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Exploring Urban Typology Impacts on Trade-Offs between Global Warming Potential, Costs, and Outdoor Thermal Comfort

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Abstract

Trade-offs between climate change mitigation, adaptation, and costs are challenging the sustainable transformation of urban neighborhoods. Guiding urban planners in dealing with this multi-objective problem promotes balanced decision-making in the early planning phases. We use a highly interconnected neighborhood simulation model to quantify trade-offs between the three aspects and investigate case study areas in Munich, Germany. Following the concept of Urban Systems Exploration, a multi-objective optimization (MOO) algorithm is utilized to search for Pareto-optimal solutions with specific characteristics. Thereby, the Pareto fronts for the best possible trade-off in row, block, and detached typologies are identified. Comparing the results indicates strongly pronounced trade-offs between global warming potential and outdoor thermal comfort for detached typologies. The MOO analysis sensitizes urban planners to such interdisciplinary considerations and provides decision-making support in the early design phases.

Background

Climate change is challenging the current state of urban areas. On the one hand, up to 76 % of greenhouse gas emissions from final energy use stem from cities, making them one of the major mitigation potentials (Seto et al. 2014). On the other hand, urban areas are highly affected by climate change impacts like urban heat or stormwater. Thus, urban planners must progress quickly and implement climate change mitigation and adaptation simultaneously. However, although these two are highly interconnected, they are often considered separately in research and practice (Daniel et al. 2023). In addition, the evidence-based urban planning process is not always fully integrated into departmental structures and is often a matter of experience (Abd Elrahman & Asaad 2021).

Urban planning takes place within an interdisciplinary framework. Each discipline brings specific aspects, objectives, and constraints to the planning process. This results in the need for compromise solutions, the aim of which must be to achieve Pareto optimality. During the inherent decision-making process, trade-offs must be explicitly identified, quantified, and included in the discussion to meet the context-specific needs of urban areas. However, urban planners are hardly provided with guidance to handle such trade-offs (Xu et al. 2019). In particular, neighborhood development is characterized by many interactions (Jenkin & Pedersen 2009), and the resulting trade-offs can vary in severity. Research has shown examples where lifecycle-based global warming potential (GWP) and outdoor thermal comfort form trade-offs, e.g. by the contradiction that low density and high green area are good for adaptation, but mitigation improves with higher urban density (Xu et al. 2019). Furthermore, economic efficiency and the energy demand of buildings, which are highly relevant to GWP, also represent a multi-objective problem (Hillebrand et al. 2014). Our paper enhances these findings by investigating the Pareto-optimal trade-offs between lifecycle-based GWP, outdoor thermal comfort, and lifecycle costs and shows how they differ for three generic urban typologies. The results allow us to identify typologies where the trade-off must be handled with particular care. Therewith, we aim to reveal urban planners' steering options in early design phases.

State of Research

Urban environment trade-off dependencies

In urban development, multiple factors interact dynamically, requiring a thorough trade-off assessment for decision-making. One pivotal aspect is the role of green elements, which amplify the interaction between climate change mitigation and adaptation (Daniel et al. 2023). The intricate trade-offs extend to seemingly subtle choices, such as the selection of tree species. Sharifi (2020) emphasizes the significant impact that this decision can have on urban trade-offs. McLeod et al. (2013) highlight the trade-off between building energy demand and indoor thermal comfort. They show that high energy standards may cause a worsening in the thermal performance of buildings. Furthermore, urban trees have been shown to influence this energy-comfort trade-off (Reitberger et al. 2023). Taking a broader perspective, Natanian et al. (2019) investigate trade-offs across diverse urban typologies. Their exploration of the trade-off between load-match and spatial daylight autonomy utilizes a parametric simulation model that captures essential metrics and represents various typologies. Their study shows significant variations among typologies, highlighting the nuanced nature of urban trade-offs. These studies underline the importance of considering environmental concerns and architectural decisions when developing balanced urban development strategies.

Trade-off exploration in urban systems

Research emphasizes the need for a multi-objective evaluation of trade-offs rather than optimizing for individual target dimensions (Li et al. 2022). While numerous studies have investigated specific multi-objective problems for various typologies (Natanian et al. 2019, Abdollahzadeh & Biloria 2022), the focus has often been more on the specific characteristics and simulation outcomes of neighborhoods rather than the behavior of trade-offs themselves. To address this behavior in the urban context, it is imperative to fully explore the trade-offs' extent. Making trade-offs assessable requires structured processes and methods. The Hyper Space Exploration provides a framework for this task. It distinguishes between modifiable variables (Design Space), target aspects (Target Space), and examined scenarios (Use Space) (Palm & Holzmann 2018). This principle was transferred to Urban Systems Exploration for investigating trade-offs in the urban context (Reitberger et al. 2024). By constructing a simulation model and performing multi-objective optimization (MOO), a comprehensive understanding of the target range and steering variables can be achieved. This approach provides a holistic perspective, moving beyond specific neighborhood characteristics to consider the range of trade-offs in urban planning. Thereby, it improves multi-objective decision-making in early design phases, where major impact on the results of urban designs is possible (Basbagill et al. 2013).

Methodology

The newly proposed methodology aims to quantify the trade-offs between GWP, lifecycle costs, and outdoor thermal comfort for different typologies. It combines the current state of research on neighborhood simulation with design exploration to investigate trade-off characteristics, providing decision support to urban planners in early design phases. A particular focus is on including complex target variables and the complete representation of Pareto fronts. This section describes its two main components: the simulation model and the MOO tool-chain, which follows the concept of Urban Systems Exploration (Reitberger et al. 2024).

Urban typology simulation model

In order to quantify the trade-offs, an urban simulation model that considers interactions between the aspects of lifecycle GWP, lifecycle costs, and outdoor thermal comfort is introduced. This model can simulate urban design scenarios and determine quantitative Key Performance Indicators for the three optimization targets. Figure 1 shows a schematic representation of the integrated interactions. The model is set up in the Grasshopper environment, where several components are combined: the Urban Weather Generator for considering the Urban Heat Island Effect (Bueno et al. 2013), Fast-Fluid-Dynamics for wind simulation (Waibel et al. 2017), building energy simulation with photovoltaics (PV) (Roudsari & Pak 2013), and a Python implementation of ecological Lifecycle Assessment (LCA) and Lifecycle Costing (LCC). Data exchange and common inputs are emphasized while setting up the model. For instance, PV areas lead to changing albedos of the respective surfaces, which serve as inputs for the Urban Weather Generator and thus influence the climatic conditions in the energy and outdoor thermal comfort assessment. Three typological Use Cases define the buildings' geometry: row, block, and detached. These typologies represent the most common in German cities and are therefore highly transferable (ZSK 2017). All case study areas are located in Munich and weather data is retrieved from Meteotest AG (2023). Table 1 summarizes the overarching boundary conditions. Refurbishment is considered for all typologies. Streets and trees in the outdoor space and building-related design variables, such as PV on roof and façades, are part of the MOO. Table 2 shows their respective design ranges.

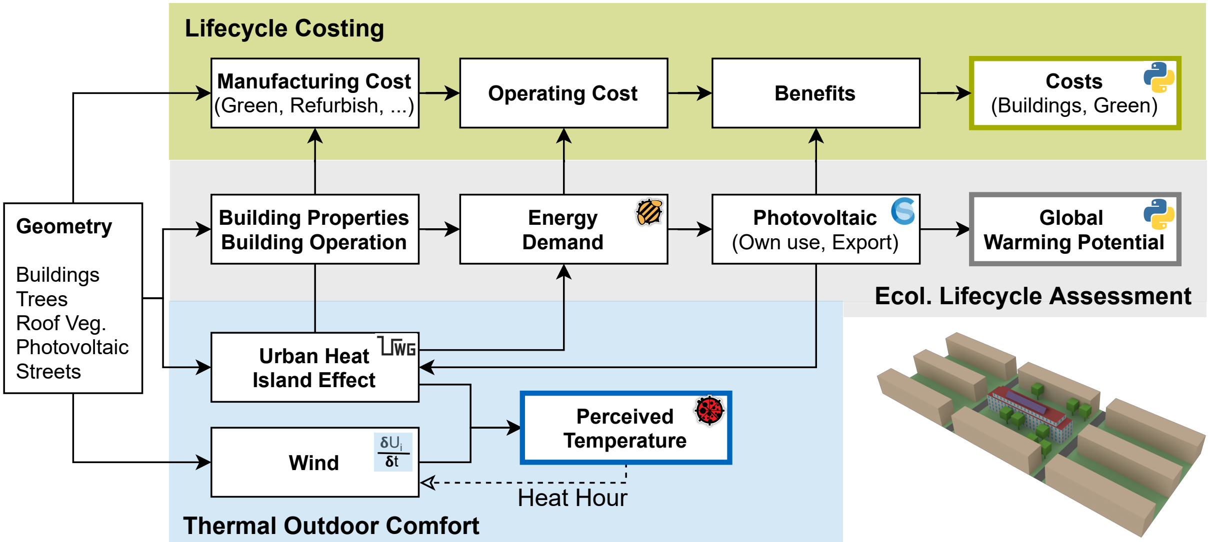

Figure 1: Simplified representation of information flow to the target variables in the simulation model.

The LCC values were compiled from sources related to the German context (BKI 2022, f:data 2022). Missing values for vegetation were obtained by literature search (Saha et al. 2019, Eschenbruch 2012). All scenarios are run with an air-heat pump (coefficient of performance = 3.0), and the cost of electricity is set at the average household price of 0.4229 € per kWh in the first half of 2023 (Statistisches Bundesamt 2023). Exported PV electricity is credited with 0.082 € to 0.058 € per kWh depending on the size of the system in accordance with the Renewable Energy Sources Act in Germany. In addition, price increases of 5 % per year on energy prices, 2 % per year for construction services, and a discount rate of 1.5 % are applied (BMI 2021). For the LCA, the phases of production (A1-A3), operation (B4, B6), and end-of-life (C3-C4) are considered. The German LCA database Ökobaudat (2020-II) is used (BBSR 2023). LCA and LCC are both conducted for a 50-year period and are related to one square meter of gross floor area. GWP and monetary benefits from electricity production are linearly reduced to zero until the assessment year 25, as by then Germany intends to be climate neutral in its electricity mix (Bundesnetzagentur 2022). The Universal Thermal Climate Index (UTCI) quantifies outdoor thermal comfort during the most uncomfortable hour of the year (Błażejczyk et al. 2013). Therefore, a point grid in the neighborhood is used, and the simulated UTCI results for the points are averaged into one value.

Multi-objective optimization

The simulation models for the three typologies are subjected to an MOO. All three targets form minimization problems for which the Pareto front (PF) needs to be identified. Focusing on Pareto points (PPs) is imperative because, for solutions that lie behind the PF, a solution that performs better in all three target aspects can be found. Hence, solutions that are not Pareto-optimal should not be pursued. Since the simulation model is computationally expensive, with one evaluation taking up to 30 minutes, an MOO environment needs to be capable of identifying many PPs with a small number of model evaluations. The tool-chain described by Reitberger et al. (2024) is used to couple the simulation models with the optimization environment. For the MOO itself, the Paref algorithm is utilized (Palm & Palm 2023). This algorithm mathematically guarantees the identification of PPs and allows to search for PPs with specific properties. Therewith, the PF edges can be identified effectively and efficiently, enabling a complete impression of the trade-off extent. The identified edge points are utilized to search for a regular grid of PPs between them. This reveals the rough shape of the PF for each of the three typologies.

Results and discussion

The presented workflow identified 28 PPs for the row housing, 36 PPs for the block housing, and 58 PPs for the detached housing. Figure 2 illus-

Table 1: Fixed simulation boundary conditions. BAC = Building Age Class according to Loga et al. (2015).

Parameter	Input	Source
Building dimensions [m]	row: 60x12x18; detached: 16x10x9; block: 70x85x25 with courtyard 40x55	(bayernatlas.de 2023)
U-value sets (BAC, constr. year) Wall, Roof, Base, Window [W/m^2· K]	row: C 1946 block: D 1956 det.: E 1962 refurbished: 0.15, 0.15, 0.15, 0.7	(Loga et al. 2015) (Passivhaus Institut 2022)
Heating setpoint [°C]	20	(DIN 2018)
Internal heatgain [people / m^2]	0.025	(DIN 2018)
Occupancy schedules	Mo-Fr: 17 - 7h; Sa-Su: 0 - 24h	-
Infiltration [m^3/s per m^2 façade]	after refurbishment: 0.0001	(Roudsari & Pak 2013)
PV efficiency [%]	modules: 22; battery: 70	(NREL 2023)
LCA insulation [-]	eco standard	(Banihashemi et al. 2022)

Table 2: Design Space for the simulation.

Nb	Input	Range
1	Tree percentage [%]	[0, 100]
2	Tree crown diameter [m]	[2, 10]
3	Tree height from ground [m]	[6, 10]
4	Crown transpar. summer [%]	[10, 30]
5	Crown transpar. winter [%]	[45, 80]
6	PV roof [%]	[0, 100]
7	PV south façade [%]	[0, 100]
8	PV east-west façade [%]	[0, 100]
9	PV battery capacity [kWh]	[0, 80]
10	Green roof soil thickness [m]	[0, 0.25]
11	Window-to-Wall Ratio [%]	[10, 50]
12	Solar heat gain coefficient [-]	[0.4, 0.85]
13	Albedo façade [-]	[0.1, 0.7]
14	Street width [m]	[3, 9]

trates the PF for the row housing typology in the three-dimensional Target Space. Each optimum in one target can only be achieved by accepting trade-offs with one or both of the other targets. The ranges of the respective target dimensions are: 29.2 to 33.9 °C for outdoor thermal comfort; -2.5 to 6.5 kgCO_2-eq./m^2·yr for lifecycle GWP; 1,780 to 2,162 €/m^2 for lifecycle costs.

For outdoor thermal comfort, the results show that a change of one heat stress level on the UTCI scale can be achieved within the Pareto solutions since the threshold between moderate and strong heat stress is 32 °C (Błażejczyk et al. 2013). The lifecycle GWP varies widely between the PPs and sometimes even becomes negative. This has been shown in other studies dealing with zero-carbon buildings, especially when PV systems are taken into account (Stephan & Stephan 2020). However, there is also contradictory research where case studies do not reach zero-carbon results. For instance, the study of Passer et al. (2016) shows no lifecycle GWP values below zero for building refurbishment in the Austrian context. These deviations may be due to differences in assessment boundaries and assumptions, such as the consideration of embodied impacts of heating systems. Our study did not include these as we only compared heat pump scenarios. Furthermore, we used the German electricity mix with the assumption of a transformation to renewables within the first 25 assessment years, while Passer et al. (2016) include a share of fossil fuels in their study. Therefore, we do not interpret our results as achieving a holistic net zero-carbon building. However, they indicate a certain range of GWP in the Pareto-optimal set.

Figure 3 shows the significant difference between the three urban typologies regarding their PF characteristics. The range of LCA results narrows from detached to row to block typology. The block typology exhibits less variation and a sharp increase in GWP in the minimal UTCI zone (green points in Figure 3). This implies that significant increases in GWP are only necessary to achieve the best possible outdoor thermal comfort. A slight reduction of outdoor thermal comfort targets opens the possibility of decreasing GWP by up to 54 % in our block case study. The detached typology shows a more even trade-off progression. Accordingly, the trade-off between GWP and outdoor thermal comfort offers a broader range of optimal solutions

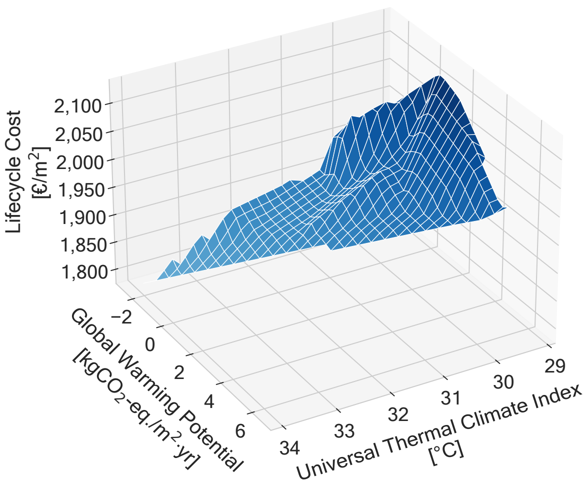

Figure 2: Pareto front of the row housing typology case study. All dimensions should be minimized.

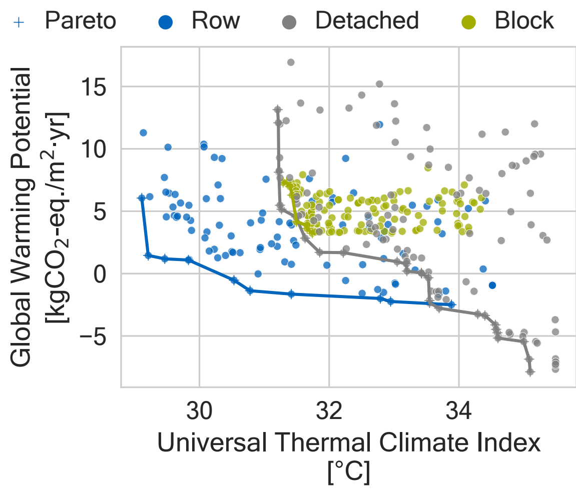

Figure 3: Pareto fronts of the considered urban typologies for the trade-off between GWP and UTCI.

in the detached typology. The trade-off extent of the row typology is located between block and detached typologies. Continuous areas can be identified where outdoor thermal comfort can be improved without a significant increase in GWP. However, completely minimizing UTCI substantially increases GWP for the row housing typology. In our study, it is possible to improve outdoor thermal comfort while keeping a small GWP trade-off up to a certain point, approximately 31 °C. One of the reasons for this trade-off is the shading effect from trees on buildings, which causes an increase in heating energy demand. Further, PV surfaces get shaded by dense tree placement, which reduces their productivity and thus increases GWP.

Figure 4 shows the Design Space associated with the identified PPs. For comparability, we normalized them according to the input ranges in Table 2. For row and block typologies, Pareto solutions behave similarly for tree percentage and crown diameter, but the values of the detached typology deviate. This shows the varying influence of vegetation on the typologies' trade-offs. While a few trees heavily shade façades and roofs of detached houses, this effect is less pronounced for the much bigger row and block typologies. Daniel et al. (2023) argue that vegetation is among the best measures for climate change adaptation. They find that interventions in outdoor spaces often have a more significant impact on climate change mitigation and adaptation than building interventions. In our study, the effect on outdoor thermal comfort is comparable for all typologies. However, the span of LCA results and therewith the balancing options of Pareto solutions are higher for the detached typology than for row and block typologies. This may explain why there are different optimal input configurations of Pareto solutions. The tree height variable is in the lower third for all typologies. Accordingly, there are still some common behaviors between the typologies when it comes to steering trade-offs.

In terms of PV surfaces, there is only a significant deviation for roof PV, which is in the medium to high range for detached and row developments and low for block developments. This may be related to the high proportion of north-facing roof surfaces in the block case study. In the simulation model, north-facing roofs are also equipped with PV systems. The row and detached typology case studies are north-south oriented, resulting in fewer low-performing north-facing roof surfaces. This makes the variable more significant for achieving optimal solutions. All typologies show high values for façade PV. Thus, the parameter has only a minor influence on the differences between the typologies in terms of trade-offs. This might change with varying densities within the typologies, as density affects the shading of façades. The PV battery capacity is determined low for smaller individual buildings since they have low own consumption. For row and block typologies, the Pareto solutions have capacities of around 40 kWh. From the remaining inputs, green roofs with low to medium thickness are beneficial for all typologies. Window-related inputs are also in comparable ranges for all typologies. The street width is in the medium to low range for all typologies, indicating optimal solutions, especially for low-traffic areas with more space for trees.

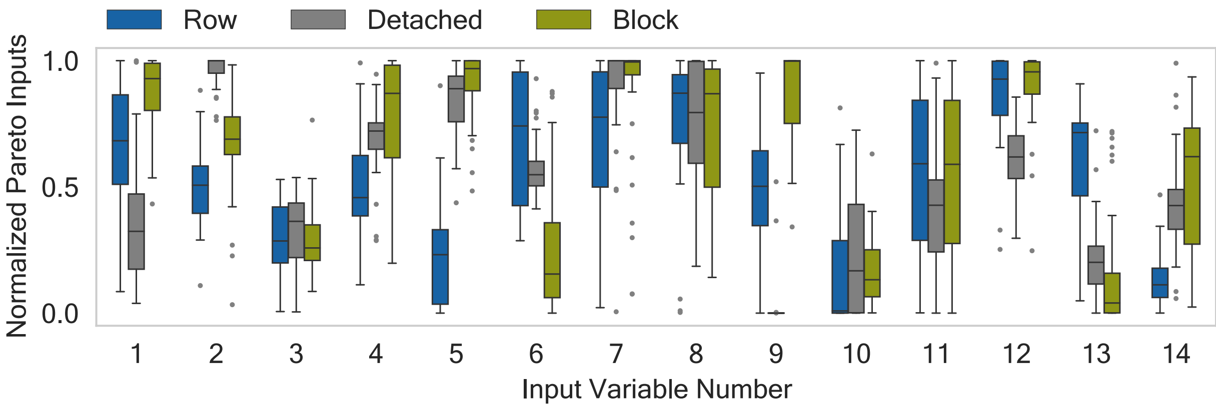

Figure 4: Boxplots of inputs leading to Pareto solutions. Input variable numbers refer to Table 2.

Limitations

In this study, we considered only one type of building arrangement per urban typology. Although these arrangements refer to a real area, they do not represent all possible configurations. Furthermore, the Use Cases define important boundary variables, such as the primary energy supply. This limits the transferability, as the multitude of types and forms within each typology introduces complexity that may give rise to distortions in the findings (Shi et al. 2021). The assumptions regarding the credits for generated electricity by PV systems significantly influence the outcomes of LCA and LCC. Additionally, volatile construction prices lead to uncertainties in the LCC results. The simulation model only offers a simplified representation of trees and their seasonal foliage dynamics. The complexity of tree behavior and the nuances of foliage throughout the seasons cannot be fully captured in the simulation, potentially limiting simulation accuracy. All case studies conducted herein are geographically constrained to Munich and rely on local weather data. Consequently, the results and conclusions drawn apply to this context.

Figure 4 compares the distribution of inputs leading to Pareto solutions. It does not allow the derivation of a certain input combination, as in MOO, optimal solutions are frequently found at the edges of the search space. However, it helps to understand which typologies are comparable regarding their trade-off behavior. Finally, there is a risk that the full range of Pareto solutions has not been discovered. Although a mathematically proven algorithm has been used, there may be solutions close to the Pareto property that were not identified within the MOO process of this study. However, such solutions could also inform urban decision-making.

Conclusion and outlook

This paper investigates how the extent of multi-objective trade-offs relates to urban typology. Neighborhood simulation models are examined for their Pareto fronts using multi-objective optimization and the associated inputs are compared. The results show that the trade-offs between lifecycle GWP, lifecycle costs, and outdoor thermal comfort differ significantly for the row, block, and detached typologies. In addition, the inputs can be used to conclude general typology constraints that support the achievement of Pareto-optimal solutions.

This holds several implications for urban planning practice and the utilization of interactions between the three aspects. Our study shows that each typology's unique characteristics significantly influence the optimal solution space. Hence, tailoring urban planning strategies to specific contexts is necessary. For instance, the block typology exhibits a narrower range of trade-offs, suggesting a more rigid relationship between thermal comfort and GWP. On the other hand, the row housing typology offers a more flexible trade-off space, emphasizing the need for balancing approaches during decision-making. The different input ranges of optimal solutions further underline the importance of typology-specific considerations. Tree and PV configurations differ significantly regarding trade-offs among GWP, costs, and outdoor thermal comfort. This contradicts one-fits-all approaches in urban planning, urging planners to strengthen their interdisciplinary and adaptable mindset. It is important to acknowledge the limitations of this study when generalizing the results. These include using simplified building geometries, assumptions about energy supply and construction costs, and the geographical constraints of the case studies.

In conclusion, this research advocates for an evidence-based and balanced approach to urban planning. Planners can design sustainable and resilient neighborhoods by recognizing and navigating the inherent trade-offs among environmental, economic, and social dimensions. To allow this, they need complete insights into the existing trade-offs, which is only possible when targets are shown next to each other and not aggregated into single values.

Future work should extend the idea of Urban Systems Exploration by incorporating typology properties into the Design Space. This would allow an in-depth understanding of the trade-off behavior, and new Use Cases could be introduced. For instance, building density could be parameterized to identify optimal configurations for the typologies and investigate the influence of density on the trade-offs. More detailed simulation models can be explored as computational power increases and simulation components improve, allowing a more detailed differentiation of design variables. Furthermore, sufficient visualizations for multi-objective decision-making should be investigated to make the findings easily accessible to urban planning practice.

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