FINAL REPORT

DIGITAL TWINS

Development and use of Digital Twins for campuses in Dortmund and Bến Cát for climate adaptation measures

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SUPERVISORS

Univ.-Prof. Dr. habil. Nguyen Xuan Thinh

M.Sc. Sinan Karakus

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List of Authors

Lena Böse

Ole Czech

Flemming Eismann

Christian Hohle

Jan Kanelias

Lea Maiwald

Raphael Michaelis-Braun

Laura Mintzlaff

Beeke Quante

Ben Luca Schumacher

Yannic Schwarz

Alina Sommer

Sophie Christine Wiegand

Marit Wissen

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Abstract

Climate Change is the leading cause for the warming of the atmosphere, land, and oceans. As a result, urban areas are particularly affected by the urban heat island phenomenon, which has a significant negative impact on human health, energy consumption and everyday life. To mitigate the effects on the environment and residents, researching new technologies such as Digital Twins in Smart Cities can be crucial. This research aims to evaluate the effectiveness of the usage of Digital Twins for developing climate adaptation measures to mitigate urban heat island effects. A key element of this evaluation is analyzing the potentials and limitations of the Digital Twin technology, emphasizing the creation process of a Digital Twin as well as the application and its usage.

A Digital Twin is created for a building on the campus of the TU Dortmund University and the Vietnamese-German University. The methods of laser scanning and 3D modeling serve as a foundation for the creation process of the Digital Twins. To analyze the effect of climate adaptation measures on built environment, microclimatic simulations are conducted. The results of the research including the 3D model and the microclimatic simulations are visualized in a geoinformation map. The evaluation process revealed multiple challenges in the development process and the usage of the Digital Twin technology. The main areas for improvement were identified in terms of data availability, data interoperability, and mesh creation. However, it is important to note that Digital Twin appears to have a significant potential for future urban development.

Der Klimawandel ist die Hauptursache für die Erwärmung der Atmosphäre, der Landmassen und der Ozeane. Im Zuge dieser Entwicklung sind insbesondere städtische Gebiete von dem Phänomen der städtischen Wärmeinseln betroffen, welche erhebliche negative Auswirkungen auf die menschliche Gesundheit, den Energieverbrauch und auf das alltägliche Leben haben. Um diese Auswirkungen auf die Umwelt und auf die Bewohner:innen zu reduzieren, kann die Erforschung neuer Technologien, wie Digitale Zwillinge in Smart Cities, von zentraler Bedeutung sein. Diese Forschung zielt darauf ab, die Effektivität des Einsatzes von Digitalen Zwillingen für die Entwicklung von Klimaanpassungsmaßnahmen zu bewerten, um den städtischen Hitzeinsel Effekt abzuschwächen. Ein wesentliches Element der Evaluation besteht darin, das Potenzial und die Grenzen der Digitalen-Zwillings-Technologie zu analysieren, insbesondere den Erstellungsprozesses des Digitalen Zwillings sowie seiner Anwendung und Nutzung.

Es wird jeweils ein Digitaler Zwilling für ein Gebäude auf dem Campus der TU Dortmund und auf dem Campus der Vietnamesisch-Deutschen Universität erstellt. Die Methoden des Laserscanning und der 3D Modellierung dienen als Grundlage des Erstellungsprozess des Digitalen Zwillings. Zur Analyse der Auswirkungen von Klimaanpassungsmaßnahmen auf die bebaute Umwelt werden mikroklimatische Simulationen durchgeführt. Die Ergebnisse der Forschung, einschließlich des 3D Modells und der mikroklimatischen Simulationen, werden in einer Geoinformationskarte visualisiert. Im Evaluierungsprozess wurden mehrere Herausforderungen aufgezeigt, die im Entwicklungsprozess und in der Anwendung der Technologie der Digitalen Zwillinge aufgetaucht sind. Die wesentlichen Verbesserungsbereiche wurden hinsichtlich der Datenverfügbarkeit, Dateninteroperabilität und der Erstellung von Netzstrukturen identifiziert. Es ist jedoch festzuhalten, dass die Technologie des Digitale Zwillings ein signifikantes Potential für zukünftige urbane Entwicklungen aufweist.

1. Introduction

The ongoing urban challenges posed by climate change further emphasize the need for innovative solutions in urban planning as reflected in the eleventh Sustainable Development goal "Make cities and human settlements inclusive, safe, resilient and sustainable" from the United Nation s(UN 2015: 24). Simultaneously the Intergovernmental Panel on Climate Change indicates that urban areas are increasingly threatened by flooding, air pollution, precipitation extremes and heatwaves (IPCC 2021: 8 f.). Urban planning is currently experiencing a significant transformation addressing the challenges of climate change in recent years, primarily driven by technological advancements (Riaz et al. 2023: 14 f.). The development in the geospatial information field has facilitated the collection and analysis of vast amounts of data which can be used for data analysis on climate change and its impacts e.g., on climate patterns, environmental conditions, and vulnerability assessments (Caprari et al. 2022: 3). The German government has responded by specifically mentioning Digital Twins in its digitalization strategy and claims "Inspired by Smart Cities and Smart Regions model projects, municipalities throughout Germany are increasingly recognizing and exploiting the potential of digitization for sustainable, future-oriented and barrier-free urban and spatial development and for equal living conditions in rural and urban areas" (German Federal Government 2022: 6 f.). According to a prediction by the Fraunhofer Institute, cities worldwide are expected to deploy 500 urban Digital Twins by the year of 2025, which will serve various application areas (Fraunhofer IESE 2021: 4). Geographical information systems combined with advanced modeling and simulation tools can support the creation of sustainable solutions in spatial planning by allowing planners to create scenarios and evaluate the potential outcomes of different interventions or policies, identify optimal solutions, and make informed decisions (Caprari et al. 2022: 1; Khajavi et al. 2019: 147408).

The Digital Twin technology has already found numerous applications across various industries, including aerospace, engineering, health care, and infrastructure and enables valuable monitoring and data collection for future-proofing initiatives (Björnsson et al. 2019: 1; Tao & Qi 2019: 1). This allows for the creation of a virtual twin testbed, enabling scenario testing and continuous learning from environmental changes. Collected data supports data analytics and ongoing monitoring to better understand and to address the impacts of climate change (Fuller et al. 2020: 3). The Digital Twin includes three interconnected parts: the physical object, the virtual object, and the data exchange between these components (Grieves 2014: 1). The underlying concept of the virtual object revolves around creating a virtual representation of the physical object, incorporating layers of real-world information such as processes, systems, behaviors, and relationships (ibid.: 2).

In the domain of spatial planning, the Digital Twin technology has emerged as a new tool often defined as an urban Digital Twin (Alva et al. 2022: 7). The urban Digital Twin represents physical spaces such as cities, neighborhoods, or individual buildings, incorporating real-time data and information which enables planners to analyze and visualize the functioning of urban systems (ibid.: 5). A universally accepted definition of the urban Digital Twin has not yet been established but to institute a comprehensive understanding of the urban Digital Twin in the context of spatial planning, Stoter et al. (2021: 2) have identified essential factors that are commonly used for urban Digital Twins such as 3D city models, semantic or geometric information, real-time sensor data, and various analysis and simulations (Corchero et al. 2018: 1). This technology is already being utilized to mitigate the impacts of climate change by analyzing and simulating climatic conditions, thereby generating insights for urban planning (Biljecki et al. 2015: 2851). An example is the city of Zurich, which is actively implementing climate adaptation measures for buildings and urban areas using a Digital Twin (Schrotter & Hürzeler 2020: 108). By creating virtual replicas of buildings, the city of Zurich can simulate and analyze various scenarios to identify the most effective strategies for reducing energy consumption, improving thermal comfort, and minimizing greenhouse gas emissions (ibid.).

The concept of a Digital Twin typically involves the bidirectional data link between a physical object and its digital representation, enabling insights and applications to be derived from the digital representation applied to the physical counterpart (see Figure 1; Deng & Wong 2020: 126 f.; Fraunhofer IESE 2021: 8). However, in the context of this research, the principles of the Digital Twin have been modified from the typical approach. Figure 2 demonstrates the change of the physical object into a virtual object since direct changes and adjustments on the physical object are not feasible during the development process of the Digital Twin under this research. Instead of applying modifications directly to the physical object to improve its performance, the results and changes obtained through data synthesis are applied to the virtual object, which is represented by a 3D model adapted with climate adaptation measures, embedded in a geoinformation environment. The virtual object influences the digital representation just as the physical object would.

The objective of this research is to evaluate the effectiveness of Digital Twin technology in establishing climate adaptation measures to counteract urban heat island (UHI) effects. The Digital Twin should be able to simulate different scenarios by dynamically reacting to the data exchange. The simulations should demonstrate which climate adaptation measures contribute

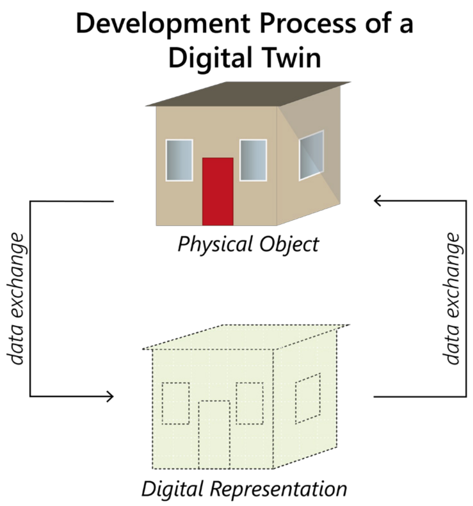


Figure 1: Development Process of a Digital Twin (own illustration)

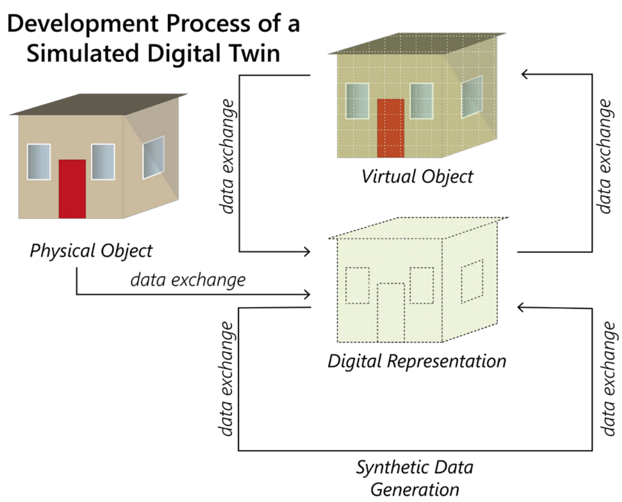


Figure 2: Development Process of a Simulated Digital Twin (own illustration)

to reducing UHI effects. The Digital Twin should be able to support planners in their actions and make decisions understandable to civil society through a user display (Alva et al. 2022: 7). The investigation of creating the Digital Twin in climate research aims to uncover the obstacles that need to be overcome to take full advantage of its benefits.

This research focuses on two study areas: The campus of the TU Dortmund University in Dortmund, Germany, and the campus of the Vietnamese-German University (VGU) in Bến Cát, Vietnam. These campus areas are selected due to their representative character, high student and employee populations, and the importance of resilient campus design in the light of climate change consequences. An increase in hot-weather extremes in both Southeast Asia and Western/Central Europe, with a high degree of confidence in the human contribution to the observed change has been recorded (IPCC 2021: 10). This increase in frequency, intensity, and duration of heat-related events, including droughts and heat waves, will continue, which has negative impacts on the environment and its inhabitants, especially in urban areas (IPCC 2022: 53 f.; Perkins-Kirkpatrick & Lewis 2020: 2).

The comparative research between the two campuses provides valuable insights into the development of Digital Twins because of the different climatic situations, the data availability, and the building complexity. These factors can also be included in answering the research question

"To what extent is the development and use of Digital Twins suitable for implementing climate adaptation measures to counteract UHI effects?"

The research objectives include identifying the specifications of the Digital Twin creation process for developing climate adaptation measures, analyzing the effectiveness of various climate adaptation measures in reducing UHIs, and assessing the conditions for their successful implementation. By discussing the implications of the research findings and highlighting the limitations and potentials of urban Digital Twins, an assessment of their usefulness can be undertaken.

This research is structured into three main working steps. The first step involves data generation in the form of laser scanning, on-site inspections and the collection of images and plans of the VGU and TU Dortmund University. In addition to manual measurements of the buildings and laser scanning data, provided building plans serve as a basis for this research. Based on the data, the 3D model is constructed, which operates as the physical object. In the second step, a microclimatic simulation of the baseline scenario of both study areas is conducted using the simulation software ENVI-met. These simulations serve as a substitute for real-time sensor data. After the baseline scenario is visualized, a simulation with climate adaptation measures is performed to investigate the effect on the buildings and its surroundings. Generated information regarding the study areas is visualized in geoinformation maps in which the 3D model is embedded. In the third step of the research the effectiveness of the Digital Twin technology is evaluated.

1.1 Study Areas

The study areas are defined as the South Campus of the TU Dortmund University, Germany, and the campus of the VGU in Bến Cát, Vietnam. The *Geschossbau III* (GB III), a building at the TU Dortmund University, and the library of the VGU are selected as the focus objects for the Digital Twins (see Figure 3).

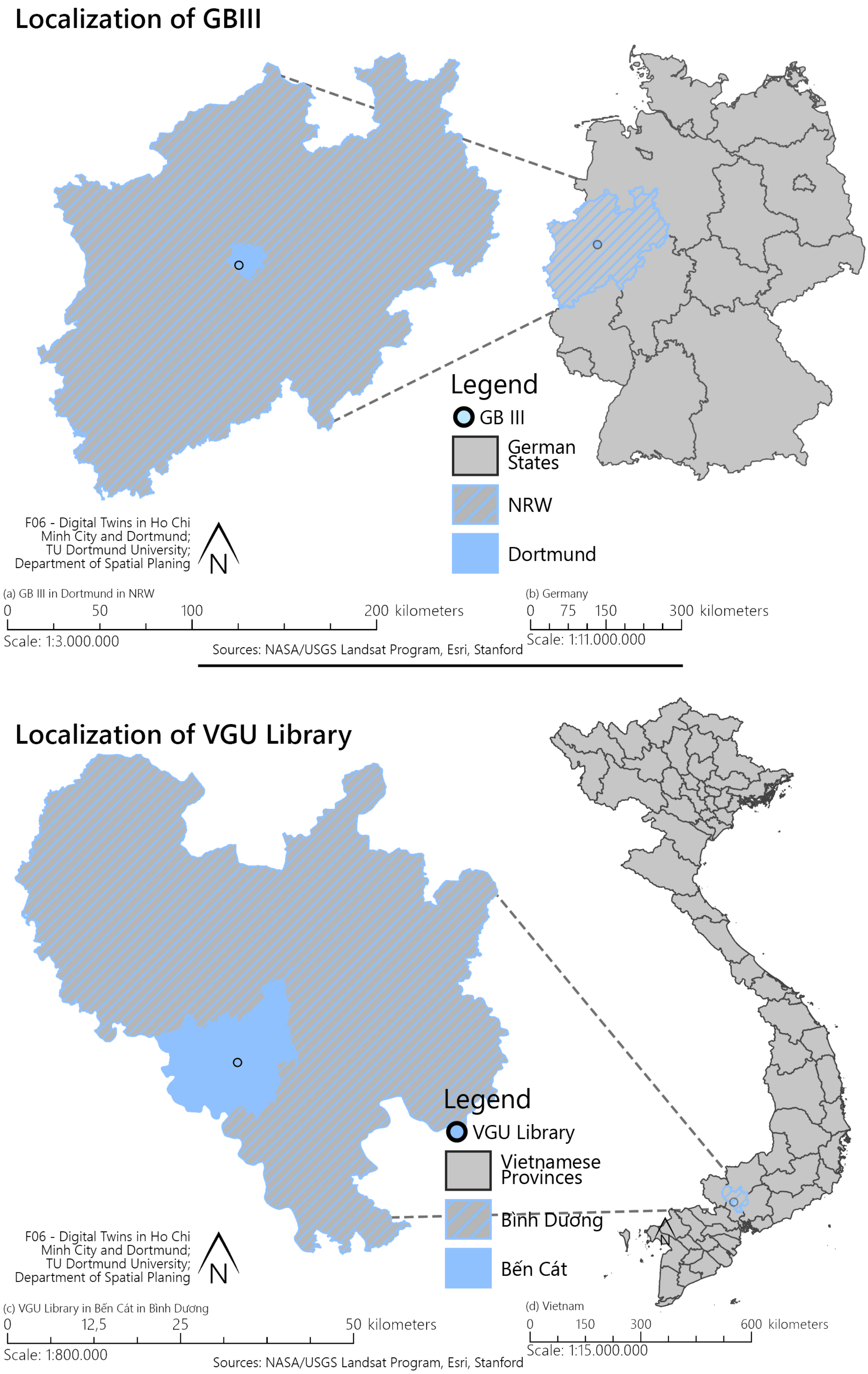


Figure 3: Study Areas (own illustration)

The city of Dortmund is located in the west of Germany and is one of the most populated and largest cities with about 603,000 inhabitants in 2022 in the east of Ruhr Metropolitan area and covers about 28,700 ha (Stock 2019: 9,15). Due to its proximity to the Atlantic Ocean, the climate in Dortmund is influenced by the maritime climate, which manifests itself in cool summers and mild winters (ibid.: 10). Occasionally, a continental climate influence prevails, resulting in higher temperatures in summer and longer cold periods in winter (ibid.). The study area VGU campus is located in Bình Dương Province in the town Bến Cát, which has a population of about 350,000 inhabitants and an area of about 24,000 ha (Tai 2023). The climate in Bình Dương is tropical, hot, and humid due to the monsoon climate, which is divided into distinct dry and rainy seasons (Binh Dương Province 2018).

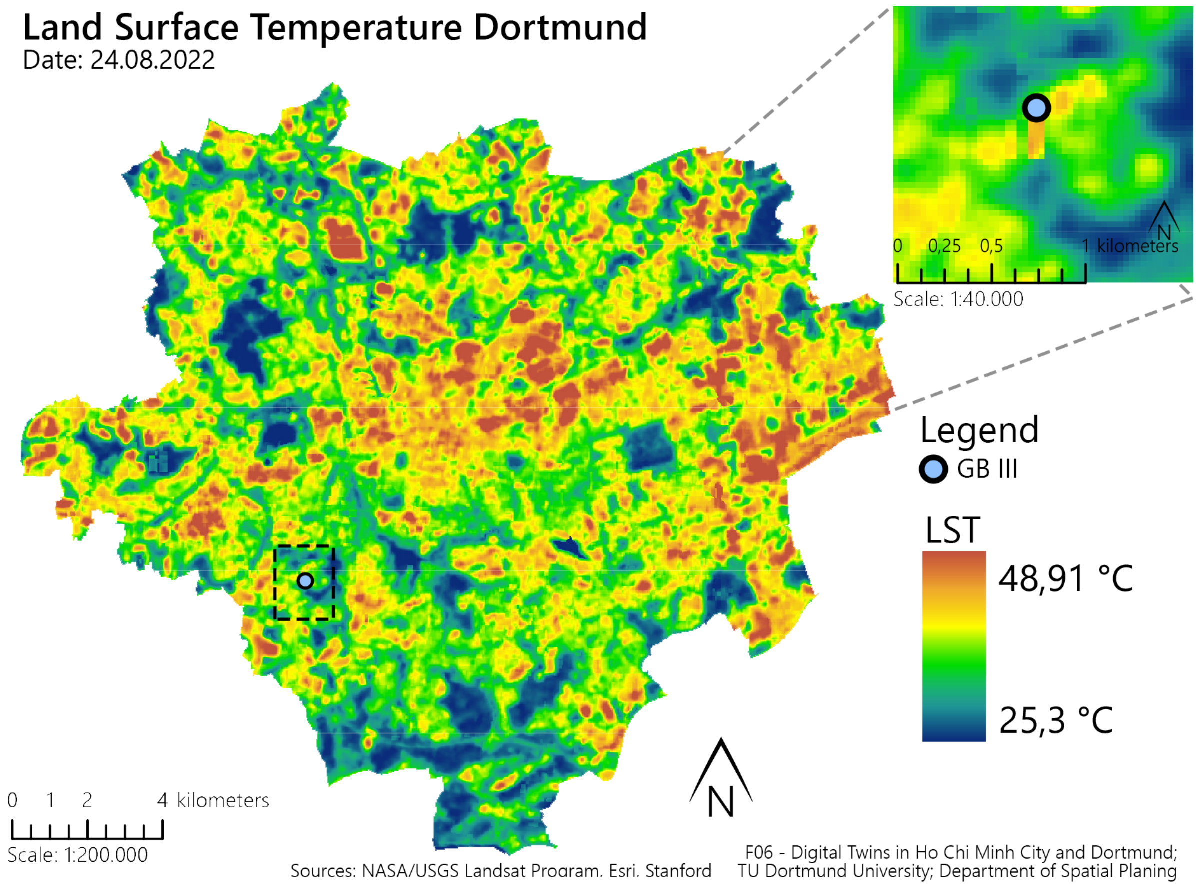
Those two study areas are chosen due to their equal function as campuses, to ensure comparability of the study areas. The TU Dortmund University, established in 1968, divided into the South Campus and the North Campus, has a student population of 32,476 and 6,900 employees in 2022 (TU Dortmund University 2023). The VGU was established in 2008 and has a significantly smaller student number of 1,700 in 2022, expecting the student number to increase up to 12,000 students by 2040 (VGU 2022). To prevent the consequences of climate change, especially UHIs from negatively impacting everyday life on campuses, a resilient campus design is important (Alshuwaikhatr & Abubakar 2008: 1778). Different baseline conditions of the climatic zones establish a difference in vulnerability to the effects of climate change (IPCC 2022: 12-17; ISPONRE 2009: 8 f.; Watson et al. 1998: 4; WetterKontor 2022). The comparison of the two study areas provides an opportunity to draw further conclusions about factors that impact the Digital Twin in the development of climate adaptation measures to counteract UHI in different climatic conditions.

1.2 Classification of Heat Emergence at the Study Areas using Landsat Data

Landsat imagery is used to identify and classify different types of land cover and helps scientists to analyze long-term climate trends, understand the impact of climate change on ecosystems, and assess carbon dynamics. The Landsat 8 satellite captures the worlds surface in eleven different bands with different wavelength spectrums (Roy et al. 2014: 156; USGS 2019: 50 f.). Due to strong cloud coverage, some bands are unsuited, necessitating the selection of data from days with minimal cloud coverage so that the Landsat sensors can produce an accurate image.

The Land Surface Temperature (LST) maps (see Figures 4 and 5), which are calculated using Landsat Level-2 Thermal Infrared Sensor (TIRS) Band 10 data, can be used to identify UHIs (USGS 2023a: 7). Level-2 data is algorithmically precalibrated information, specifically band 10 is optimized for LST calculations (USGS 2023b: 18 f.). To create the LST maps for Dortmund and Bến Cát, the band 10 Level-2 data has to be clipped to the study areas and then processed and calculated using the Raster Calculator (USGS 2023c). Level-2 Data sometimes contains gaps with no data, which are resolved by filling the gaps with calculated values of their raster neighbors using the nibble tool.

The Normalized Different Vegetation Index (NDVI) (see Figures 4 and 5) is an index that can measure the health and density of vegetation on a spectrum from -1 to 1. The higher the value of



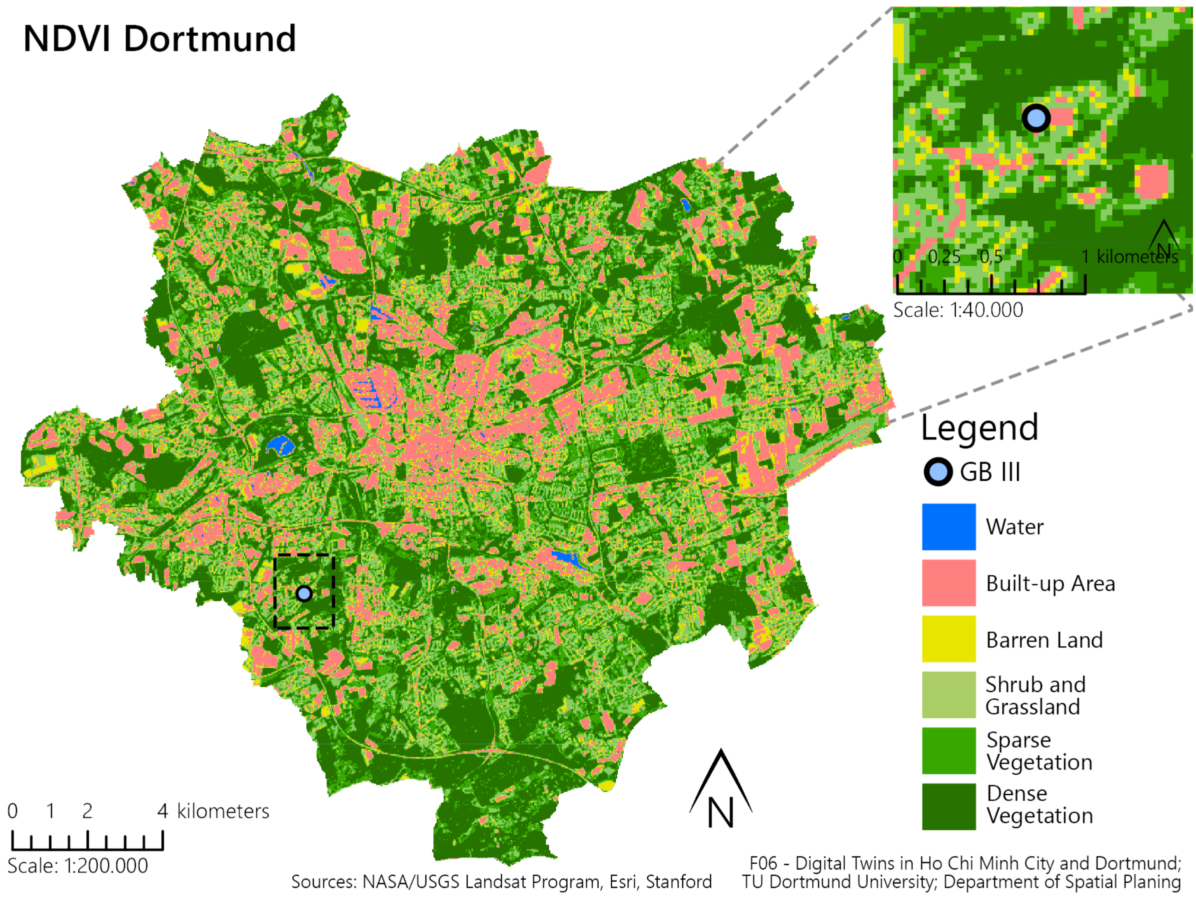


Figure 4: LST Map and NDVI Map of Dortmund (own illustration)

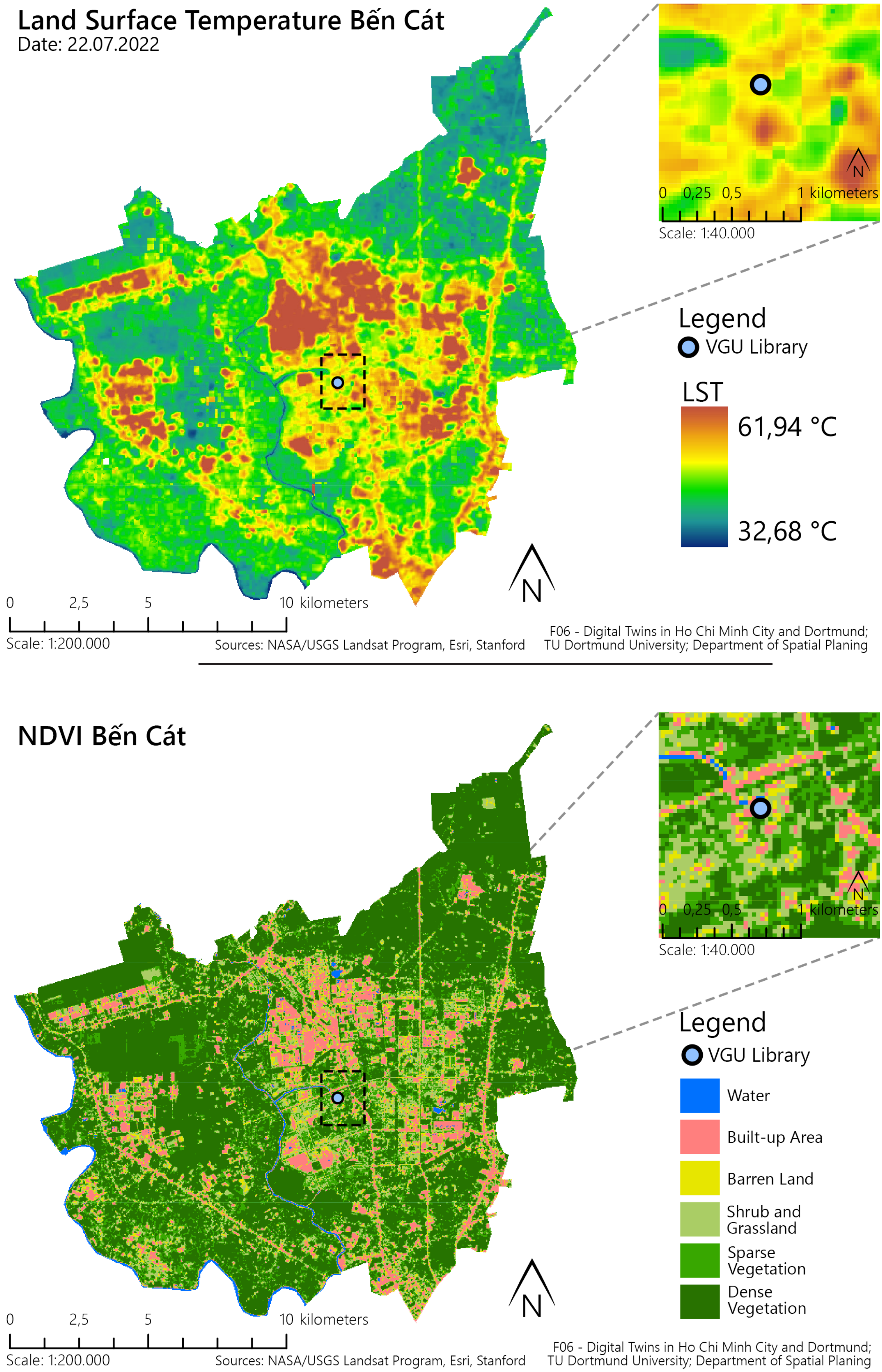


Figure 5: LST Map and NDVI Map of Bến Cát (own illustration)

the NDVI is, the healthier and denser the vegetation.The NDVI index is based on the difference in reflectance between near-infrared (NIR) and red the NDVI is, the healthier and denser the vegetation. The NDVI value range of 0.1 and less is usually barren rock or snow. Moderate values range from 0.2 up to 0.5 and usually contain sparse vegetation such as shrubs and grassland. The high NDVI values range from 0.6 to 0.9 and correlate with dense vegetation such as tropical forests or corps (USGS 2018).

The NDVI index is based on the difference in reflectance between NIR and red light. Landsat 8 Level-1 data, specifically Band 4, the red Band, and Band 5, the NIR are used to calculate the NDVI.

To create the NDVI maps both bands must be clipped to the study area, then the raster calculator is used to generate the values using the NDVI equation (USGS 2023d):

$$NDVI = \frac{NIR-R}{NIR+R} \qquad (1)$$

Where as
NIR: Near infrared, Landsat 8 Band 5
R: Red wavelength spectrum, Landsat 8 Band

The comparison between the LST and NDVI map in both study areas demonstrates the positive impact of vegetation on the surface temperature. There is a direct correlation between the build-up area, with extensive sealing urbanization and a lack of vegetation, and higher temperatures. The focus buildings for the VGU as well as the TU Dortmund University are located in build-up areas that show higher temperatures on the LST maps. Areas with lower temperatures on the LST maps show healthy and dense vegetation on the NDVI maps. These findings emphasize the significance of vegetation in mitigating the UHI effect and highlight the importance of incorporating green spaces in urban planning and design.

2. Methodical Procedure

The methodical procedure (see Figure 6) incorporating laser scanning, 3D modeling, simulation and visualization techniques enables the creation of a Digital Twin by capturing precise physical data, generating an accurate virtual representation, and simulating climatic conditions. The used results from ENVI-met are needed for the insertion into the 3D model, which is based on the laser scanning part. The focus building and the synthetic data are visualized in a geoinformation map.

2.1 Creation of laser scans

In this research, the method of laser scanning is employed for data acquisition. The primary

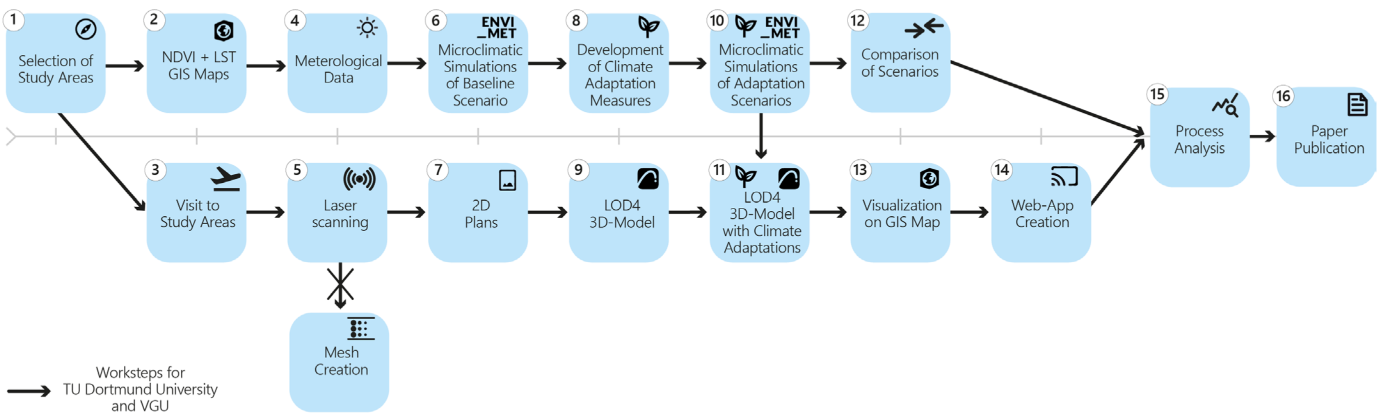


Figure 6: Methodical Procedure (own illustration)

objective is to ascertain the suitability of laser scanning in generating a 3D model of a physical object. For the interior scanning of buildings, the kinematic laser scanner ZEB-Horizon from GeoSLAM is utilized. Compared to static laser scanners, kinematic laser scanners offer the advantage of significantly faster scanning processes, which is important for scanning larger areas (Wiedemann 2020: 50). Static laser scanning is more time consuming because several scans must be performed to capture an object and the scanner needs to be set up at a different location for each scan (ibid.: 49).

The resulting point clouds derived from the laser scans are subsequently processed using the GeoSLAM software programs Connect Viewer and Draw. These point clouds serve as the foundation for generating 2D plans, originally intended to form the basis for constructing the 3D model.

2.2 3D Modeling

3D models of the library at VGU and the GB III at TU Dortmund University are generated as a virtual representation of the physical object. For each building, two versions are modeled, one representing the current state, and one showcasing the desired state after implementing climate adaptation measures derived from results of conducted microclimatic simulations. This approach ensures that the virtual representation accurately reflects the present condition, and the virtual object accurately reflects the envisioned future of the buildings. To represent the reality as accurately as possible, the 3D models are created in Level of Detail (LOD) 4. As shown in Figure 7, the LOD describes different levels of complexity of an object and can be divided into five levels (Biljecki 2017: 55). Subsequent LODs become increasingly complex up to LOD4, which represents the most complex model and describes an architectural model with doors and windows including interior e.g., furniture (ibid: 42 f.).

To accurately replicate the reality, ArchiCAD, a computer aided design software, is utilized to create the 3D models in LOD4. This software allows urban planners, architects, and designers to model detailed 3D representations. By using the plan mode and the supplied areal views, front views and sections, the software allows a comprehensive visualization with high precision (Onur & Nouban 2019: 2725 f.). ArchiCAD provides a wide range of tools and components for exterior and interior design. Corresponding to reality, materials can be applied to components such as walls and roofs, enabling customization to match real-life prototypes. Standardized components like stairs, railings, and facades can be modified using the software's versatile tools (Graphisoft 2023b). An integrated surface catalog and object library offer a diverse selection of objects to enhance the realism of the 3D model (Graphisoft 2023a). Therefore, ArchiCAD is a suitable tool for creating highly realistic 3D models.

2.3 ENVI-met

Since no real-time climate data is used, which can be collected for example with sensors, synthetic data from microclimatic simulations are used. Conducting microclimatic simulations to analyze the microclimate in the study areas is an important part of the research and plays a crucial role in understanding and analyzing the complex interactions between urban environments and climate conditions at a local scale. Simulations provide valuable insights into the spatial and temporal variations of microclimates, aiding in the design and evaluation of climate adaptation strategies for enhanced human comfort, energy efficiency, and environmental sustainability (Chatzinikolaou et al. 2018: 74; Liu et al. 2021: 2 f.; Zölch et al. 2016: 313). The simulations are undertaken on a hot day, which is defined as a day on which the maximum air temperature is at least 30 °C (German Meteorological Service 2023). A hot day was selected to be able to analyze the heat trends and test the adaptation scenarios under the extreme heat conditions.

For conducting microclimatic simulations, the three-dimensional, non-hydrostatic, and computational fluid dynamics-based model ENVI- met V5.1.1. is applied, which is widely used for simulating the urban microclimate due to the outstanding features of the detailed vegetation model and the ability to simulate surface-plant-atmosphere interactions (Bruse & Fleer 1998: 383; Tsoka et al. 2018: 6). Further advantages to other approaches are the high spatial resolution and the inclusion of atmospheric processes, such as wind field, temperature, humidity and turbulence (Vidmar & Roset 2013: 16). ENVI-met provides dynamic boundary conditions that consider temporal variations, enabling simulations to accurately reflect realworld climate dynamics. For modeling the turbulent airflow, the non-hydrostatic incompressible Navier-Stokes equations with density removed are used (Bruse 1999: 13–15):

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}= -\frac{1}{\rho}\frac{\partial p'}{\partial x}+\frac{\partial}{\partial x}\left(K_m\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_m\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) +f(v-v_g)-S_u(x,y,z) \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}= -\frac{1}{\rho}\frac{\partial p'}{\partial y}+\frac{\partial}{\partial x}\left(K_m\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_m\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right) -f(u-u_g)-S_v(x,y,z) \tag{2.1}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}= -\frac{1}{\rho}\frac{\partial p'}{\partial z}+\frac{\partial}{\partial x}\left(K_m\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_m\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right) -S_w(x,y,z) \tag{2.2}$$

Where as
ρ': Local pressure perturbation
K_m: Local exchange coefficient
$\partial p'$ and ∂x_i: Gradients of the dynamic pressure perturbation
x_i: Three-dimensional advection and diffusion terms written in Einstein summation [$x_i = x, y, z$ with $i = 1,2,3$]

$f(v - v_g)$ and $f(u - u_g)$: Rotation of the wind S near ground compared to the geostrophic wind components u_g and v_g
f: Coriolis parameter [$f = 2\Omega \sin \varphi$]
Ω: Pulsatance of the earth's rotation [$\Omega = 7 \times 10^{-5} s^{-1}$]
φ: Latitude of the model's location
S_u, S_v, S_w: Local source/sink terms that model the wind drag of semi permeable obstacles
$S_{u_i}(x,y,z) = c_{d,p} LAD(x,y,z) u_i W(x,y,z)$
$c_{d,p}$: Mechanical drag coefficient of the leaves [$c_{d,p} = 0.2$]
LAD: Leaf area density [m^2/m^3]
$W(x,y,z)$: Mean wind speed in the grid cell [$W(x,y,z) = \sqrt{u^{2(x,y,z)} + v^2(x,y,z) + w^2(x,y,z)}$]

The lateral and outflow boundary conditions for wind employ a zero-gradient Neumann condition, and the inflow wind profile at the boundary is derived from a one-dimensional reference model (ibid.: 108–111). As physical boundary conditions, surface temperatures of the ground and buildings are used. The energy balance of the outside facade surface node is calculated using the dynamic multiple-node wall and roof model (Huttner 2012: 30 f.; Simon 2016: 154-156):

$$EB = Q_{sw,net}^{abs} + \varepsilon\,(Q_{lw} - \sigma T_1^4) - H_w - LE_w - G_w \cong 0 \qquad (3)$$

Where as
$Q_{sw,net}^{abs}$: Net shortwave solar radiation by the facade surface
ε: Emissivity of the façade
$\varepsilon \times Q_{lw} - \sigma T_1^4$: Longwave radiation balance depending on the surface temperature of the outside node T_1 and the incoming longwave radiation Q_{lw}
H_w: Sensible heat flux into the atmosphere
LE_w: Latent heat flux into the atmosphere due to evaporation or condensation of water at the outside facade surface
G_w: Conduction heat flux from or to the adjacent node inside the wall / roof

Alongside the effects of adaptation measures on buildings, particularly the effects on human thermal comfort are considered using indices such as Physiological Equivalent Temperature (PET), which is one of the most frequently used indices for measuring heat stress in outdoor environments and can be calculated in ENVI-met BIO-met (Liu et al. 2021: 7). PET is defined as the air temperature at which, in a typical indoor environment, the energy balance of the human body is balanced at the same core and skin temperature as under outdoor conditions. It is calculated based on the Munich Energy-balance Model for Individuals (MEMI), which is based on the energy balance equation for the human body (Höppe 1984: 49):

$$M + W + R + C + E_d + E_{Re} + E_{Sw} + S = 0 \qquad (4)$$

Where as
M: Metabolic rate
W: Physical work output
R: Net radiation of the body
C: Convective heat flow
E_d: Latent heat flow to evaporate water diffusing through the skin
E_{Re}: Sum of heat flows for heating and humidifying the inspired air
E_{Sw}: Heat flow due to evaporation of sweat
S: Storage heat flow for heating or cooling the body mass

2.4 Geoinformation Maps

Two geoinformation maps are employed to depict the surrounding areas of the study sites with buildings in LOD2, where the 3D models of the library at VGU and GB III at TU Dortmund University are integrated. The interface functions as a visual representation of comprehensive information accumulated throughout the entirety of the research process. The maps illustrate the South Campus of TU Dortmund University and the campus of VGU containing information about the

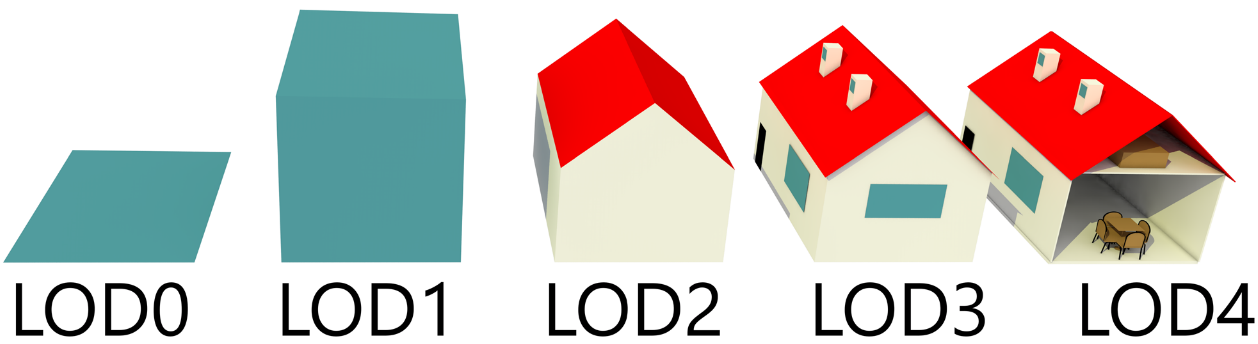


Figure 7: Level of Detail (own illustration according to Biljecki (2017: 7))

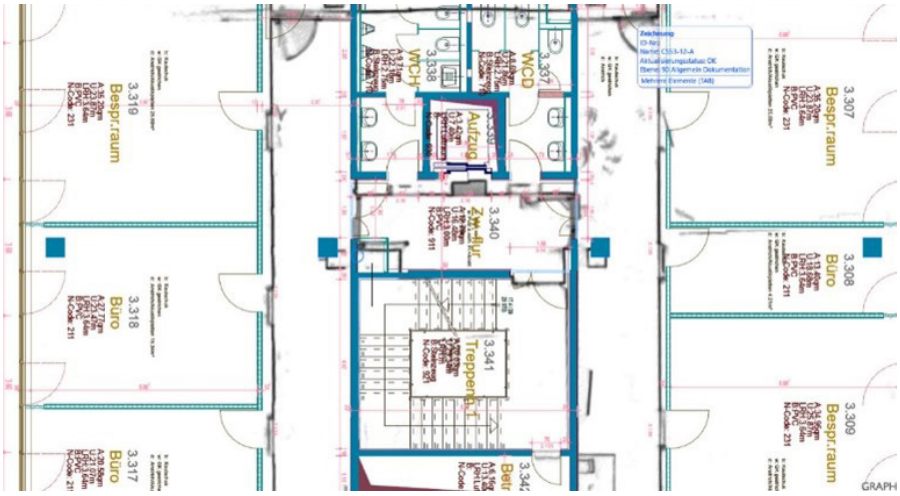


Figure 8: 2D Laser Scanning Plan (Black) Compared to Provided Building Plan (blue) (own illustration

buildings, the climate adaptation measures and partly the results of the microclimatic simulations. ArcGIS Pro and QGIS are used to visualize the geoinformation maps and serve as an interface between the software programs used, such as ENVI-met and ArchiCAD, and enable the results to be displayed.

3. Laser Scanning

A fundamental requirement for implementing the laser scanning method is a basic floor plan of the object, to design a scanning route. The

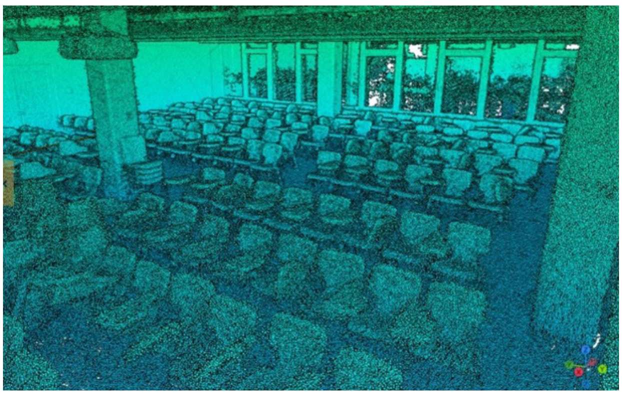


Figure 9: Point Cloud (own illustration)

scans are created floor by floor with a scanning duration of ten minutes and a ten-minute break in between the different scans to increase the probability of a successful quality scan as the scanner does not always deliver reliable results. The size of the object to be scanned is decisive for the number of scans to be performed.

The successfully created scan is imported into the GeoSLAM Connect Viewer to check the quality of the generated point cloud. The quality is defined by the point density and the ability to represent the physical object (see Figure 9). Afterwards the file is exported in LAZ format, which can be imported into GeoSLAM Draw. A horizontal cross section that eliminates the floor and ceiling, is created, resulting in a PNG file suitable for an import in ArchiCAD. The intention was to employ the 2D plans as the foundation for the subsequent 3D modeling process. This was not feasible, due to imprecise representation, resulting in unsatisfactory quality of the 2D plans. Each individual plan has varying and inconsistent scales, complicating their usability (see Figure 8).

The initial workflow for Dortmund and Bến Cát aimed to use the scanning data to create a 3D mesh, which connects the points of the point clouds to create a polygon mesh. The large amount of data, lack of expertise and software issues made this process not efficient in comparison to building the 3D Model in ArchiCAD.

4. 3D Model with ArchiCAD

The workflow of 3D modeling in ArchiCAD is based on the building information modeling (BIM) modeling guidelines of Graphisoft (2022: 6–8) and on the workflow of MacKenzie et al. (2015: 34–36). The described workflow is applicable to both study areas, as the process remains largely consistent with no significant variations.

4.1 Modeling the Baseline Scenario

The building plans provided by VGU and TU Dortmund University, consisting of aerial views, front views and sections, are used as the basis plan for the 3D models. To initiate the modeling process, a floor structure is established to systematically arrange the imported building plans according to their corresponding floors. Based on the information from the building plans, foundations are laid, and custom walls are created and gradually placed with the help of the

Figure 10: Section of the 3D Models of TU Dortmund University and VGU (own illustration)

built-in tool palette. Specific tools for stairs and railings are employed and extensively modified to accurately represent the physical building.

The built-in object library is utilized for the interior design of the 3D models, providing a wide range of objects. If specific components are not accessible in the object library, additional BIM 3D objects are sourced from a BIM database. This is done to augment the existing library and ensure the creation of comprehensive 3D models that accurately represent reality (see Figure 10). The architecturally sophisticated facade of the VGU library is created using a custom facade design.

5. Creation of the physical setting in ENVI-met

The microclimatic simulation is based on two inputs, the Area Input File (see Figure 11), which contains the physical settings of the model areas, and the simulation file, including the local meteorological conditions such as air temperature, relative humidity, wind speed and wind direction.

5.1 Area Input File

The preparation of the Area Input File started in ArcGIS Pro, where geometric data of the buildings, bare soil materials and tree locations were created. The ENVI-met Database-IDs are integrated directly into the Area Input File by using the attribute table of the geometric shape files. The building data for Dortmund is obtained from LOD1 building data provided by the state of North Rhine-Westphalia (Geobasis NRW 2023a). Since no open building geodata is available for Bến Cát, the building outlines are generated from aerial imagery in ArcGIS Pro. The building heights are derived from building construction plans pro- vided by the VGU. The data on the bare soil material is gathered by on site data acquisition and the analysis of aerial imagery. The materials are integrated into the Area Input File by inserting the ENVI-met Database-IDs into the object-specific attribute tables of the geometric shape files. Regarding the tree locations in both study areas, different approaches are employed. To determine the tree locations for Dortmund, NDVI is calculated using NIR orthophotos and the red band from orthophotos. The normalized digital surface model (DSM) provided by the state of North Rhine-Westphalia is blended over 2 m with the NDVI vegetation mask (Geobasis NRW 2023b; Schaefer et al. 2021: 6). First, the tree crowns are determined using focal statistics and then the tree centers are determined using slope. Point shapefiles are created to represent the tree locations. The tree height could be taken from the normalized DSM and integrated into the Area Input File by using the object-specific attribute table. For the model area in Bến Cát, tree locations are identified using aerial imagery since a DSM and orthophotos are not available. Similar to Dormund, point shapefiles represent the tree locations. Standard trees in Dortmund are modeled with heights ranging from 5 to 25 m at 5-meter intervals. The majority of trees in Bến Cát are smaller than the trees in Dortmund, as a result, smaller standard trees are generated. Trees with a height of 5 and 10 m and a lower leaf density are created additionally to be able to use them for the model in Bến Cát. The import of vector-based geometric data is possible through the ENVI-met Monde tool, which expedites the process of model creation by using available geodata. Using this tool, the automatic conversion of spatial information as the 2.5D building and vegetation data and the bare soils into the Area Input File is conducted. In the ENVI-met Spaces tool, adjustments are made to incorrect conversions of the vectorized geometric shapes into the ENVI-met voxel format, leading to inaccurate building shapes and bare soils. Additionally, in ENVI-met Spaces, the building facades become more detailed by the insertion of windows.

5.2 Simulation File

In order to obtain representative meteorological data for the study areas, available data from the nearest weather stations is utilized. To simulate heat stresses on the campuses, a heat day with a tropical night is selected for Dortmund and Bến Cát, which is one of the hottest days in recent years (see Table 1). The roughness of the model areas is measured according to a procedure of the German Meteorological Service in dependence of the wind direction by an averaging of roughness values tabulated depending on land uses in a 3 km radius (Koßmann & Namyslo 2019: 7).

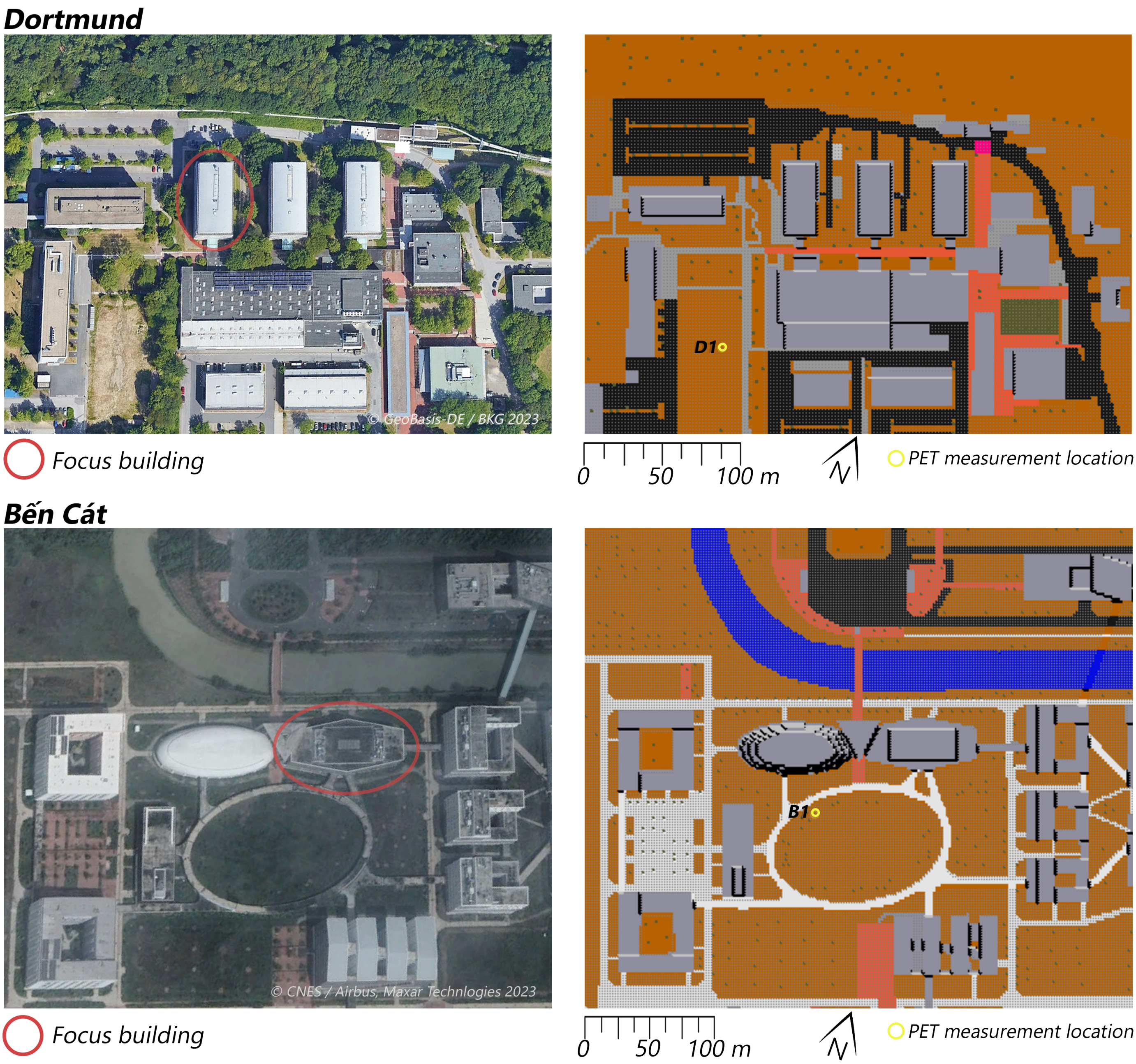


Figure 11: Aerial Images and Area Input Files as 2D Models of the Study Areas in Dortmund and Bến Cát (own illustration)

The thermo-physiological input parameters for calculating PET are defined according to the Klima-Michel model as a male, 35 years old, wearing summer clothes (0.5 clo) with a constant internal heat production of 80 W.

Type	System	Dortmund	Ben Cat
Model domain settings	Model location	Lati. 51°48 ´N, Long. 7°41´E	Lati. 11°11´N, Long. 106°61´E
	Model geometry	X-Grids = 173, Y-Grids = 124, Z-Grids = 20, dx = 2, dy = 2, dz = 2, Model rotation out of grid north = 28°	X-Grids = 217, Y-Grids = 185, Z-Grids = 25, dx = 2, dy = 2, dz = 2, Model rotation out of grid north = 20°
		Nesting Grids = 6	Nesting Grids = 6
General simulation settings	Simulation starting date	21st July 2021	27th April 2022
	Simulation starting time	6 am.	6 am.
	Simulation duration	24 h	24 h
Basic meteorological settings	Wind speed at 10 m above ground level [m/s]	1.87	3.44
	Wind direction	South (180°)	East-South-East (135°)
	Air temperature [°C]	Min = 21.0 at 6:00 a.m. Max = 34.0 at 3:00 p.m	Min = 27.0 at 6:00 a.m. Max = 36.0 at 3:00 p.m
	Relative humidity [%]	Min = 26.0 at 3:00 p.m. Max = 64.0 at 5:00 a.m	Min = 44.4 at 2:00 p.m. Max = 94.5 at 4:00 a.m
	Roughness length [m]	0.974	0.274

Table 1: Parameters of the Simulation of Dortmund and Bến Cát (own illustration)

6. Scenario Building with Climate Adaptation Measures

To investigate different adaptation options, different scenarios were modeled in ENVI-met. The Baseline Scenario represents the status quo of the two campus areas and provides the foundtion to measure the direct effects of the applied adaptation measures in the further scenarios. In the environmental adaptation scenario, green, gray and blue infrastructure is applied and, in the building greening scenario, facade and roof surfaces are greened to the maximum extent feasible (see Figure 12). By the selection of these scenarios, the effect of climate adaptation measures on the building and environmental adaptations can be considered separately from each other. This allows conclusions to be drawn about the specific cause of the temperature reductions. The adaptation measures are intended to contribute to the main objective of the sponge city concept of creating a climate-adaptive and natural stormwater management (Siemer 2022: 55). In addition to the natural water management, the sponge city concept also pursues the aim of prevention and reduction of heat events and drought and is therefore a suitable approach for the study.

6.1 Environmental Adaptation Scenario

In terms of green infrastructure, trees are incorporated and integrated into the models of both study areas. Trees have a significant impact on the microclimate of urban environments. They absorb solar energy and radiation, thereby contributing to the cooling of the surrounding environment through plant transpiration. Additionally, trees provide shade, which further contributes to the mitigation of heat and sunlight exposure in the area. A study in Beijing, China shows that a single tree can reduce the air temperature ranging from -0.8 °C to -0.9 °C. Trees which are planted near to each other in a cluster-can achieve a reduction of -1.0 °C to -1.6 °C. The improved thermal comfort also increases by the lower relative humidity (Amani-Beni et al. 2018: 3). The trees are carefully placed in the model to ensure that their canopies do not overlap, thus avoiding the issue of overlapping foliage (Koch et al. 2018; Zheng et al. 2018: 20).

In Dortmund, the species Acer Platanoides is chosen for the additional tree plantings due to its recognition by the City of Dortmund as a tree species well-suited for heat tolerance (City of Dortmund 2023). Due to the different climatic condition in Vietnam, a different tree species must be used that is more compatible with the drier and hotter climates. The tree Khaya Senegalensis is native to tropical Africa and Madagascar and has also been implemented in Australia and South Asia (Hung & Trueman 2011: 118). The tree is adapted to periods of heat and grows in urban areas (Moser-Reischl et al. 2018: 1).

Gray infrastructure in the form of cool pavements is installed in the environmental adaptation scenario to improve the microclimate of the large, sealed areas. The pavements in the model are improved by the albedo, as they have a great influence on the urban climate (Santamouris 2013: 226). The heating of the surfaces is conditioned by the amount of absorbing solar radiation. This is strongly influenced by the material used for the asphalt, as the solar radiation is absorbed or reflected to different degrees. The degree of absorbed radiation is influenced by the color of the material and the roughness of the surface. Light colors cause less absorption to the visual spectrum of solar radiation and flat surfaces cool more than very rough ones. An albedo of 0.8 is selected for the cool pavements, while the initial asphalt material has an albedo of 0.2 to achieve higher reflectivity (Kappou et al. 2022: 10; Santamouris 2013: 226).

To integrate the blue infrastructure, a water body is added to the model in the Bến Cát environmental scenario to test the effect on the microclimate. Water has an impact on the microclimate of the environment due to enhanced evaporation. The surface temperature of water is cooler in comparison to the mainland due to latent heat sink and evaporative cooling. The cooler surface of the water provides cooler ambient air (Wong et al. 2011: 81). The model of Dortmund does not include a water surface due to lack of sufficient space. Small water surfaces do not have a relevant cooling effect on the environment, as cooling effects are only noticeable when they are large enough (Jacobs et al. 2020: 12).

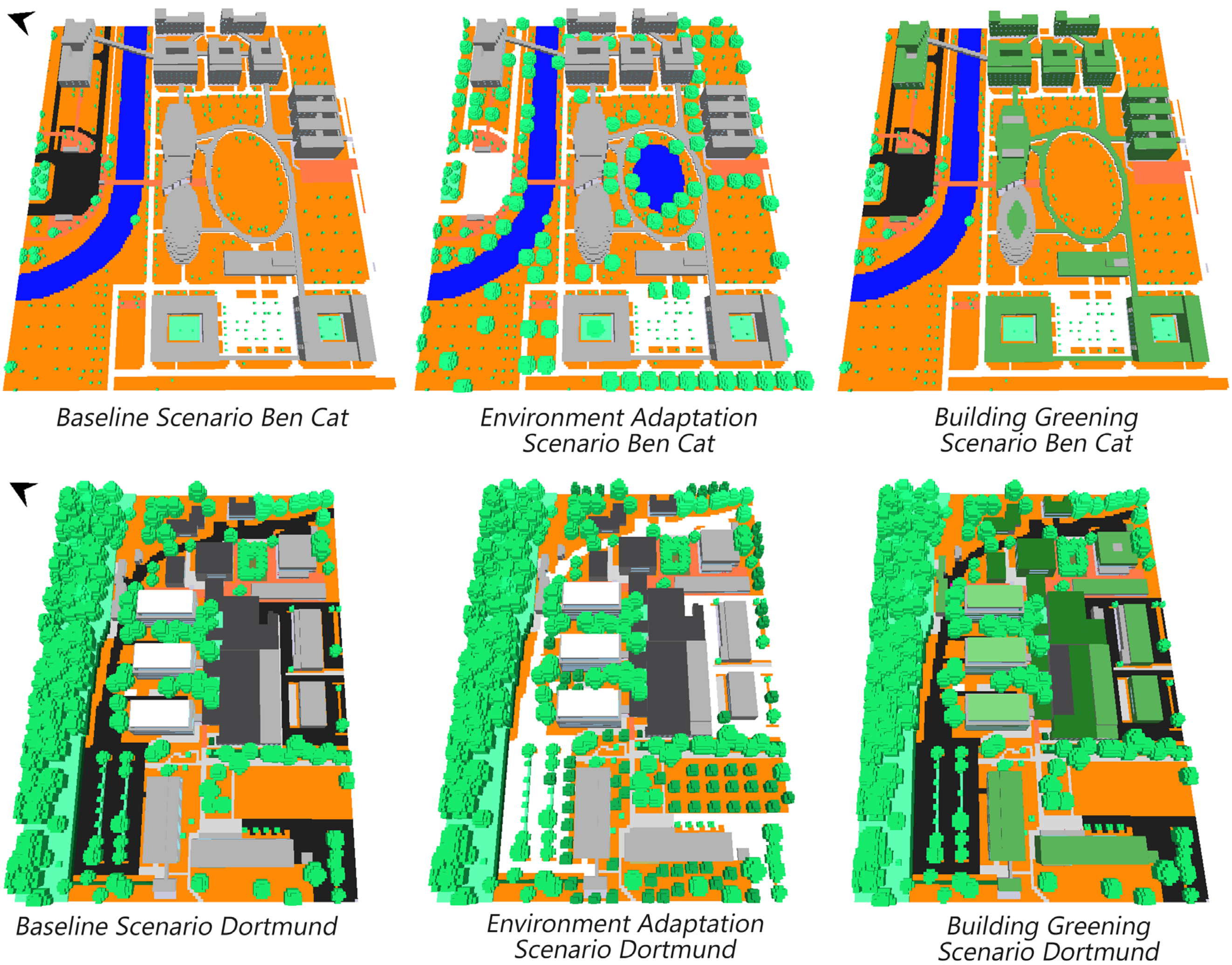


Figure 12: 3D Models in the Different Scenarios of the Study Areas in Dortmund and Bến Cát (own illustration)

6.2 Building Greening Scenario

A building greening scenario is created in which facade and roof greening are integrated. Green buildings can reduce UHIs by shading surfaces, through evapotranspiration of plants, and by converting incoming solar radiation into latent heat (Dimoudi & Nikolopoulou 2003: 69 f.). In the case of surface temperature, studies have shown that facade greening can lead to a temperature decrease ranging from 2 °C to over 10 °C. This significant reduction in surface temperature can help mitigate the UHI effect and improve thermal comfort in buildings (Pfoser 2016: 74 f.). Comparative measurements have revealed that the exterior side of the facade exhibits the least temperature differences, indicating the cooling effect of facade greening (BuGG 2014: 92–96). In terms of evapotranspiration rates, facade greening with climbing plants can result in evaporation rates of 10 to 15 liters per square meter per day, considering a 20-meter-high facade. This evaporation contributes to a cooling effect, with an estimated cooling capacity of 280 kilowatt-hours per facade per day (City of Ber- lin 2010: 35 f.). Green foliage, such as climbing plants, can absorb or reflect 40 % to 80 % of solar radiation (Rath et al. 1989: 32). Deciduous facade greening can provide shading rates of 70 % to 95 %, reducing solar heat gain (City of Berlin 2010: 35 f.).

In hot and dry climates, the effect of reducing temperature and thus counteracting UHI is stronger, compared to other regions (Shafique et al. 2018: 765). If 70% of roofs are greened, the summer temperature in an urban area can be reduced by up to 10 °C. The reason for the cooling effect of green roofs is the reduction of secondary radiation and radiation reflection, as well as the evaporation of water from the plants (Bing 2011: 2763–2765). Green roofs improve the thermal performance of buildings and increase energy efficiency (Besir & Cuce 2018: 920; Bevilacqua et al. 2016: 78).

The equipment of the buildings with greening is conducted based on indicators: the roof slope, the current use of the roof area and possible obstacles such as technical constructions. To evaluate the green roof potential in Dortmund, the green roof cadaster of the Ruhr Regional Association is used in addition to the indicators (RVR 2023).

Greening type	Substrate thickness [m]	Plant thickness [m]	Leaf area density
Extensive green roof	0.15	0.20	0.3
Intensive green roof	0.60	1.00	0.3
Facade greening using modules	0.15	0.20	1.85
Facade greening using climbing plants	-	0.20	0.3

Table 2: Selected Greening Parameters for the Simulation for Dortmund and Bến Cát (own illustration)

While intensive green roofs can only be realized at an angle of inclination of 0 to 5°, extensive green roofs can be planted up to an angle of inclination of 45° (Pfoser et al. 2013: 64-68). Due to practicability, mainly extensive roof greening is planned for the roof greening, with a maximum of one quarter of the roof areas having intensive greenings.

The evaluation of the facade greening potential was conducted based on field observations and aerial image analyses. For the implementation of facade greenings, the building facades are analyzed for height, soil sealing, facade structure and possible obstacles (Pfoser et al. 2013: 53-55). In Dortmund, module greening systems are applied to the facades and extensive greening is applied on the roof of the focus building. At the focus building in the model for Bến Cát, two facade greening systems are used, climbing plants and module greening. Intensive greening is used for the roof greening (see Table 2).

7. Results of the Simulations

The scenario results imply the effectiveness of adaptation measures to moderate thermal conditions. The results consider the hottest time of day at pedestrian level of 1 m. Human comfort is evaluated based on the grading of PET values into levels of physiological stress (see table 3).

PET values [°C]	Thermal perception	Grade of physiological stress
< 4	Very cold	Extreme cold stress
4 - 8	Cold	Strong cold stress
8 - 13	Cool	Moderate cold stress
3 - 18	Slightly cool	Slight cold stress
8 - 23	Comfortable	No thermal stress
23- 29	Slightly warm	Slight heat stress
29 - 35	Warm	Moderate heat stress
35 - 41	Hot	Strong heat stress
> 41	Very hot	Extreme heat stress

Table 3: PET thresholds (Own illustration according to Matzarakis (1990: 77))

7.1 Results for the Study Area in Dortmund

Baseline scenario Dortmund

In the baseline scenario of Dortmund, the potential air temperature is 32.6 °C on average at the hottest time of day at 3 p.m (see table 4). There is a temperature difference between the warmer southern part, which is characterized by more sealing due to traffic development and parking lots, and the northern part, which is characterized by a higher proportion of vegetation. Pedestrians experience strong heat stress on average, but also moderate and extreme heat stress in partial areas. In Dortmund, pedestrians in northern areas perceive higher human thermal comfort below 35 °C due to shading from trees in the forested area than in southern areas, where heat stress increases due to reduced wind speeds through buildings and due to low reflection from asphalt surfaces of incoming solar radiation.

Environmental adaptation scenario Dortmund

In the environmental adaptation scenario of Dortmund, cool pavements have the greatest influence on the potential air temperature reduction. In these areas, potential air temperature reductions of - 1.1 °C have become evident. The soil temperature is reduced by cool pavements by a maximum of -16.4 °C (-31.0 %).

Within the context of the Dortmund environmental adaptation scenario, the average PET is observed to decrease by -3.5 %, resulting in a value of 37.3 °C (see table 4). When considering the effects of the specific measures in the scenario, tree plantings have the highest impact on the PET reduction with a maximum reduction of -16.8 °C, due to shading and evapotranspiration (Bowler et al. 2010: 152 f.; Shashua-Bar & Hoffman 2000: 234 f.) The implementation of tree plantings has the potential to mitigate extreme heat stress, reducing it to a more moderate level. The environmental adjustments have no effect on the surface temperature on the building surfaces of the target building. On parts of the

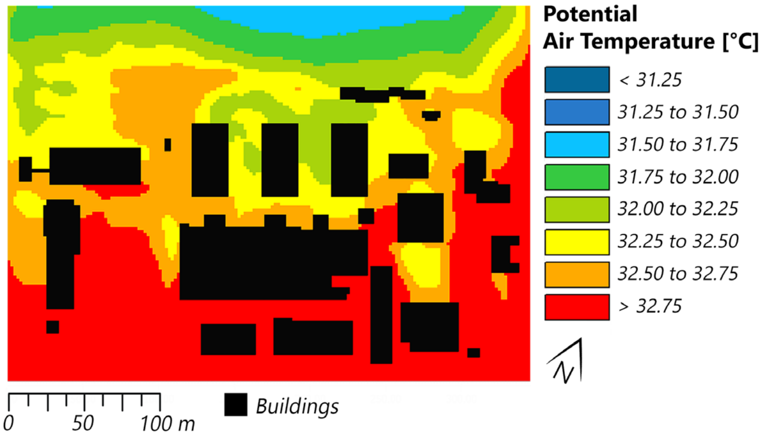


Figure 13: Potential Air Temperature in the Baseline Scenario of Dortmund (own illustration)

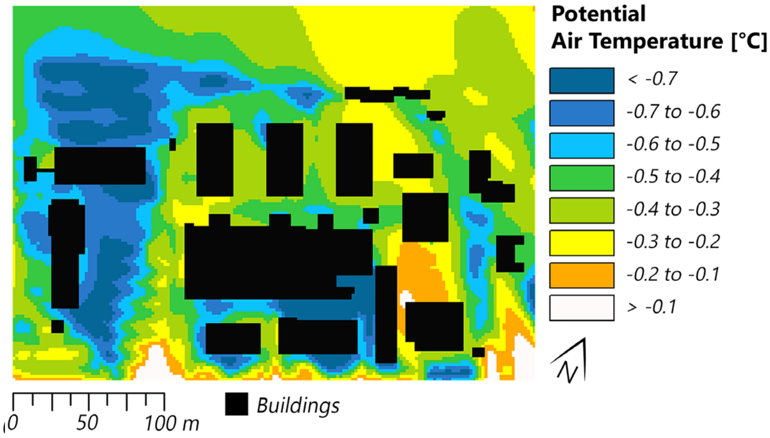


Figure 14: Differences of the Potential Air Temperature in the Environmental Adaptation and Baseline Scenario of Dortmund (own illustration)

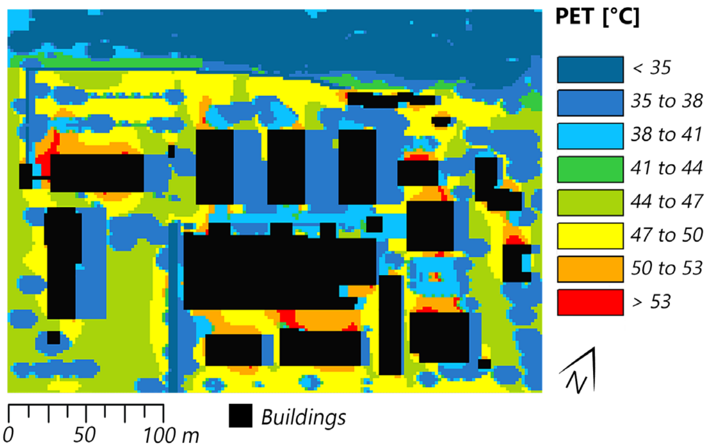


Figure 15: PET in the Baseline Scenario of Dortmund (own illustration)

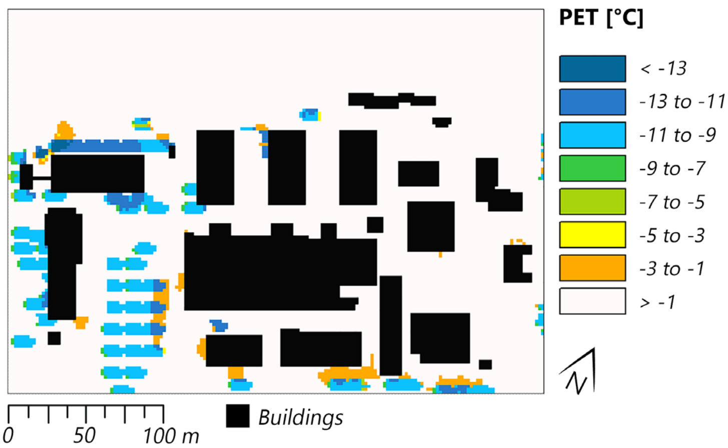


Figure 16: Differences of PET in the Environmental Adaptation and Baseline Scenario of Dortmund (own illustration)

		Baseline scenario	Environmental adaptation scenario	Building greening scenario
Potential Air Temperature	Max.	34.27 °C	34.00 °C	34.16 °C
	Median	32.61 °C	32.17 °C	32.36 °C
	Reduction	/	-0.44 °C / -1.35 %	-0.25 °C /-0.77%
PET	Max.	57.45°C	57.36°C	57.37 °C
	Median	38.83°C	37.30°C	38.08 °C
	Reduction	/	-1.53 °C / -3.94 %	0.75 °C / -1.93 %

Table 4: Simulation Results for the Scenarios of Dortmund (own illustration)

facade, the surface temperature is reduced by up to -8.9 °C due to the shading provided by tree plantings.

Building greening scenario Dortmund

When observing the surface temperature of the buildings, large differences can be detected. The highest surface temperatures are reached around 2 p.m., ranging from 19.9 °C to 68.4 °C. On the south and western facades, surface temperatures reach up to 44.1 °C, whereas the maximum surface temperatures on the north and eastern facades reach 29.3 °C. The higher temperatures on the south and western facades can be attributed to direct solar irradiation. As for the metal roof, its temperature reaches a maximum of 36.0 °C by 2 p.m. The most substantial reduction in surface temperature is on the south and western facades, with a maximum decrease of -22.0 °C. On average, the surface temperature of these facades experiences a reduction of -34.5 %, resulting in a value of 26.5 °C.

As for the building roof, extensive roof greening leads to a maximum surface temperature reduction of -6.5 °C and an average reduction of -6.0 °C (-17.0 %). Additionally, the implementation of building greening contributes to PET reductions ranging from -0.7 °C to -1.4 °C in the direct vicinity of the buildings.

7.2 Results for the Study Area in Bến Cát

Baseline scenario Bến Cát

Higher potential air temperatures are located in the south, extending into the central area of the campus. In the northern part of the campus, the potential air temperature reaches values below34.8 °C, which is mainly due to the cooling

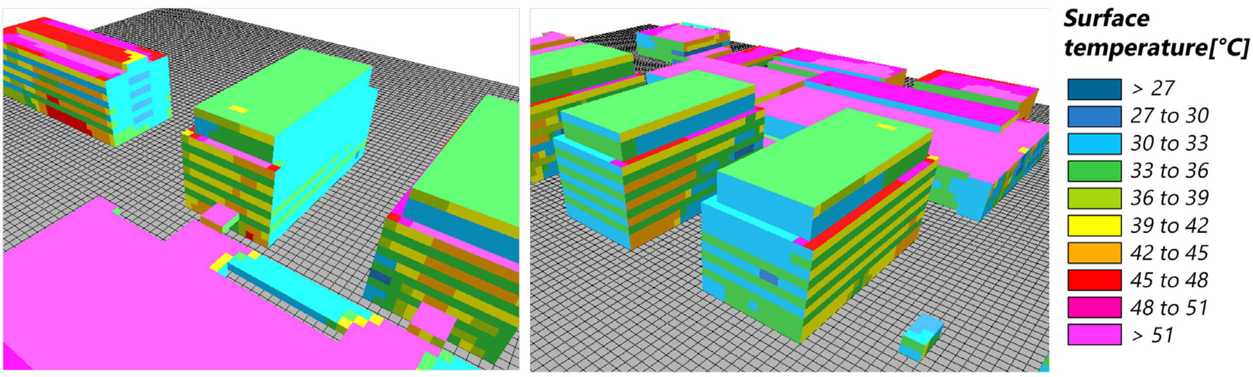


Figure 17: Surface Temperature in Baseline Scenario Dortmund (own illustration)

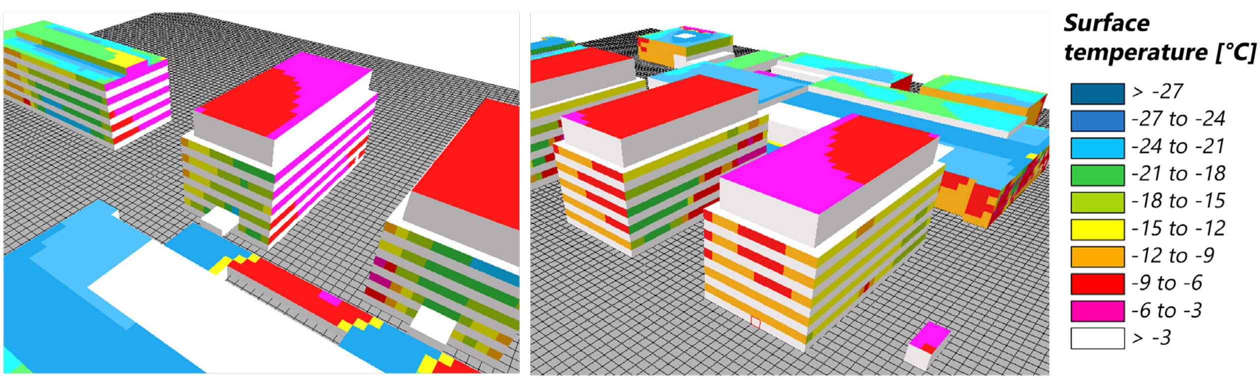


Figure 18: Difference of Surface Temperature in the Baseline and Building Greening Scenario of Dortmund (own illustration)

effect of the river (Park et al. 2019: 31–34). Cooler PET values are recorded in shaded areas near buildings. On the north sides of the buildings and in the courtyards where the air collects, warmer temperatures can be observed. When observing the surface temperatures of the buildings, large differences can be detected, resulting in surface temperatures ranging from 28.4 °C to 69.0 °C at 2 p.m. in the model area.

Environmental adaptation scenario Bến Cát

Applying the climate adaptation measures in the environmental adaptation scenario, the potential air temperature was reduced to the greatest extent by the water body, with a maximum reduction of -1.3 °C. Tree plantings led to a maximum reduction of potential air temperature of -0.9 °C and cool pavements to a reduction of -0.7 °C (see table 5). Cool pavements reduced the soil temperature by a maximum of -13.2 °C.

In Bến Cát, the PET recorded average value of 50.8 °C at 3 p.m. This represents a reduction of 5.1 % compared to the baseline scenario conditions. Pedestrians are exposed to extreme heat stress throughout the study area. Especially the northern side of the buildings and the courtyards have temperatures above 57 °C. Considering the adaptation measures in this scenario, tree plantings have the strongest influence on human comfort with a maximum reduction of -13.9 °C.

Tree plantings can reduce the heat stress in this scenario by one level from extreme to strong heat stress. Cool pavements and the water body decrease the PET by -2.7 °C and -2.1 °C. The environmental adjustments also affect the wall temperature, which decrease by a maximum of -6.4 °C at 2 p.m..

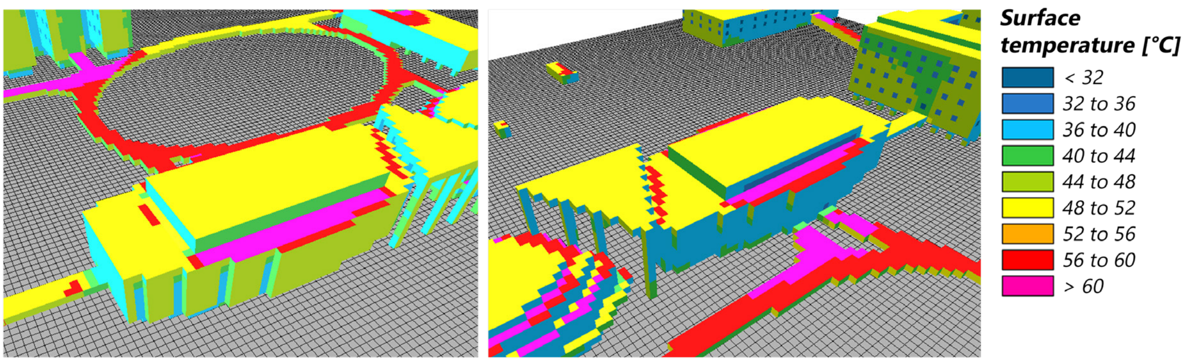


Figure 19: Surface temperature in the baseline scenario Bến Cát (own illustration)

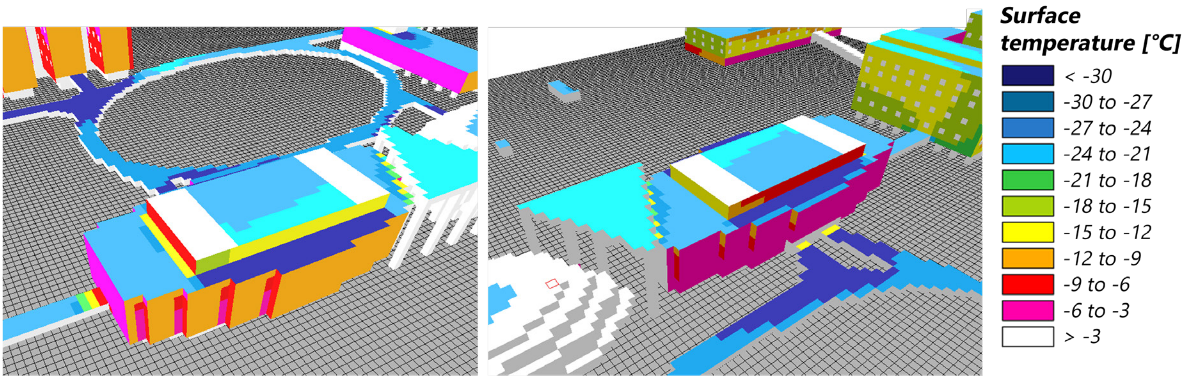


Figure 20: Difference of Surface Temperature in the Baseline and Building Greening Baseline Scenario Bến Cát (own illustration)

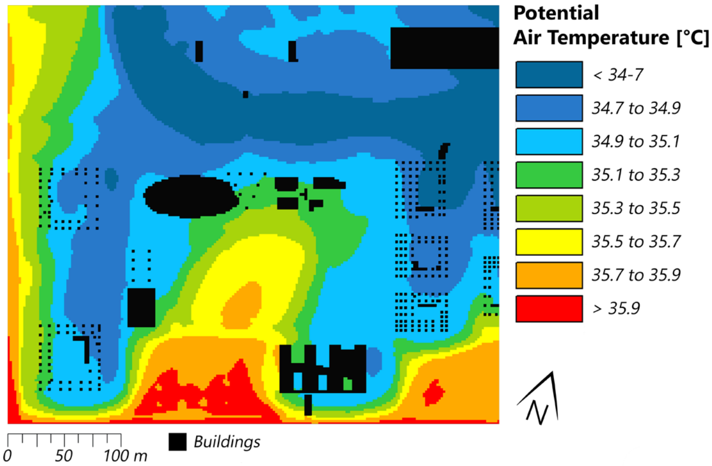


Figure 21: Potential Air Temperature in the Baseline Scenario of Bến Cát (own illustration)

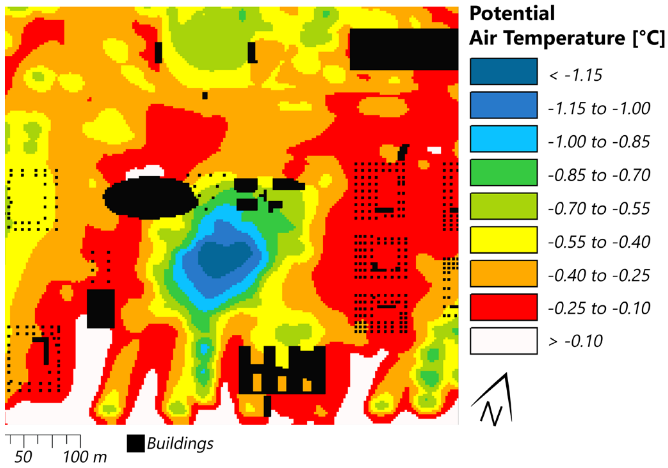


Figure 22: Differences of the Potential Air Temperature in the Environmental Adaptation and Baseline Scenario of Bến Cát (own illustration)

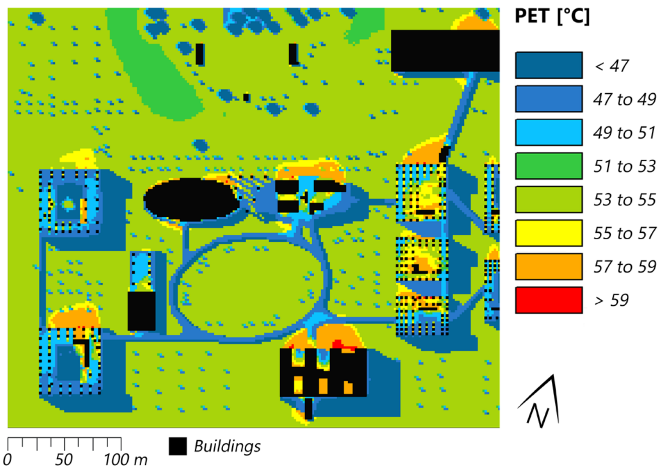


Figure 23: PET in the Baseline Scenario of Bến Cát (own illustration)

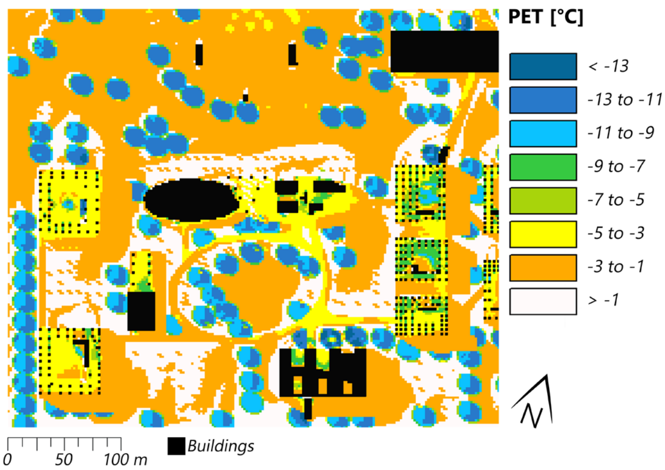


Figure 24: PET in the Baseline Scenario of Bến Cát (own illustration)

		Baseline scenario	Environmental adaptation scenario	Building greening scenario
Potential Air Temperature	Max.	36.18 °C	36.11 °C	36.17 °C
	Median	34.98 °C	34.65 °C	34.72 °C
	Reduction	/	-0.33 °C / -0.94 %	-0.26 °C / -0.74 %
PET	Max.	59.50 °C	59.23 °C	59.02°C
	Median	53.61 °C	50.87 °C	53.15°C
	Reduction	/	-2.74 °C / -5.11 %	0.46 °C / -0.86 %

Table 5: Simulation Results for the Scenarios of Bến Cát (own illustration)

Building greening scenario Bến Cát

In the building greening scenario, the highest reduction is in the courtyards with a maximum of -2.0 °C. The building greening also resulted in PET reductions of -1.5 °C to -4.0 °C in the direct vicinity of the buildings. Especially in the inner courtyards the PET could be strongly reduced by up to -11.3 °C. The PET reductions on pedestrian level can be assumed to be caused by the effects of the green facades, since green roofs are more distant from the pedestrian level, as various studies have shown (Srivanit & Hokao 2013: 171 f.).

When observing the focus building in this study area, the library of the VGU, different impacts of building greenings can be identified. On average, the intensive green roof on the library reduced the surface temperature by -27.2 °C (-50.3 %), with a maximum of -40.2 °C at 2 p.m. On the southern and eastern facades, the surface temperature decreased by an average of -10.7 % to 34.2 °C due to the greening with climbing plants.

On the northern facade of the building, which experiences higher solar radiation-induced heating, the implementation of facade greening resulted in a reduction of -22.3 % in surface temperature, leading to an average temperature of 34.9 °C. The facade greening modules on the roof structure reduced the surface temperature by a maximum of -34 %.

7.3 Comparison of the Results

The evaluation of the microclimatic simulations reveals that the implementation of climate adaptation measures contributes to the reduction of PET values, subsequently mitigating heat stress, and lowering surface temperatures. Considering the PET, larger differences become apparent, with a larger decrease detected in Bến Cát. In Dortmund, the environmental adaptations reduced the PET by -3.9 °C and in Bến Cát by -5.1 °C. The better performance of PET in Bến Cát can be attributed to the low vegetation density in the baseline scenario.

In both study areas, tree plantings are found to have the greatest impact on reducing PET due to shading from the tree canopy. Comparing PET values at locations D1 and B1 (see Figure 11) on open space in the baseline scenario with the same location in the environmental adaptation scenario after tree planting, significant reductions in PET are seen in both study areas (see Figure 25). The highest PET reduction in Dortmund is at 4 p.m. at -10.6 °C. In Bến Cát, the highest PET reduction is also at 4 p.m. with -12.5 °C. In both cases, heat stress can be reduced from extreme to strong. After 5 p.m., the positive cooling effect of tree plantings on human comfort decreases. The PET value approaches the baseline scenario as the importance of the shadow effect diminishes and wind speeds are reduced by the tree plantings. From the results of the environmental adaptation scenario, it can be concluded that tree plantings in areas with extreme and high heat stress can make these areas accessible to pedestrians by reducing heat stress.

Building greening does not provide shade for open spaces, but by shading the building elements, its surface temperature can be reduced. Differences between the effects of the greening systems can be observed, with module greening resulting in slightly higher reductions in building surface area than climbing plants greening. The largest reduction in building surface temperature from green roofs occurs with the intensive green roof on the focus building in Bến Cát (see Figure 22). In areas where tree plantings are not practicable, such as inner courtyards, the application of facade greening can also contribute to a reduction in heat stress, as observed in the building greening scenario of Bến Cát.

7.4 Validation of the Results

The simulation results are consistent with the results of previous research. In a study by Cortes et al. (2022: 99 f.), microclimatic strategies were developed for a campus in Mandaue City on the island of Cebu in the Philippines. With the implementation of urban spaces and trees, there has been an average reduction in air temperature of 0.2 °C (Cortes et al. 2022: 104 f.). In Dortmund, the temperature has decreased by 0.4 °C, and a similar trend is observed in Bến Cát with a decrease of 0.3 °C.

In the study of Srivanit & Hokao (2013: 171), the environment of the Saga University campus in Japan is modeled in ENVI-met and climate adaptation measures are implemented. By maximizing the tree coverage, an air temperature reduction of -2.3 °C was achieved. In a simulation in which road surfaces are removed and new vegetation is added, a temperature reduction of -2.3 °C is observed. It is described that the cooling effects are primarily due to the quantity of trees (ibid.: 170–172). In this research, the maximum cooling in Dortmund is -1.1 °C and -1.3 °C in Bến Cát in the environmental adaptation scenario, which is slightly lower than the result of the comparative study. It can be assumed that a higher tree density would further maximize the cooling of the campus. The significant reduction of heat stress by tree planting in Dortmund is in line with Schaefer (2022: 9), although slightly lower maximum PET reductions were achieved in this research. The orientation of the facades has an influence on the reduction of the surface temperature by facade greening due to sun exposure in both study areas, consistent with the study of Morakinyo et al. (2019: 50).

By conducting field measurements of air temperature, humidity and wind speed as input parameters for the simulations, more realistic results could be obtained. On-site measurements of plant-specific parameters such as leaf area density led to a more realistic model. Other greenings could be modeled and compared to

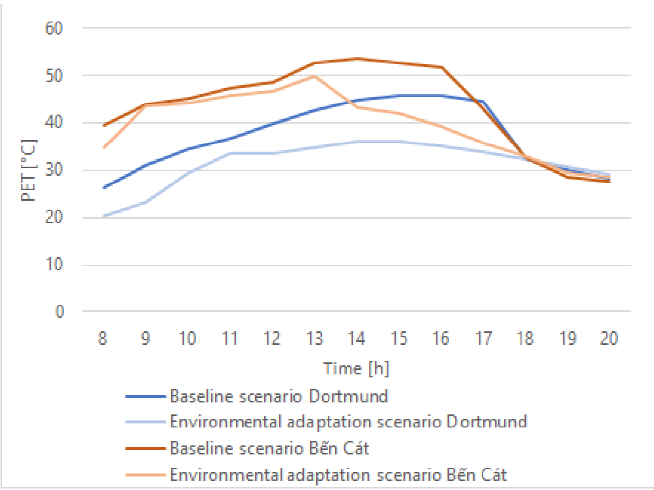


Figure 25: Development of PET on an Open Space in the Baseline and in the Environmental Adaptation Scenario with the Tree Planting in Both Study Areas over the Course of the Day (own illustration)

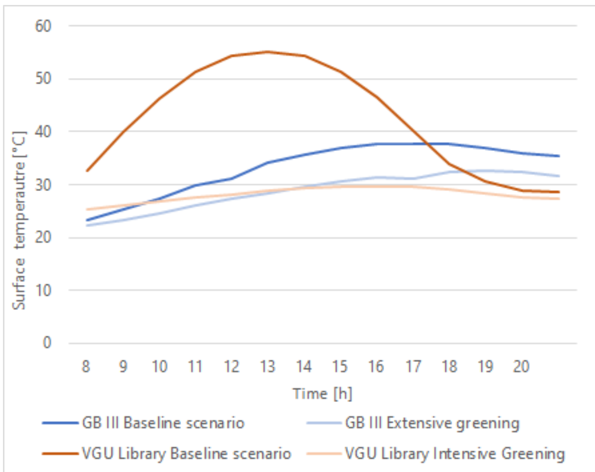


Figure 26: Development of the Roof Surface Temperature of the Focus Buildings GB III in Dortmund and VGU Library in Bến Cát in the Baseline Scenario and in the Building Greening Scenario over the Course of the Day (own illustration)

investigate different abilities on reducing heat (Liu et al. 2021: 11). Changes in atmospheric flow characteristics such as wind speed and direction are not reflected in the model, as they remain constant over the duration of the simulation, which are general limitations of ENVI-met (Acero & Arrizabalaga 2018: 467).

7.5 Modeling the Building with Climate Adaptation measures

The data of the microclimatic simulations conducted with ENVI-met indicate, that the facades and roofs of the buildings heat up quickly due to direct solar radiation. Based on the ENVI-met simulation and identification of diverse climate adaptation measures, as elaborated in chapter 5 (ENVI-met), these measures are visually represented in the pre-existing 3D model (see Figure 27). Green roofs are used to reduce the temperatures of the roofs of the VGU Library and GB III of TU Dortmund University. Due to the barrel roof of GB III, extensive green roofs are used. The roof of the VGU library is an accessible flat roof and therefore offers the possibility for an intensive green roof.

Different types of facade greening are used to reduce its temperature. Due to the open space between the window fronts, the GB III can be equipped with wall-mounted modular systems to cool the facade in the most efficient way. Because of the special structure of the facade of the VGU library, wall-mounted plant containers can

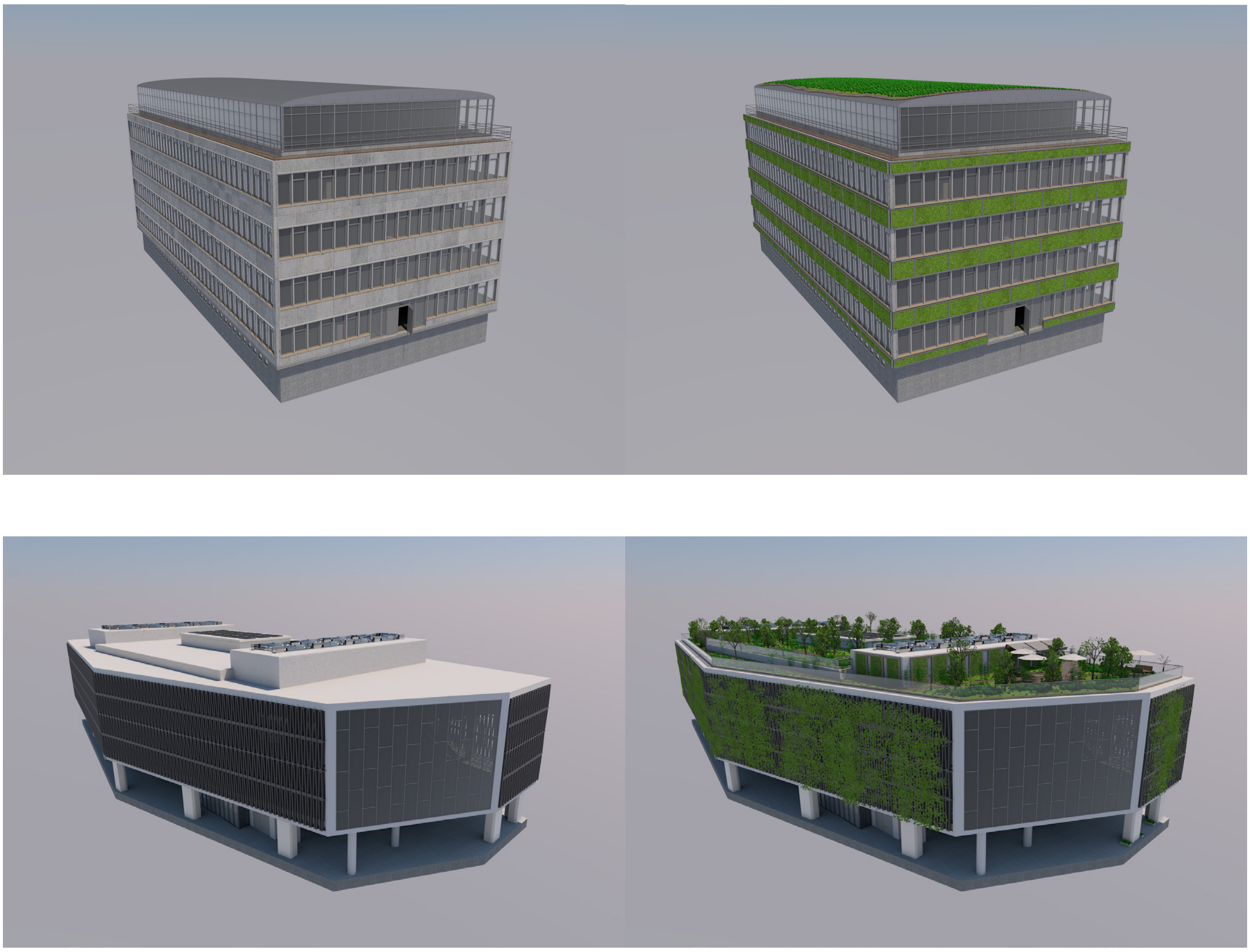


Figure 27: Comparison between TU Dortmund University and VGU Baseline Scenario with Climate Adaptation Measures (own illustration)

ideally be used. To visualize the measures in the ArchiCAD 3D Model, green roofs are depicted using a range of plants and textures sourced from the object library. Facade panels incorporating a combination of morphing elements and vegetation are strategically positioned on the exterior walls.

8. Geoinformation Maps

All information resulting from the Digital Twin process is visualized and collected in a LOD 2 geoinformation map in ArcGIS Pro.

8.1 Process of Creating the Geoinformation Map for TU Dortmund University

To represent the terrain of the South Campus of TU Dortmund University, a Digital Terrain Model (DTM) is incorporated into the local scene within ArcGIS Pro. The DTM is provided as open data by North-Rhine-Westphalia. For the visualization of the campus, buildings in LOD 2 are uploaded into ArcGIS Pro, also provided as open geodata by Geobasis NRW (2023c). The 3D model of the GB III and the tree locations are imported into ArcGIS Pro. The DTM is intersected with the LOD2 buildings to ensure that the buildings are embedded in the correct height. Several building parts are summarized into functional units in reference to the Campus Administration of TU Dortmund University. Various objects, including pergolas, open roofing, and canopies, have undergone modifications to enhance their LOD and achieve a more accurate representation within the model. The buildings of the campus are enriched with specific information e. g. height, usage, facade and roof material.

8.2 Process of Creating the Geoinformation Map for VGU

The same creation process of the geoinformation map for VGU is not feasible. Site plans of the VGU Campus are used as an alternative approach to compensate the lack of limited open data availability. The first site plan offers essential details regarding the building footprints

Figure 28: Geoinformation Map TU Dortmund University (own illustration)

and their respective locations. The second site plan provides information regarding the height of the buildings. Due to the absence of specific data, such as roof shape and pitch angle, aerial imagery and self-captured photographs are utilized to accurately model the shapes of the roofs. The created LOD 2 building is inserted into an ArcGIS Pro local scene. These files, which are created in Vectorworks software, must be georeferenced to place them in the correct location.

temperature and PET are each imported into QGIS, where the information is filtered and converted. In ArcGIS Pro the information is converted into a point raster file to add time data and modify the location. The time controller is activated to visualize the temperature change over time. Due to the lack of interoperability, it is not possible to implement the 3D climatic results from the ENVI-met simulations into ArcGIS Pro.

Figure 29: Geoinformation map VGU (own illustration)

The 3D model of the library is imported, and tree locations are manually identified and created using aerial imagery. Similar to the geoinformation map of the TU Dortmund University the buildings are supplemented with specific information. The presented geoinformation maps deviate in their representation of the environment in order to illustrate different degrees of abstraction (see Figure 28 and 29).

8.3 Process of Implementing ENVI-met Simulation Results

The lack of interoperability between ENVI-met and ArcGIS Pro leads to multiple steps to integrate the ENVI-met results into the geoinformation map. The simulated data for air

9. Results

The Ishikawa diagram is chosen to analyze and evaluate the process of creating the Digital Twin. This diagram is well-suited for process analysis as it visually illustrates the interrelationships between various workflow steps and their respective impacts on other aspects of the research. The process is presented by a horizontal line, while the lines extending from it represent various key factors that exert influence on the process. The variables are in turn also affected by certain aspects, creating ramifications (Brüggemann & Bremer 2020: 23). The revealed obstacles can then be weighted using ABC analysis method. The application of the ABC method is multifaceted, frequently applied with the objective of

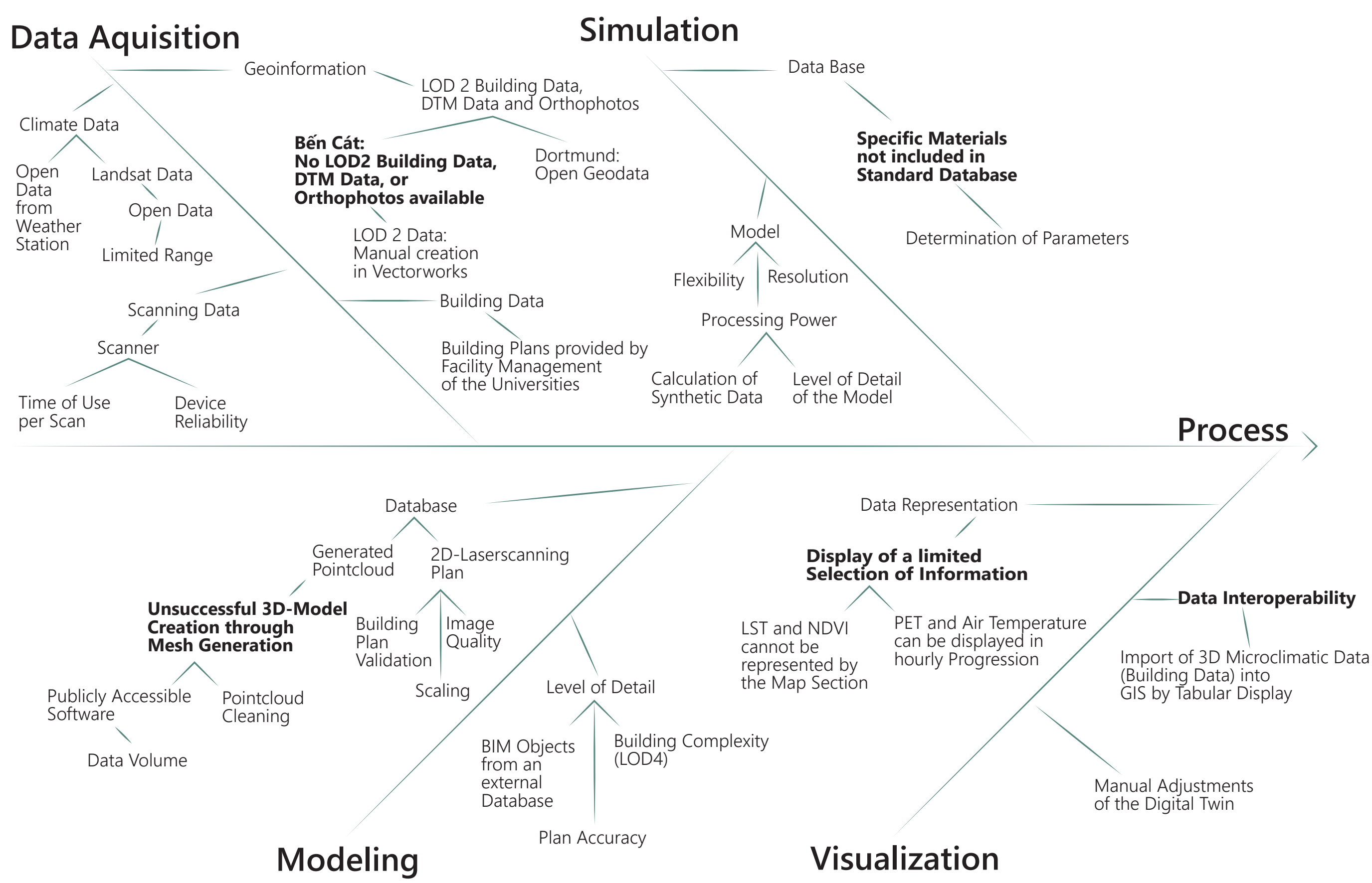


Figure 30: Ishikawa Diagram (own illustration)

avoiding uneconomical efforts (Kaufmann 2021: 210). For this research, the application of the ABC method aims to identify the most influential factors affecting the process (ibid.: 214). The evaluation criteria A, B, and C are modified to suit the evaluation of the process. Utilizing these criteria, the main factors influencing the process are evaluated. Criterion A focuses on resources as for example hardware, software and data. Criterion B refers to time-related aspects, in relation to the workload. Criterion C assesses the quality aspect, considering the impact on the result. In addition to the categorization of the factors into the A, B, and C, categories, the factors are rated. For this purpose, an evaluation scheme with the classification "very important", "important", and "less important" is applied. Once a factor is classified as "very important" it implies that it has the most significant impact on resources, time or quality and has significantly affected the process and needs to be resolved or improved urgently. Followed by "important" which has a noticeable impact on resources, time or quality and has a remarkable impact on the process. Factors that are classified as "less important" only have a minor impact on resources, time or quality and slightly affect the process. This negative impact can be more easily remedied.

9.1 Summary of the Ishikawa Diagram

The diagram (see Figure 30) illustrates the creation process of the Digital Twin and the main influencing variables are oriented towards the methodological approach: data acquisition, 3D modeling, simulation, and visualization.

Data acquisition

The data acquisition includes the generation of various datasets, including geoinformation data, building data, climate data and scanning data. The geoinformation data includes LOD 2 building data, DTM data, DSM data and orthophotos, which are publicly available for Dortmund. For Bến Cát, LOD 2 building data, DTM data, DSM data or orthophotos were not available which influenced the workflow (see chapter 8). Building plans are provided by the facility management of the universities, climatic data is also freely available and is taken from the nearest weather stations. Although Landsat data is publicly accessible, it is only available for a limited number of days (see chapter 1.2). Scanning data is self-generated using a kinematic scanner which has certain limitations (see chapter 2.1).

3D modeling

The attempt to create the 3D model through mesh generation was unsuccessful due to the inadequacy of publicly available software for handling large volumes of data and a lack of expertise. As a result, an alternative workflow is implemented for this research, which involves utilizing building plans as a substitute for the unsuccessful mesh generation. The 2D plans derived from the laser scans are intended to verify the building plans and provide more accurate representation of the interior architecture. The software of GeoSlam Viewer and Draw do not allow assigning a scale to the 2D plans generated from the point clouds, resulting in a scaling error. This error cannot be corrected upon importing into ArchiCAD, as the program does not provide the necessary parameter accuracy, leading to distortions in the 2D plans. Therefore, the 2D laser scanning plans are not accurate and precise, resulting in the unusability of the plans. The building plans can only be verified by individual measurements. By relying on building plans, the research can proceed and achieve the desired objective of creating a 3D model (see chapter 4). The LOD likewise influences the creation process, as this is prolonged for the model in LOD4 due to the complexity of the buildings. For the interior individual BIM objects that are not available in the ArchiCAD database must be downloaded from external databases to represent the buildings realistically.

Simulation

To obtain data for the simulation, research must be carried out, as some parameters are not available in the ENVI-met database. The model in ENVI-met can be easily adapted to changing conditions and displayed in different resolutions. It should be noted that a higher resolution also directly increases the required computing power. The simulation duration increases with the increase in size of the modeled area, since significant computational resources are required for the synthesis of the data. This limits the scope of the model.

Visualization

The visualization is mainly influenced by the data interoperability, as the import of 3D microclimatic data from ENVI-met into ArcGIS Pro can only be done via the attribute table (see Chapter 8). Therefore, the data representation is limited in its display of information. Potential air temperature and PET can be displayed at hourly intervals, LST and NDVI maps can not be integrated. The Digital Twin must be manually adapted to changed conditions in simulations or environmental changes.

9.2 ABC Analysis

Based on the Ishikawa diagram, six influencing factors are identified that have a particularly negative impact on the creation process of the Digital Twin. The influence is divided into the factors resources, time, and quality. These factors will now be presented and subsequently justified to be categorized as „less important," „important," and „highly important" (see Table 6). Additionally, reference is made to the current state of research in the barriers of the urban Digital Twin.

Evaluation of the data acquisition

One of the major challenges faced during the data generation process is the limited availability of relevant data in Vietnam. The shortage of data poses a significant obstacle to the research, as it hinders the comprehensive collection of necessary information for the study. By exploring alternative data sources and various data generation techniques, effort is made to compensate for the lack of readily available data. This represents a significant challenge in terms of resources, leading to a classification of „highly important" for its impact. Manual efforts are required to compile building and tree location data (see chapter 8). This additional effort significantly impacts the time factor in the creation of the Digital Twin. Therefore, the temporal factor is also classified as „highly important". The absence of DTM and DSM data have negatively influenced ArcGIS Pro calculations and generating input data in ENVI-met models. Due to the lack of LOD2 data, the modeling of buildings for the geoinformation map and establishment of climate adaptation measures, have occurred using aerial imagery, resulting in a loss of quality. Consequently, the quality factor is evaluated as „important". The challenge of data quality in the implementation of urban Digital Twins also gets reflected in the state of the art. The study Lei et al. (2023: 4) particularly pointed out the issue to integrate 3D buildings with terrain models, resulting in buildings that partially float or sink. This problem also occurs in this research and can negatively impact the results (ibid.).

Evaluation of the 3D modeling

During the 3D modeling process, two problems are encountered, including the unsuccessful generation of the mesh from the point cloud, which is considered as „highly important" in terms of the resource factor (see Chapter 3). This also has a „highly important" impact on the temporal factor, as automated mesh generation could have greatly improved the workflow but must be replaced with manual work. Considering that the mesh has the potential to accurately represent the spatial details of the interior, the impairment of the quality of the 3D model is considered „important." By utilizing ArchiCAD for modeling,

	Data Acquisition	3D Modeling		Simulation		Visualization
	Data - Vietnam	Mesh Generation	2D Scanning Plan	Limited Databank	Limited Model	Data Interoperability
Resource	Highly important	Highly important	Important	Important	Less important	Highly important
Time	Highly important	Highly important	Less important	Important	Highly important	Highly important
Quality	Important	Important	Less important	Important	Important	Important

Table 6: ABC Method (own illustration)

the quality of the model can be maintained at a high level, though it requires significantly more time and effort than initially anticipated. The importance of software in the development ofDigital Twins is identified as a significant issue in the study by Lei et al. (2023: 5). This licensing barrier has a decisive impact on the deployment of the mesh, leading to the adoption of an alternative approach. In addition, Lei et al. (2023: 5) states that "3D geospatial data, e.g. point cloud, remains critical in building digital twins".

The inability to create a mesh necessitated the utilization of ArchiCAD for the 3D modeling procedure. The second problem is the lack of information in the 2D plans regarding the interior architecture which can be supplemented by using other sources like images and measurements. Considering these circumstances, the creation of the 3D model can be considered „important" in terms of the resource factor. The temporal factor is deemed „less important" in this case, as the modeling can still proceed based on the building plans. In terms of model quality, the distorted 2D plans are considered „less important", as they do not meet the required quality standards to serve as a basis for the 3D model. Instead, the building plans are used, though manual measurements are required for verification purposes. The barrier of data availability occurs regarding building data for both study areas (see chapter 4). The literature emphasizes the high confidentiality of the data, meaning a significant amount of data remains inaccessible or can only be accessed through specific requests (Lei et al. 2023: 4).

Evaluation of the simulation

Regarding the simulations, two main problems are identified. Firstly, the limited database of ENVI-met poses a constraint on resources, making it an „important" influencing factor as material parameters must be derived from literature. Thus, the limited database also has an „important" impact on the temporal factor, as the parameter acquisition process from literature sources requires additional time. In terms of determining the quality the parameters have an „important" impact since material parameters influence the simulation outcomes, and deviations from real-world parameters could lead to divergent simulation results. This issue is highlighted in the study by Waqar et al. (2023: 6) in the problem of the usefulness of data. If the data is unstable or unreliable, it can negatively impact the efficiency of the Digital Twin and hinder its operations, as it would be processing inaccurate or incomplete data (ibid.).

The second problem is a limitation in simulation capabilities, influenced by computational capabilities of the ENVI-met software, necessitating a focus on a specific section of the campus rather than simulating the entire area. This resource factor is deemed „less important." Increased computational capabilities directly affect simulation times, resulting in the temporal factor being considered „highly important." Striking a balance is necessary to select an appropriate model resolution that accurately assesses the microclimatic situation while minimizing simulation time, allowing for adjustments and repetitions. This aspect has an „important" influence on the quality since the model size is restricted. Simulating larger campuses or extensive urban areas presents a challenge, as the software's performance may be hindered by the demanding computational requirements. The study by Lei et al. (2023: 5) elaborates that the computational demands in dealing with urban datasets are substantial. Urban data is characterized by its extensive size, significant volume, and complexities arising from the dynamic activities within cities (ibid.).

Evaluation of the visualization

The most important barrier encountered during the visualization process is the data interoperability between ENVI-met and ArcGIS Pro. The resource factor is assessed as „highly important" due to the inability of ENVI-met to visually transfer the simulated data into ArcGIS Pro. Instead, data is transferred in a tabular format in ArcGIS Pro. As a result, only the PET and potential air temperature are loaded into the geoinformation map, excluding information on the facade temperature. The lack of data interoperability also has „highly important" impacts on the temporal factor, as the data cannot be automatically integrated and requires manual input. This has an „important" influence on the quality factor, as not all data can be transferred, although many can be reflected in the user interface through manual entry. The barrier of data complexity occurs in visualizing the research results. The visual representation provided by ENVI-met, which could enhance user-friendliness, is limited due to the process, making it difficult to present large amounts of information in a comprehensible format for the end user. Interoperability stands out as a prominent challenge discussed in the literature and surveys, specifically focusing on the exchange of information between different systems (Lei et al. 2023: 9). Within this context, a particular barrier that arises is data conversion (ibid.).

10. Discussion

The results of the ABC analysis are used to answer the research question "To what extent is the development and use of Digital Twins suitable for implementing climate adaptation measures to counteract UHI effects?". To evaluate the suitability of Digital Twins in addressing UHI effects, it is crucial to establish a benchmark or ideal conception of an urban Digital Twin. This vision of the ideal urban Digital Twin is taken from the "Connected Urban Twins" (CUT) project (Schubbe et al. 2023: 15). The CUT project in Germany aims to develop and test Digital Twins for the urban areas of Hamburg, Leipzig and Munich by integrating various data sources and systems (ibid.). These Digital Twins are intended to serve as tools for analyzing urban challenges and supporting decision-making processes which corresponds to the Digital Twin created for this research (ibid.: 15 f.). The project further aims to establish standards for urban Digital Twins in Germany and has initiated a guideline to develop a common understanding of Urban Digital Twins in collaboration with industry, research, and municipalities in the year of 2024 (Schubbe et al. 2023: 21). Even though this publication is not yet obtained, at least the described vision of the project can be used. This ideal urban Digital Twin is envisioned as being (1) intelligent, (2) open, (3) interoperable, modular, realistic, (4) user-friendly, (5) reliable and (6) trustworthy (ibid.: 16).

The findings of the ABC analysis are compared with the characteristics of the ideal urban Digital Twin. This research aims to provide comprehensive insights into the potential of Digital Twins for implementing climate adaptation measures to counteract UHI effects. The outcomes of this study will contribute to advance the understanding of how Digital Twins can be effectively utilized in urban planning and development processes, ultimately promoting resilient and sustainable cities.

Intelligent: The project CUT envisions an urban Digital Twin to be intelligent and defines it as enabling data-driven decision-making through integrated workflows, analysis, simulations, predictions, and machine learning. It can also respond to changes and events, such as the consequences of architectural modifications. This research primarily concentrates on investigating the implications of climatic change within the context of the urban Digital Twin (Schubbe et al. 2023: 16).

The Digital Twin created for the research has certain characteristics that align with the vision but also presents limitations. The Digital Twin can generate synthetic data based on the input data and is therefore able to make predictions. This data generation process can be considered intelligent as it allows the exploration of different scenarios and the extraction of insights. A notable observation is that the data has to be manually loaded into the simulation software, which implies the lack of an automated workflow. This manual intervention limits the efficiency and scalability of the data generation process and highlights the need for further development in automated data integration and simulation workflows.

Whenever changes occur in the environment, the geoinformation map also requires manual editing and does not automatically insert new data. The manual editing process involves updating the map to reflect the altered surroundings accurately. This manual workflow introduces additional effort and time requirements, which can impact the overall efficiency and reliability of the Digital Twin. In terms of advanced capabilities, the Digital Twin does not incorporate machine learning techniques. Machine learning in the context of Digital Twins could hold significant importance in the analysis and extraction of patterns from complex data sets, enabling more accurate predictions and decision support (Güleş & Schweitzer 2021: 19). Its absence in the Digital Twin limits the ability to leverage the full potential of machine learning algorithms for improved insights and decision-making. The interpretation of simulation results also relies on manual effort. This manual interpretation process introduces subjectivity and potential biases, which can affect the reliability and objectivity of the findings. Incorporating automated analysis and interpretation mechanisms, such as machine learning algorithms, could enhance the objectivity and efficiency of result interpretation.

While the Digital Twin created for the research demonstrated some intelligence in terms of data generation through simulations, there are limitations in terms of automation, machine learning integration, and result interpretation. Addressing these limitations would contribute to realizing the full potential of an intelligent urban Digital Twin, as envisioned in the CUT project, for data-driven decision-making and urban development.

Open, interoperable, modular: The envisioned urban Digital Twin is open, interoperable, and modular, built on existing standards, reference models, and future-oriented technologies. It consists of standardized, connected, and configurable components, enabling interaction between different urban Digital Twins (Schubbe et al. 2023: 16).

The implementation of the Digital Twin in ArcGIS Pro provides flexibility for future enhancements and the integration of additional functionalities, allowing for ongoing development and expansion. The tabular representation not only facilitates easy updates and modifications but also enables efficient data management and manipulation. While the interoperability of the Digital Twin with other Digital Twins is not specifically tested, the underlying infrastructure of ArcGIS Pro offers compatibility and the potential for integration with other Digital Twin systems. It is conceivable that the Digital Twin could be linked to other urban Digital Twins, facilitating collaborative and comprehensive analyses and simulations. However, it is important to acknowledge that the created Digital Twin deviates from the standardized conception of an urban Digital Twin. Unlike an ideal urban Digital Twin that establishes a bidirectional relationship with the physical world, the current Digital Twin primarily operates within the virtual environment (see chapter 1). This means that it lacks a direct feedback loop with real-world data and events, which could limit its ability to accurately reflect and respond to dynamic changes and influences in the urban context.

The implementation of the Digital Twin is successful and provides a foundation in ArcGIS Pro for further investigation and improvement. To address the limitations by incorporating mechanisms for real-time data integration, enabling a more dynamic and responsive Digital Twin that better aligns with the vision of an open, interoperable, and modular urban Digital Twin.

Realistic: The urban Digital Twin is ideally realistic, providing a current and needs-oriented representation of the municipality, ensuring a connection to reality (Schubbe et al. 2023: 16).

The Digital Twin created for this research reflects the campus in LOD2 and the focus buildings in LOD4, allowing for a comprehensive and recognizable representation of the area. This enables a more accurate representation of various urban aspects. The Digital Twin is supplemented with additional information such as the building height, building materials, and sensoric data like albedo and building temperature. The simulations conducted within the Digital Twin strive to capture the dynamics and behavior of the real-world environment. By incorporating an LOD2 model, the Digital Twin can simulate and analyze different scenarios, evaluating factors such as the PET, potential air temperature, and surface temperature. Those characteristics are essential to represent heat realistically. It is important to acknowledge that the direct connection to reality is not fully established in the Digital Twin. The Digital Twin replaces the physical object with a virtual representation, and the data exchange occurs in a virtual environment. Consequently, any changes or updates that occur in the real world need to be manually incorporated into the Digital Twin to ensure its accuracy and alignment with reality. This manual effort introduces a potential delay and additional workload in keeping the Digital Twin up to date.

In summary, the Digital Twin strives to provide a realistic representation of the campus and incorporates simulations that capture aspects of reality. The inherent limitations in terms of the direct connection to real-time data and the manual intervention required for updates are essential. The Digital Twin remains a realistic system which can be used as a valuable tool for analysis and decision-making.

User-friendly: The envisioned urban Digital Twin is user-friendly, accessible without technical barriers, and designed with simple, understandable, and tailored tools and interfaces. It promotes user-centered design, sharing and reusability of work results (Schubbe et al. 2023: 16).

To align the Digital Twin with the vision, it will be available to the public through an ArcGIS web app. This platform offers several advantages to create a user-friendly interface that simplifies navigation and interaction. Users can interact with the Digital Twin without requiring extensive technical knowledge. Users of the urban Digital Twin have the capability to access and explore diverse layers of information, including land use patterns, vegetation distribution, and more. This multi-layered approach enables users to gain a comprehensive understanding of the urban environment from different perspectives. By adjusting the point of view within the Digital Twin, users can examine specific areas of interest, navigate through the virtual representation of the study area. The user can gain information about the buildings through a table that contains, for example, information on the building height, used materials, building temperature, adaptation measures for both study areas and the energy consumption of the TU Dortmund University. The web app serves as a platform for presenting comprehensive and clear explanations of the research. Through a combination of visuals, such as images and illustrations, and explanatory text, users can easily understand the purpose, features, and significance of this research, even if they are not familiar with it beforehand. Users can access the Digital Twin from various devices with an internet connection, making it widely available to different user groups. By leveraging the capabilities of the ArcGIS web app, the research aims to create an interface that is user-friendly, accessible, and supports the sharing and reusability of research results. The platform's intuitive design, interactive visualization, customization options, clear explanatory content, and broad accessibility contribute to an enhanced user experience.

Reliable and trustworthy: The vision of the urban Digital Twin is that it is reliable and trustworthy, delivering accurate and regularly updated information while considering information security and data protection. It adheres to legal requirements and local data governance structures, ensuring availability, fault-tolerance, and error-free processing through standardized quality assurance processes (Schubbe et al. 2023: 16).

An encountered challenge to create a reliable and trustworthy Digital Twin is the data availability in Vietnam. Given the restricted access to geo-information data in Vietnam, the required data for the Digital Twin has to be constructed, while ensuring its accuracy and precision. By leveraging satellite imagery and aerial photographs, this research obtains valuable insights into the physical characteristics and features of the urban environment. These data sources enable reconstructing the geospatial data with a high degree of confidentiality, enhancing the realism and reliability of the Digital Twin. The focus buildings are modeled based on building plans which are available only due to collaboration. While the limitations on data accessibility requires more effort, the Digital Twin still accurately reflects the reality of the urban environment it represented. The Digital Twin of this research provides users with reliable information. However, the absent quality control to verify reliability in this research can be criticized.

In conclusion, the development and utilization of the Digital Twin offers valuable insight and support for implementing climate adaptation measures to counteract UHI effects. The constant adjustments make the Digital Twin an effective and suitable technology to mirror the challenges caused by climate change. By addressing the identified limitations and continuing to refine the Digital Twin, it has the potential to significantly contribute to data-driven decision-making and urban development strategies. Addressing these issues will contribute to the advancement of research in the field and enable more intelligent, interoperable, realistic, user-friendly, reliable and trustworthy Digital Twins for urban planning and climate resilience. Despite the potential issues mentioned earlier, the use of Digital Twins remains suitable for implementing climate adaptation measures and mitigating UHI effects.

11. Outlook

To achieve the optimal outcomes in the future, it is important to explore the promising possibilities of this technology and improve them with the potential through research. To overcome the issue of a lack of available data, future research can focus on improving data acquisition methods and establishing comprehensive geodata portals worldwide. Efforts should be made to improve the quality and quantity of standardized data used in Digital Twins. Developing data integration frameworks will facilitate seamless data sharing and interoperability among different stakeholders involved in urban planning.

The problems faced during the generation of meshes from point clouds indicate the need for improved software capabilities and workflows. Developing algorithms for efficient mesh generation from massive point cloud datasets can accelerate the Digital Twin creation process and enable real-time or near real-time applications. Future research can explore software solutions to create detailed meshes on an urban scale, while ensuring data and programs are publicly accessible to enable future researchers and planners to utilize and enhance these approaches for decision-making.

The integration of real-time data, such as sensor inputs, into the simulation would establish a real-time data connection between the data and the object, enabling an automated process that would not require manual adjustments. Incorporating these sensor data within Digital Twins will enable urban planners to have a basis for testing different scenarios, evaluate the effectiveness of various adaptation strategies, and make informed decisions regarding urban development. Additionally, efforts should be made to incorporate 3D visualization capabilities to enhance the understanding and interpretation of simulation results.

The use of machine learning and AI algorithms within Digital Twin platforms can enable predictive modeling, variance detection, and decision support systems. Future research should explore the potential of these technologies in analyzing complex urban data, identifying patterns, and predicting future UHI occurrences. Efforts should be made to automate data processing tasks to reduce manual efforts and enhance data quality. Additionally, developing AI-driven optimization algorithms can assist in generating adaptive measures and identifying the most efficient and sustainable urban planning interventions.

In the context of participatory planning, user-friendliness of Digital Twins is crucial in facilitating collaboration between different stakeholders, such as citizens, experts, and decision makers. When the interface is intuitive and easy to navigate, stakeholders are more likely to engage with the Digital Twin and explore its features. With the additional use of virtual reality and augmented reality, it is possible to interact with Digital Twins and move through the virtual world. This can increase the acceptance of participatory planning which can lead to a broader range of perspectives and ideas being shared, enriching the overall outcomes.

This research provides an initial classification in a previously neglected area of Digital Twins, as it focuses on climate adaptation to combat UHI. In the future, knowledge gained from the Digital Twin could help not only to reduce UHI but also to cope with other extreme weather events. Future research should focus on refining data integration techniques, incorporating climate simulations, leveraging machine learning and AI applications, and promoting interdisciplinary collaboration. The technology of Digital Twins can become a powerful tool for evidence-based decision-making and creating more resilient and sustainable cities.

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