and shading elements are designed in a way to discourage high traffic speed and encourage pedestrians to walk and interact. In prototypes 2 and 3, the traffic flow is made more efficient and pedestrian safety is increased by a clear demarcation for motorized traffic and the introduction of calming traffic measures such as parking bays, vegetation pockets and pedestrian crossings.

The second main challenge is related to the implementation of interventions within livable public areas. In prototype 4 for example, public seating areas, vegetation and playground infrastructure has been introduced to create open public space that encourages social interactions. Prototype 3 addresses this challenge in a similar fashion, by creating a widened and planted traffic island, which uses the space freed up through the reduction of traffic lanes.

The third main challenge is the need of including residents in the development and implementation process of climate-adaptive interventions. The workshop with local students has shown that interventions which respond to local socio-cultural contexts result in higher presumed feasibility. Including people who understand local culture, customs and traditions improves the potential for implementation and maintenance of these climate-adaptive interventions. This potential can only be realized if residents are involved and take ownership of the interventions. In addition, this can also benefit a sense of place (e.g., place identity and social cohesion) (Norberg-Schulz, 1979). However, the feasibility of such grassroots organizing is under the current political circumstances limited.

Limitations

The designs presented in this thesis present a possible way to introduce the climate-adaptive interventions collected in the prototypes into the local circumstances. However, as mentioned in the last point of the challenges section above, only through close interactions with residents could the feasibility of these interventions within the context be fully evaluated. Such an interaction with residents could not be realized in the scope of this research, due to time/budget limitations and the current political situation in Egypt.

The lack of the possibility for direct contact with residents was part of a general difficulty to obtain data. Only a limited amount of GIS data and no open-source information (OpenStreetMap, CADMAPPER) is available for the study area. Due to the lack of accurate maps that could have been used for the site analysis and design, a lot of information had to be extracted from aerial and street-level pictures. This turned out to be extremely time-consuming and added to general time constraints. Due to these site-specific constraints, it unfortunately became necessary to leave climate calculations out of the thesis. It was originally planned to calculate the difference in PET before and after the interventions were implemented, which would have included modelling of the effects of the interventions on the urban climate using ENVI-MET. While these calculations could not be done, it is expected that they would be in line with the results of this first explorative research, due to its multidisciplinary team of experts. Calculating the modeled effects of these interventions should be taken up in follow-up research.

A further limitation of the methodology of this research is, that only the current climatic situation was analyzed. Rising temperatures due to climate change have not been considered. It can though be assumed that these interventions will be even more efficient with increased levels of heat stress.

9. CONCLUSION

The objective of this thesis is to provide decision-makers and designers with practical knowledge on how to reduce heat stress within the streetscape of unplanned urban areas. To this end, an unplanned urban area within a neighborhood in Cairo, Egypt, is selected as study area. The first phase (RFD) focuses on the development of a toolbox, containing effective and feasible climate-adaptive design interventions. During the second phase (RTD) these interventions are implemented within representative street typologies, which results in different design prototypes. To test the applicability of these prototypes within the study area, a site-specific design is developed.

To deal with urban heat stress within streetscapes of unplanned urban areas in arid climates this thesis presents a set of climate-adaptive design interventions. The criteria defining the selection process are based on their effectiveness to regulate microclimatic conditions and feasibility in unplanned urban areas. Interventions scoring low on either of the two selection criteria, are excluded from this study. For the climate-regulation criteria, low scoring interventions are for example extended eaves of buildings or use of rubberized asphalt. Concerning the second criteria, cost-intensive or resource-depended interventions are assessed as not feasible, such as adapting buildings shapes and/or urban geometry (e.g., windcatchers or solar chimney) and the use of water features (e.g., misters or fountains).

Interventions with the most potential to comply well with both selection criteria are combined in an integrated toolbox. This toolbox consists of the following interventions: high albedo facade/pavement, cool surface material, depaving, vertical and horizontal shading elements along building facades, canopies (canvas, pergola, and louvre), vertical shading structure, trees, shrubs, planters, ground cover vegetation, green facades, and passive evaporative cooling systems. The chosen interventions are further validated through site specific observations. During the field visit it was observed that many of the proposed interventions, such as vegetation, louvres, and canvas canopies, are already applied by residents. These are therefore also the interventions that are identified to have the highest feasibility to reduce heat stress in unplanned areas. Although the interventions have differences in climate regulation potential and feasibility, there is no hierarchy within the toolbox. All selected interventions address one or multiple of the three identified cooling strategies, which are: changing urban materials, introducing shade, and increasing evaporative cooling.

To create replicable knowledge and present how the shortlisted climate-adaptive interventions can be applied in representative street profiles, this thesis presents a set of design prototypes. Four street typologies are identified based on their H/W ratio: narrow streets, medium streets, wide streets, and open spaces. These are further subdivided according to their street orientation (i.e., N/S and E/W). The total amount of eight typologies is decreased to five, since not all of them occur within the study site (i.e., medium street E/W), and two street typologies show no difference between effectiveness of interventions for both orientations (i.e., wide street and open spaces E/W and N/S).

The prototypes are developed and tested in three iterations and present the most effective way to combine the identified interventions within the street typologies. Within narrow street profiles the number and scale of interventions is limited due to space. In addition, vegetation and other non-flexible interventions pose the risk of trapping heat within the urban canyon and obstructing potential cooling through wind. In the other street typologies, all interventions can be implemented, varying in scale and number. Depending on the predominant functionalities in a specific street typology, differences occur. For example, within wide and medium streets the area of paved surfaces is large due to mobility needs, while open spaces provide more room for interventions.

The adaptation of urban materials effectively increases reflexivity and reduces heat storage, which leads to a decrease in local ambient temperatures. However, feasibility is reduced due to high-costs and mobility needs. Implementation of shade within the urban canyon decrease the amount of incoming shortwave radiation and effectively decrease peak temperatures during the day. The feasibility of these type of interventions is high since they are cost-effective and already implemented by residents in an ad-hoc manner. Increasing evaporative cooling by planting vegetation is effective since it also affects the other two cooling strategies. However, its feasibility is challenged by the high maintenance needs due to irrigation, required space or the reduced plant health due to motorized traffic.

The site-specific design of the unplanned neighborhood in Shubra shows the applicability of the developed prototypes in this setting. Rooted in an extensive analysis addressing social, spatial, and climatic topics, the design tackles identified problems and opportunities. Besides the aim to improve microclimatic conditions, the design intents to improve spatial quality of the area. This is reached by focusing on functionality, landscape aesthetics, preservation of cultural landmarks and sense of place. The microclimatic assessment of the three detailed designs confirms the potential of the prototypes for climate regulation. In this way, the design gives a clear insight in how the prototypical knowledge relates to real-life situations.

To maximize the cooling effect, pocket parks with a high local cooling potential are designed across the neighborhood. Existing open spaces and newly created open spaces are strategically positioned and connected by a network of cool streets. This network focuses on the most frequented spaces and connecting streets to maximize the experienced cooling effect by residents. Although motorized traffic takes up most of the space in medium and wide streets, pedestrian experience is improved by extending sidewalks, reducing traffic speed, adding vegetation, and implementing shading structures. To allow for increased nocturnal cooling, design interventions are designed in the most flexible way considering the specific context of an unplanned area. To reduce irrigation needs and maximize shading potential, the selection of species considers water requirement, drought tolerance and high shading potential. To further diversify the shading potential, different heights and shapes of vegetation are proposed.

This thesis demonstrates the potential of climate adaptive design to reduce heat stress in urban unplanned areas. The results suggest that the regulatory effects on microclimates can be achieved, while the public space for social interactions and traffic safety can be improved. Through the inclusion of local design elements and a focus on systematizing interventions that residents already implement in an ad hoc manner, the suggested acceptance of residents is enhanced.

The presented results are thought to be perceived as an explorative study describing a potential. Further research would be needed to quantify the cooling effects of the prototypes through microclimatic modelling. The feasibility of the prototypes within the specific context has to be further evaluated in close collaboration with residents, who are already taking the initiative to implement several of the described interventions (e.g., shading covers and vegetation). There is no doubt, that any future implementation of these interventions would have to include residents, allowing them to take decisions on and ownership of these changes to their neighborhood. Only through such an approach can the proposed climate-adaptive interventions fulfill their potential to reduce heat stress within unplanned urban areas.

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APPENDIX I

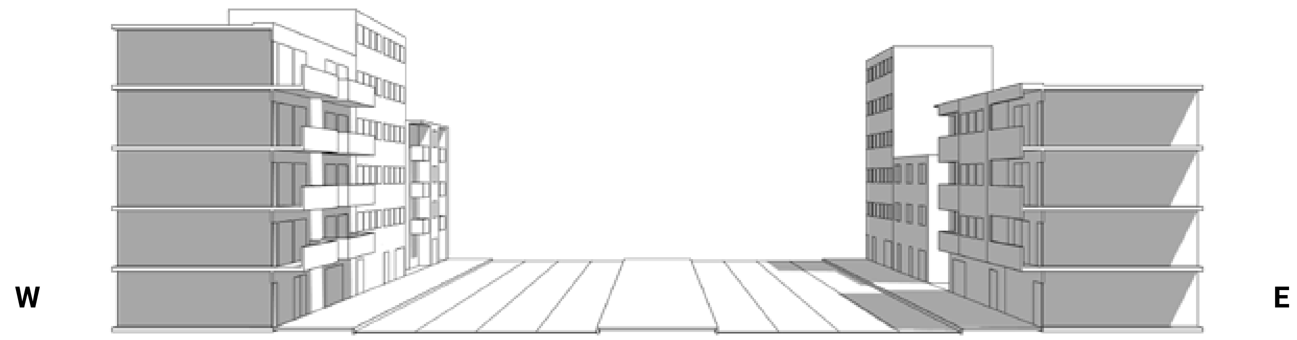
DETAILED ASSESSMENT TABLE OF INTERVENTIONS

	CLIMATE REGULATION in arid climates				
	reduce shortwave radiation	reduce longwave radiation	reduce air temperature	regulate ventilation	increase evaporative cooling
high albedo facade	1	5	3	n/a	n/a
high albedo pavement	1	5	4	n/a	n/a
cool surface material	1	3	3	n/a	2
depaving	2	5	4	n/a	5
shading elements (vertical/horizontal)	5	4	4	2	n/a
canvas canopy	5	4	4	3	n/a
pergola canopy	4	5	4	3	3
louvre	5	4	4	3	n/a
colonnade	5	3	5	3	n/a
vertical shading structure	4	4	4	2	n/a
trees	5	4	5	3	5
shrubs	3	3	3	2	3
planters with trees or shrubs	4	3	3	2	4
ground cover vegetation	1	3	2	n/a	2
green facade	3	5	3	2	3
passive evaporative cooling system	4	4	4	2	5

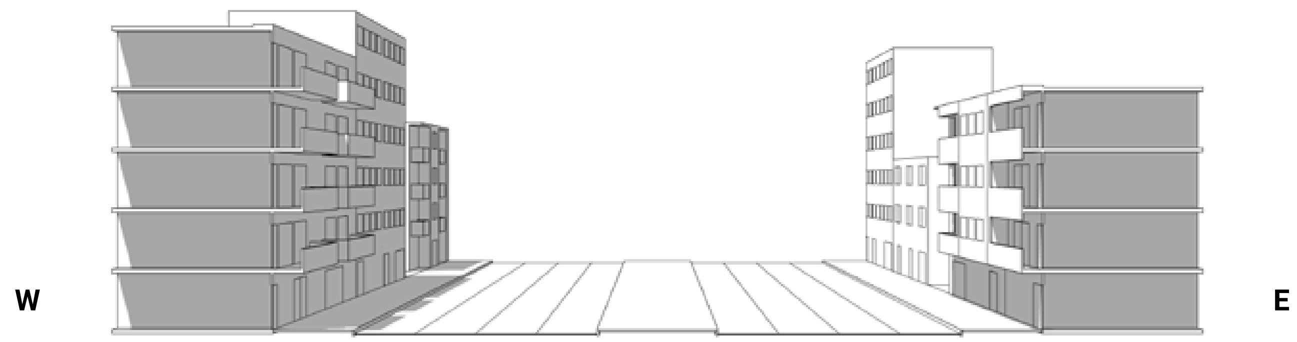
	FEASIBILITY in unplanned areas		
	low capital costs	ease of construction	spontaneous maintenance
high albedo facade	3	3	3
high albedo pavement	3	3	4
cool surface material	3	3	4
depaving	5	5	5
shading elements (vertical/horizontal)	5	3	3
canvas canopy	5	5	3
pergola canopy	3	3	3
louvre	4	4	3
colonnade	2	2	3
vertical shading structure	3	3	3
trees	4	2	5
shrubs	4	4	3
planters with trees or shrubs	4	4	3
ground cover vegetation	4	4	2
green facade	2	3	4
passive evaporative cooling system	3	3	3

APPENDIX II

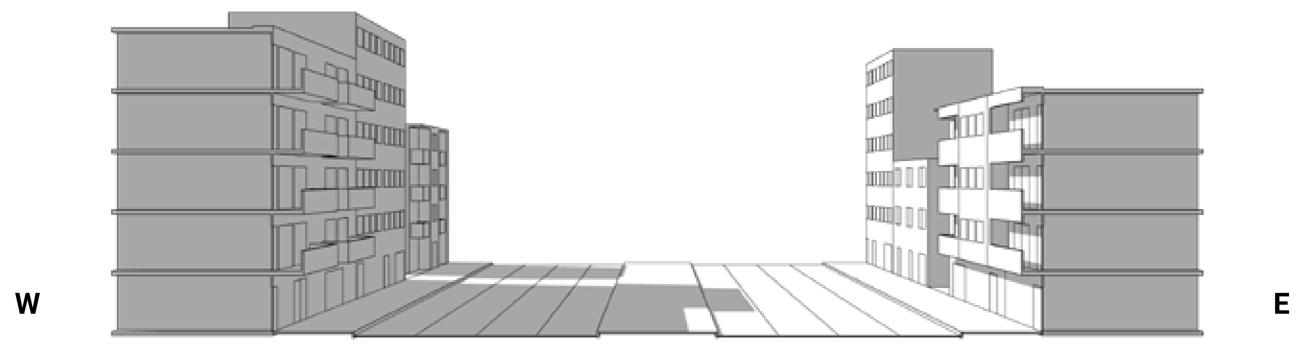
DETAILED SHADOW ANALYSIS WIDE STREET N/S



Wide street T3 N/S current situation: shadow analysis 21 June 10 h morning

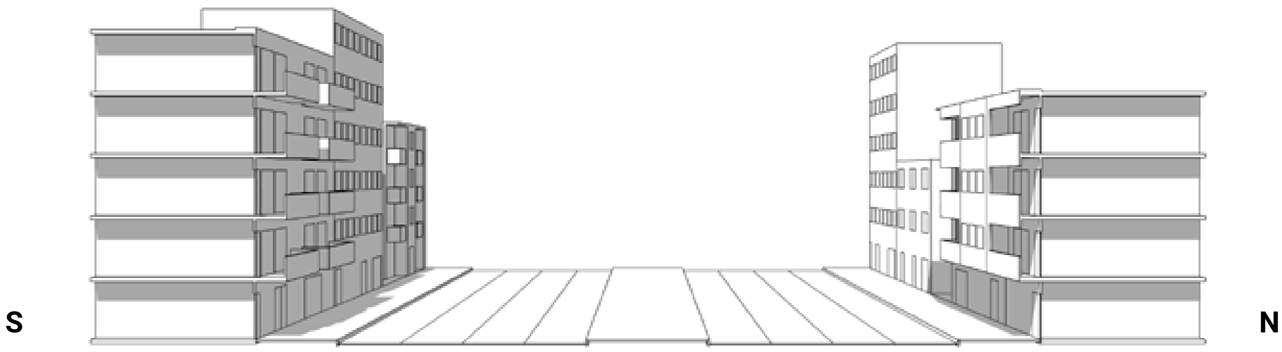


Wide street T3 N/S current situation: shadow analysis 21 June 13 h afternoon

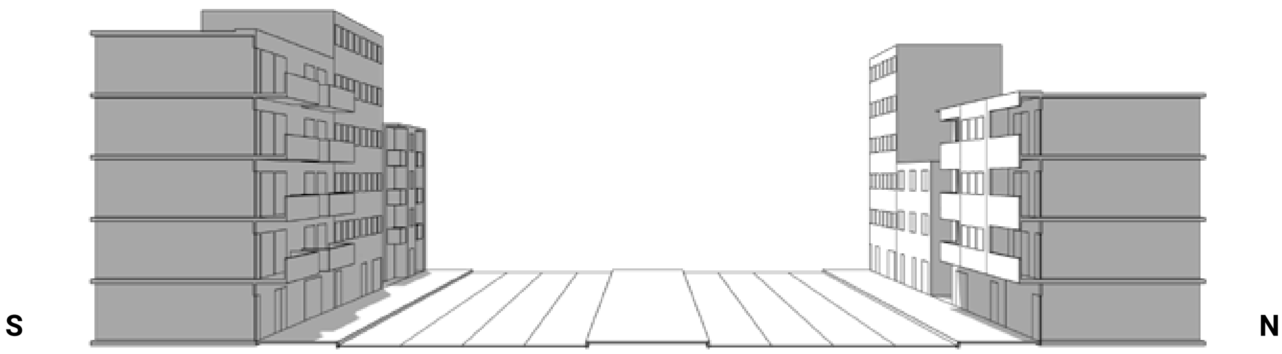


Wide street T3 N/S current situation: shadow analysis 21 June 16 h afternoon

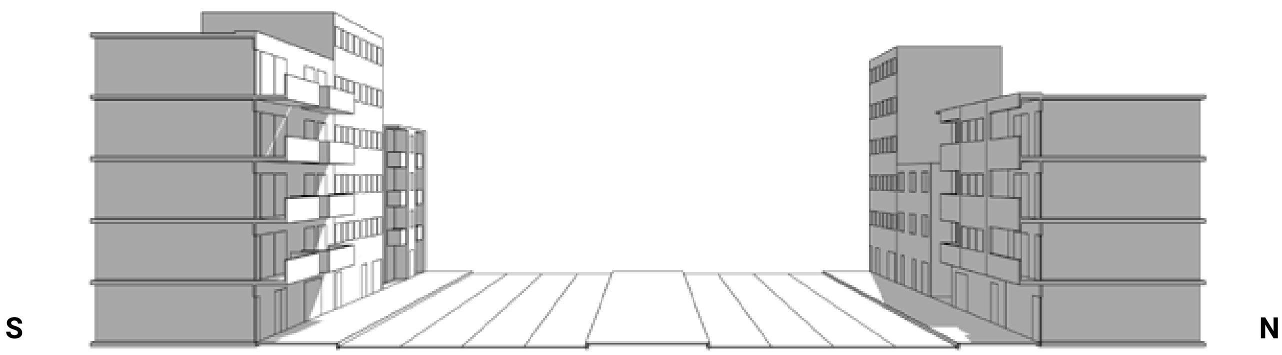
DETAILED SHADOW ANALYSIS WIDE STREET E/W



Wide street T3 E/W current situation: shadow analysis 21 June 10 h morning



Wide street T3 E/W current situation: shadow analysis 21 June 13 h afternoon



Wide street T3 E/W current situation: shadow analysis 21 June 16 h afternoon

APPENDIX III

LIST OF APPROPRIATE TREE SPECIES

Number	Name of specimen (Botanical Name)	Large/ Long Leaves 15cm >	Hairy/ Throned/ Toothed/ Waxy/ Rough leaves	Desnse twigs	Rough Bark	Form (Decidious / Evergreen)	Drought Tolerance (H/M/L)	Water Requirment (H/M/L)	Earned Points
									Max. 6
1	Sesbania Sesban	1	1	1	1	Decidious	1.00	1.00	6
2	Castanea Sativa Miller	1	1	1	1	Decidious	1.00	0.67	5.67
3	Citrus Limon	1	1	1	1	Evergreen	1.00	0.67	5.67
4	Citrus Medica	1	1	1	1	Evergreen	1.00	0.67	5.67
5	Cordi myxa	1	1	1	1	Evergreen	1.00	0.67	5.67
6	Ficus Bebghalensis	1	1	1	1	Evergreen	1.00	0.67	5.67
7	Ficus Lyrata	1	1	1	1	Evergreen	1.00	0.67	5.67
8	Ficus macrophylla	1	1	1	1	Evergreen	1.00	0.67	5.67
9	Gleditsia triacanthos	1	1	1	1	Decidious	1.00	0.67	5.67
10	Melia azdarach	1	1	1	1	Decidious	1.00	0.67	5.67
11	Terminalia catappa	1	1	1	1	Decidious	1.00	0.67	5.67
12	Morus Alba	1	1	1	1	Decidious	0.67	0.67	5.34
13	Balanites aegyptiaca	0	1	1	1	Evergreen	1.00	1.00	5
14	Ficus Auriculata	1	1	1	1	Evergreen	0.33	0.67	5
15	Olea Europaea	0	1	1	1	Evergreen	1.00	1.00	5
16	Plumeria Alba	1	1	1	0	Decidious	1.00	1.00	5
17	Tamarix aphylla	0	1	1	1	Evergreen	1.00	1.00	5
18	Aberia Caffra	0	1	1	1	Evergreen	1.00	1.00	5
19	Aphanamixis polystachya	1	0	1	1	Evergreen	1.00	0.67	4.67
20	Callistemon Viminalis	1	0	1	1	Evergreen	1.00	0.67	4.67
21	Casimiroa edulis	1	0	1	1	Evergreen	1.00	0.67	4.67
22	Cassia Fistula	1	0	1	1	Evergreen	1.00	0.67	4.67
23	Cassia Nodosa	1	0	1	1	Decidious	1.00	0.67	4.67
24	Cassia spectabilis	1	0	1	1	Evergreen	1.00	0.67	4.67
25	Casuarina Cunninghamiana	1	0	1	1	Evergreen	1.00	0.67	4.67
26	Ceratonia Siliqua	1	0	1	1	Evergreen	1.00	0.67	4.67
27	Citrus Paradisi	1	0	1	1	Evergreen	1.00	0.67	4.67
28	Cupressus macrocarpa	1	0	1	1	Evergreen	1.00	0.67	4.67
29	Cupressus sempervirens	1	0	1	1	Evergreen	1.00	0.67	4.67
30	Delonix Regia	1	0	1	1	Decidious	1.00	0.67	4.67
31	Enterolbium cyclocarpum	1	0	1	1	Decidious	1.00	0.67	4.67
32	Eriobtyra japonica	1	1	1	0	Evergreen	1.00	0.67	4.67
33	Erythrina Caffra	1	0	1	1	Evergreen	1.00	0.67	4.67
34	Ficus benghalensis	1	0	1	1	Evergreen	1.00	0.67	4.67
35	Cupressus macrocarpa	1	0	1	1	Evergreen	1.00	0.67	4.67
36	Ficus Decora	1	1	1	0	Evergreen	1.00	0.67	4.67
37	Ficus Maclellandii	1	0	1	1	Evergreen	1.00	0.67	4.67
38	Ficus religiosa	1	1	1	0	Decidious	1.00	0.67	4.67
39	Jacranda ovalifolia	1	1	1	0	Decidious	1.00	0.67	4.67
40	Magnolia grandiflora	1	1	1	0	Evergreen	1.00	0.67	4.67

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41	Melaleuca Leucadendroa	1	1	1	0	Evergreen	1.00	0.67	4.67
42	Parkinsonia Aculeata	0	1	1	1	Decidious	1.00	0.67	4.67
43	Peltoporum africacum	0	1	1	1	Decidious	1.00	0.67	4.67
44	Populus Alba	0	1	1	1	Decidious	1.00	0.67	4.67
45	Salix Babylonica	0	1	1	1	Decidious	1.00	0.67	4.67
46	Sophora Secundiflora	1	1	1	0	Evergreen	1.00	0.67	4.67
47	Spathodea Campunalata	1	1	1	0	Decidious	1.00	0.67	4.67
48	Tabebuia argentea	1	1	1	0	Decidious	1.00	0.67	4.67
49	Tecoma Stans	1	1	1	0	Evergreen	1.00	0.67	4.67
50	Conocarpus Erectus	0	0	1	1	Evergreen	1.00	1.00	4
51	Annona Muricata	1	0	1	0	Evergreen	1.00	0.67	3.67
52	Artocarpus Heterophyllus	0	0	1	1	Evergreen	1.00	0.67	3.67
53	Dalbergia Sissoo	1	0	1	0	Evergreen	1.00	0.67	3.67
54	Certonia Siliqua	1	0	1	0	Evergreen	1.00	0.67	3.67
55	Ficus Benjamina	0	1	1	0	Evergreen	1.00	0.67	3.67
56	Ficus infectoria	0	1	1	0	Decidious	1.00	0.67	3.67
57	Ficus Microcarpa	0	1	1	0	Evergreen	1.00	0.67	3.67
58	Araucaria Heterophylla	0	0	1	1	Evergreen	0.67	0.67	3.34
59	Carica Papaya	1	0	1	0	Evergreen	0.67	0.67	3.34
60	Diospros Kaki	1	0	1	0	Decidious	0.67	0.67	3.34
61	Acacia Nilotica	0	0	1	0	Evergreen	1.00	1.00	3
62	Acacia Smallii	0	0	1	0	Evergreen	1.00	1.00	3

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LIST OF APPROPRIATE PALM TREE SPECIES

Number	Name of specimen (Botanical Name)	Large/Long leaflets 2 m >	Hairy / throned/ toothed /waxy/ rough leaflets	Leaflets compactnes	Rough trunk	Form (Decidious/ Evergreen)	Drought Tolerance (H/M/L)	Water Requirment (H/M/L)	Earned Points
									max. 6
1	Pheonix Cnariensis	1	1	1	1	Evergreen	1.00	0.67	5.67
2	Washingtonia Robusta	1	1	1	1	Evergreen	1.00	0.67	5.67
3	Pheonix Dactylifera	1	1	1	1	Evergreen	1.00	0.67	5.67
4	Livistona Australis	1	1	1	1	Evergreen	0.33	0.67	5
5	Pitchardia Pacifia	1	0	1	1	Evergreen	1.00	0.67	4.67
6	Washingtonia Flifera	1	0	1	1	Evergreen	1.00	0.67	4.67
7	Chamaeropes Humilis	1	0	0	1	Evergreen	1.00	1	4
8	Hyphhaene Thebaica	1	0	0	1	Evergreen	1.00	1	4
9	Licuala Grandis	1	0	1	1	Evergreen	0.33	0.67	4
10	Chrysalidocarpus Lutescens	1	0	1	0	Evergreen	0.67	0.67	3.34
11	Cycus Revoluta	1	0	0	1	Evergreen	0.67	0.67	3.34

Directly cited from: Youssef, A. (2020). Unique plants and grouping strategies promoting Cairo's streets air quality. Ain Shams University/Stuttgart University.

LIST OF APPROPRIATE SHRUBS AND GROUNDCOVER SPECIES

Number	Name of specimen (Botanical Nam)	Large/ Long Leaves 10cm >	Hairy / Throned/ Toothed / Waxy/ Rough leaves	Desnse twigs	Rough bark	Form (Decidious/ Evergreen)	Drought Tolerance (H/M/L)	Water Requirment (H/M/L)	Earned Points
									Max. 6
1	Acokanthera Spectabilis	1	1	1	1	Evergreen	1.00	1.00	6
2	Myoporum laetum	1	1	1	1	Evergreen	1.00	1.00	6
3	Nerium Oleander	1	1	1	1	Evergreen	1.00	1.00	6
4	Pittosporum tobira	1	1	1	1	Evergreen	1.00	1.00	6
5	Rhaphiolepis Indica	1	1	1	1	Evergreen	1.00	1.00	6
6	Dasylirions quadrangulatum	1	1	1	1	Evergreen	1.00	1.00	6
7	Euphorbua lactea	1	1	1	1	Evergreen	1.00	1.00	6
8	Euphorbia milii	1	1	1	1	Evergreen	1.00	1.00	6
9	Pachypodium lamerei	1	1	1	1	Decidious	1.00	1.00	6
10	Yucca aloifolia	1	1	1	1	Evergreen	1.00	1.00	6
11	Yucca elephantipes	1	1	1	1	Evergreen	1.00	1.00	6
12	Yucca filametosa	1	1	1	1	Evergreen	1.00	1.00	6
13	Verbena Hubrida	1	1	1	1	Evergreen	1.00	0.67	5.67
14	Acalypha Margianta	1	1	1	1	Evergreen	1.00	0.67	5.67
15	Aralia Japonica	1	1	1	1	Evergreen	1.00	0.67	5.67
16	Caesalpinia pulcherrima	1	1	1	1	Decidious	1.00	0.67	5.67
17	Cassia tomentosa	1	1	1	1	Decidious	1.00	0.67	5.67
18	Euphorbia	1	1	1	1	Decidious	1.00	0.67	5.67
19	Euphorbia pulcherrima	1	1	1	1	Decidious	1.00	0.67	5.67
20	Ficus Carica	1	1	1	1	Decidious	1.00	0.67	5.67
21	Hibscus rosa-sinensis	1	1	1	1	Evergreen	1.00	0.67	5.67
22	Murraya exotica	1	1	1	1	Evergreen	1.00	0.67	5.67
23	Bouganivillea stans	1	1	1	1	Evergreen	1.00	0.67	5.67
24	Carissa grandiflora	0	1	1	1	Decidious	1.00	1.00	5
25	Dodonea Viscosa	0	1	1	1	Evergreen	1.00	1.00	5
26	Leucophyllum frutescens	0	1	1	1	Evergreen	1.00	1.00	5
27	Rosa hybrida	1	1	1	1	Evergreen	0.33	0.67	5
28	Santolina chamaecypaissus	0	1	1	1	Evergreen	1.00	1.00	5
29	Calotropis procera	1	1	1	0	Evergreen	1.00	1.00	5

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Number	Name of specimen (Botanical Nam)	Large/ Long Leaves 10cm >	Hairy / Throned/ Toothed / Waxy/ Rough leaves	Desnse twigs	Rough bark	Form (Decidious/ Evergreen)	Drought Tolerance (H/M/L)	Water Requirment (H/M/L)	Earned Points
									Max. 6
30	Carpobrotus edulis	1	1	1	0	Evergreen	1.00	1.00	5
31	Calliandra Haematocephala	1	1	1	0	Evergreen	1.00	0.67	4.67
32	Callistemon rigidus	0	1	1	1	Evergreen	1.00	0.67	4.67
33	Cassia Alata	1	1	1	0	Decidious	1.00	0.67	4.67
34	Crotalaria madurensis	0	1	1	1	Evergreen	1.00	0.67	4.67
35	Eranthemum pulchellum	1	1	1	0	Evergreen	1.00	0.67	4.67
36	Justicia adhatoda	1	1	1	0	Evergreen	1.00	0.67	4.67
37	Lawsonia Alba	0	1	1	1	Evergreen	1.00	0.67	4.67
38	Myrtus commius	1	1	1	0	Evergreen	1.00	0.67	4.67
39	lantana montevidensis	0	1	1	1	Decidious	1.00	0.67	4.67
40	Senecio cineraria	1	1	1	0	Evergreen	1.00	0.67	4.67
41	Monestera Deliciosa	1	1	1	0	Evergreen	0.33	0.67	4
42	Agava americana	1	1	0	0	Evergreen	1.00	1.00	4
43	Agave angustifolia	1	1	0	0	Evergreen	1.00	1.00	4
44	Agave atrovirens	1	1	0	0	Evergreen	1.00	1.00	4
45	Agave attenuata	1	1	0	0	Evergreen	1.00	1.00	4
46	Agave Desmettiana	1	1	0	0	Evergreen	1.00	1.00	4
47	Agave ferox	1	1	0	0	Evergreen	1.00	1.00	4
48	Aloe striata	1	1	0	0	Evergreen	1.00	1.00	4
49	Aloe vera	1	1	0	0	Evergreen	1.00	1.00	4
50	Cereus peruvianus	0	1	1	0	Evergreen	1.00	1.00	4
51	Opuntia ficus indica	1	1	0	0	Evergreen	1.00	1.00	4
52	Sansevieria trifasciata	1	1	0	0	Evergreen	1.00	1.00	4
53	Annona Muricata	1	0	1	0	Evergreen	1.00	0.67	3.67
54	Annona Muricata	0	1	1	0	Evergreen	1.00	0.67	3.67
55	Cestrum Aaurantiacum	1	0	1	0	Evergreen	1.00	0.67	3.67
56	Lavandula angusifolia	0	1	1	0	Evergreen	1.00	0.67	3.67
57	Catharanthus roseus	0	1	1	0	Evergreen	1.00	0.67	3.67
58	Anisacanthus thuberi	0	1	1	0	Evergreen	0.67	0.67	3.34
59	Plumbago capensis	0	1	1	0	Evergreen	0.67	0.67	3.34
60	Aglaonema species	1	1	0	0	Evergreen	0.33	0.67	3
61	Anthurium species	1	1	0	0	Evergreen	0.33	0.67	3
62	Echinocacus grusonii	0	1	0	0	Evergreen	1.00	1.00	3

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