INVESTIGATING URBAN HEAT ISLAND AND VEGETATION EFFECTS UNDER THE INFLUENCE OF CLIMATE CHANGE IN EARLY DESIGN STAGES

For Performance-Based Early Urban Design Decisions

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Abstract. Different criteria need to be considered for optimal strategies in the early design stages of urban developments. Under the influence of climate change, the urban heat island effect (UHI) is a phenomenon that gains importance in the early design stages. Here, different parameters, for instance, vegetation ratio in the city district and building density, play a significant role in the UHI effect. These parameters need to be quantified through different simulation tools for optimal climate adaptation and mitigation measures on the urban district scale. However, not all parameters and their influence are clear to the decision-makers and actors in the early design stages. Hence, we propose a Monte Carlo based sensitivity analysis (SA) and uncertainty analysis (UA) to show the significance of different parameters and quantify them. The SA aims to identify the major influencing parameters, whereas the UA quantifies the effect on the energy performance and indoor thermal comfort of occupants. The workflow is integrated into a collaborative design platform and applied in a case study to support decision-makers in the early design stages for new developments, densification, or refurbishment scenarios.

Keywords. Monte Carlo Simulation; Sensitivity Analysis; Uncertainty Analysis; Building Energy Simulation; SDG 13; SDG 11.

1. Introduction

Climate change and urbanization and the resulting transformations are challenges that need to be considered in the early design stages of buildings and urban districts. The density of the built environment, the resulting lower natural ventilation in the urban canyons, and the utilized materials in buildings instead of natural resources lead to warmer nighttime and temperature peaks in cities compared to a rural site,

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acknowledged as the urban heat island effect (UHI) (Nakano et al., 2015).

Designing new urban districts, retrofitting, and densifying the current stock requires a holistic approach that assesses the environmental impacts over the whole life cycle of buildings. In the life cycle assessment (LCA) of buildings, the usage stage of buildings is usually considered over a time span of 50 years. During this period, the morphology of urban districts might change. Hence, climate change and UHI need to be considered to optimize not only the outdoor spaces of the buildings but also the energy demand and thermal comfort of the occupants. In the usage stage, a double-side effect between buildings and the surrounding environment is present. Therefore, optimization of the buildings is dependent on the decisions made on the whole district or neighbourhood. Consequently, a performance-based approach in early design stages should be considered to enable a holistic method. The holistic method would allow climate adaptation and mitigation (SDG 13) measures on a district scale and help in developing sustainable cities and communities (SDG 11).

The influence of urban heat island (UHI) effect and climate change on the performance of buildings have been addressed by previous research in this field (Nakano et al., 2015). Adaptation measures from building to district level can reduce the impact of the changing climate and UHI on the occupants and the energy performance of buildings. This impact can be quantified through coupling building energy simulation (BES) and climate model tools.

Different climate model tools exist, which differ in their temporal and spatial resolution, and computational complexity. These climate models can be grouped into microscale and mesoscale tools. An obstruction in the early design stages is that detailed information is not available. For instance, the microclimate model tool Envi-met (Bruse et al., 1998) requires detailed information about the green infrastructure and the buildings. Furthermore, the tool is computationally time demanding. The output of the simulation results is limited to a small grid in a neighbourhood and the temporal resolution is not sufficient for an annual BES. Hence, the temporal resolution and computational costs limit its usability in BES.

Urban Weather Generator (UWG) is a physics-based climate simulation tool with low computational expense (Bueno et al., 2013) that requires limited input from the user. The performance of UWG is comparable to more computationally expensive mesoscale models (Nakano et al., 2015), and the tool can capture seasonal effects of the UHI phenomena (Bande et al., 2019). A workflow of integrating UWG in the urban modelling interface (umi) (Reinhart et al., 2013) was introduced in (Nakano et al., 2015). A sensitivity analysis was performed to identify the key parameters influencing UHI, energy performance, and thermal comfort under the influence of climate change. It was shown that the sensitivity of the parameters is case-specific and dependent on the investigated climate locations (Nakano et al., 2015). In another research paper, the authors performed a global sensitivity analysis based on Monte Carlo techniques on different input parameters to identify the significant ones for the case of Abu Dhabi (Mao et al., 2017). Hence, a general approach for different case studies and climate zones is required in the early design stages.

In this paper, we build upon previous research and introduce an iterative approach to support decision-makers in the early design stages. The approach and method are integrated into the Collaborative Design Platform (CDP) (Schubert, 2021) as a plugin, which is described in section 2. As proof of concept, we deployed our method in a case study in Kempten, Germany. Section 3 demonstrates the case study and its boundary conditions for an urban densification project in the early design stages. One iteration of the workflow is demonstrated in the case study with the results shown in section 4. Finally, the discussion and conclusions drawn are summarized in sections 5 and 6, respectively.

2. Method

The method in this paper is an iterative approach that assists the decision-makers in the early design stages. It is based on a global uncertainty and sensitivity analysis to aid urban planners, energy analysts, architects, and other decision-makers. The approach enables the identification of significant input parameters influencing the energy performance and indoor thermal comfort through sensitivity analysis (SA). Furthermore, the uncertainty analysis (UA) helps to recognise the potential of optimizing/defining the mentioned input parameters. The SA and UA in this work are performed by a Monte Carlo based technique and aims to aid the decision-makers to focus on specific parameters to improve the design decision and to retrieve more robust results. Through the combined SA and UA the decision-makers get feedback on the CDP in each design iteration, which enables them to define relevant parameters, and enhance the urban design. The readers are referred to (Schubert, 2021) for detailed information on the CDP.

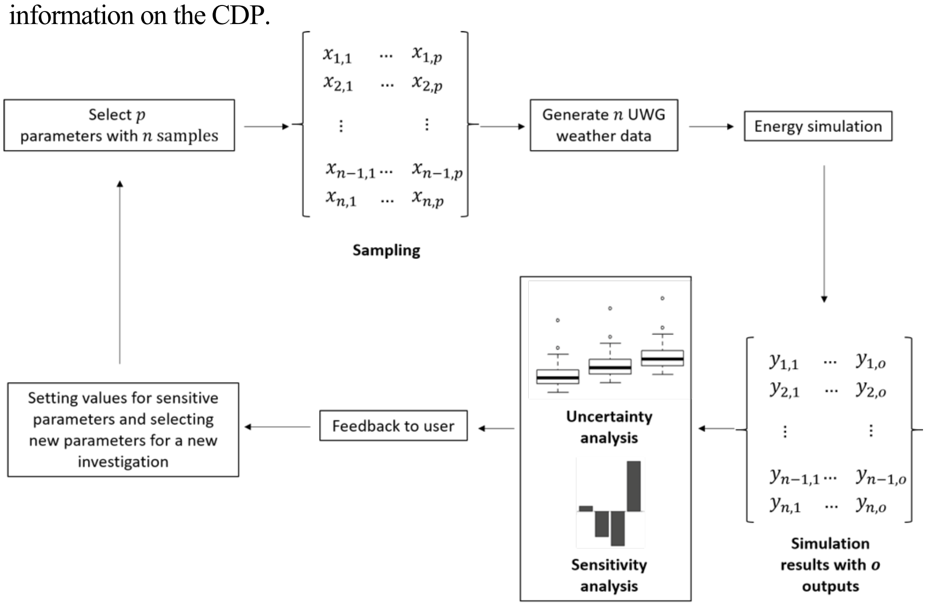

Figure 1: The Monte Carlo based sensitivity and uncertainty analysis

The different steps of the iterative method are summarized in Figure 1. In the first step, UWG parameters (p) that need to be investigated can be either set manually by the CDP user or general parameters are selected. In the next step, a sample matrix is generated through random sampling of the parameters in a pre-defined range. The sampling in this paper is performed through quasi-random samples generated through Sobol's algorithm (Sobol and Levitan, 1999). The matrix size is the multiplication of the number of samples (n) and the number of parameters (p). Through the sampled parameters n weather data is morphed for the investigated urban district. The simulations and generation of the morphed weather data are performed through UWG Python Application Programming Interface (API) which is part of Ladybug tools (Ladybug Tools, 2021). The UWG tool is also implemented in practical component based tools (e.g. Dragonfly (Ladybug Tools, 2021)) but for the results of this paper the original code was utilized to enable multiprocessing through the Python API. The simulated weather data are used in a building energy model (BEM) in Honeybee (Sadeghipour and Pak, 2013). The outputs from the BEM simulation build the basis for the UA and SA. In the proposed method, different output parameters (o) can be investigated. Furthermore, the UHI calculated by the morphed weather data can also be utilized for the SA and UA, which is out of the scope of this study. Through the results, the decision-makers can define values for the sensitive parameters and iterate the process with more detailed parameters.

3. Case study

The approach is investigated in a current urban district in Kempten, Germany. The district is planned to undergo densification and refurbishment of the current stock. The proposed approach aims to aid decision-makers in integrating microclimate performance into their design process. For the BEM simulations, Ladybug with Energy Plus backend was utilized. One of the current buildings was modelled for the investigation. Surrounding buildings and shadowing effects were excluded, as the procedure aims to only investigate the influence of the morphed weather data on the energy performance and quantify the uncertainties. The BEM is a multi-zone model and its geometry is illustrated in Figure 2. Three different constructions were analysed in our investigation, which are based on German standards GEG, KfW 55, and KfW 40. The U-values of the standards are summarized in Table 1. The output of the simulations is the net cooling and heating demand and overheating degree hours. As the investigated building is a multi-zone model, the zone with the highest overheating degree hours was selected for the results. The simulation boundaries were set based on the (DIN V 18599-10:2018-09, 2018) standard.

General urban parameters were selected for the UWG simulation. The selected parameters and the corresponding mean and standard deviation (std) are summarized in Table 2, the more detailed description of the variables is available in (Ladybug Tools, 2021). The broad range of the parameters aims to give the decision-makers feedback in the first design iteration. The sample size (n) for the input parameters was set to 100 based on previous research on Monte Carlo techniques in building simulations (Macdonald, 2009).

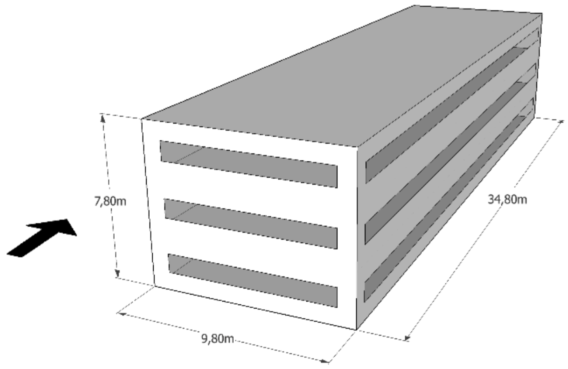

Figure 2: Investigated BEM located in Kempten, Germany

Energy standard	Base [W/m2k]	Wall [W/m2k]	Roof [W/m2k]	Window [W/m2k]
GEG	0.3	0.24	0.20	1.10
KfW 55	0.25	0.20	0.14	0.90
KfW 40	0.19	0.15	0.11	0.70

Table 1: Investigated energy standards and the corresponding surface U-values. The solar heat gain coefficient (SHGC) is set to 0.85 for all the investigated standards

Property	Description	Mean	Std
blddensity	Building footprint to urban area ratio	0.30	0.23
treecover	Tree coverage to urban area ratio	0.30	0.23
grasscover	Grass coverage to urban area ratio	0.30	0.23
albwall	Building albedo	0.50	0.23
glzr	Glazing ratio	0.50	0.23
vegroof	Roof vegetation coverage	0.50	0.23
albroof	Roof albedo	0.50	0.23
lattree	Fraction of latent heat absorbed by urban trees	0.50	0.23
latgrss	Fraction of latent heat absorbed by urban grass	0.50	0.23
albveg	Vegetation albedo	0.50	0.23
vertohor	Façade to urban site ratio	0.50	0.23
bldheight	Average building height [m]	17.50	7.20

Table 2: Investigated UWG input parameters (Ladybug Tools, 2021) and their mean, standard deviation after Sobol's sampling

The rural climate data were generated through the Meteonorm software (Remund et al., 2020). The moderate scenario Representative Concentration Pathway (RCP) 4.5 was selected for the two climate years 2020 and 2070. The selection of the climate years is based on the building's Reference Service Life (RSL) of the usage stage. The rural climate for Kempten builds the basis for generating the morphed weather data through UWG.

4. Results

4.1. UNCERTAINTY ANALYSIS

The simulation results for net heating and cooling demand, and overheating degree hours of the three construction standards are summarized in Figure 3 for the two years of 2020, and 2070. The uncertainty of the results is due to the 100 generated weather data through UWG. The simulation results demonstrate that the heating demand, and overheating degree hours as an index for thermal comfort are more robust to the generated weather data compared to cooling demand in our investigation. Furthermore, through only adapting higher energy standards the results do not get more robust. This shows the high impact of the microclimate situation on the investigated building.

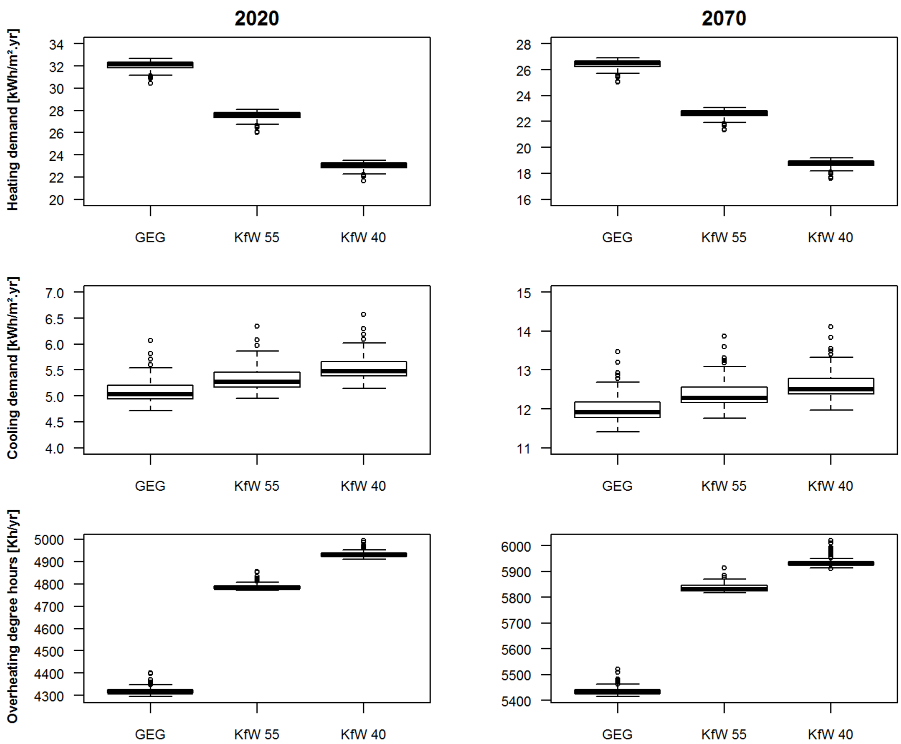

Figure 3. Net heating and cooling demand, and overheating degree hours of the three energy standards in the year 2020 and 2070

Comparing the simulations of the year 2020 and 2070 shows that the heating demand of the building will decrease due to climate change. However, the increase of the potential cooling demand especially in higher energy standards shows the requirement for climate adaptation measures.

4.2. SENSITIVITY ANALYSIS

Based on the results of the uncertainty analysis we investigated the sensitivity of the UWG input parameters on the cooling demand of the building. The selection of the SA technique is crucial, and the method should be selected carefully. Our investigation analysed correlation-based SA through Spearman's rank correlation coefficient (Spearman's rho) utilizing the Sensitivity package in R (Iooss et al., 2021). The sensitivity analysis was performed for both investigated years and the results are demonstrated in Figure 4. The SA shows that the building density in the urban district has the highest positive correlation to cooling demand in both years. This means that higher densities lead to an increase in the potential cooling demand due to the UHI effect. Tree and grass coverage decrease this negative impact on the cooling demand. The findings that these parameters have a significant influence on the cooling demand are consistent with previous research (Nakano et al., 2015).

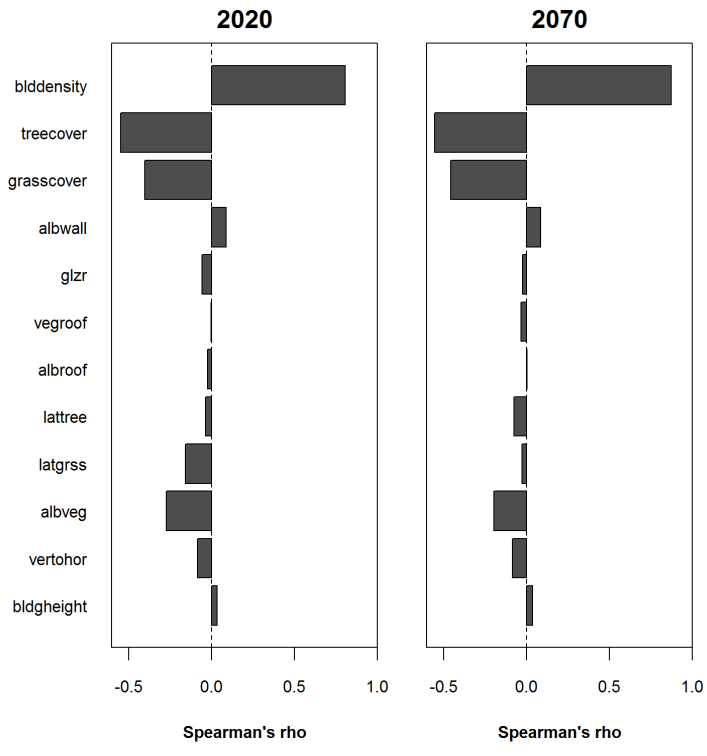

Figure 4. Sensitivity of different input parameters of UWG on the net cooling demand in the year 2020 and 2070 based on Spearman's rank correlation coefficient (Spearman's rho)

Comparing the SA for the climate years 2020 and 2070 demonstrates that the major sensitive parameters were consistent. The other input parameters investigated through the SA need to be reconsidered after defining the significant ones. As the SA coefficients are smaller compared to the three major ones. In this step, the decision-makers get feedback on these parameters on the CDP. After defining concrete values for the significant parameters, the process of UA/SA with other more detailed parameters should be iterated.

5. Discussion

The application of the method in the case study showed the significant influence of the microclimate on the energy performance of the building, especially the potential net cooling demand. The majority of residential buildings in Germany are not equipped with active cooling systems. Hence, climate adaptation measures both on the building itself and its surrounding should be considered to avoid the requirement for a mechanical cooling system. This requires a holistic approach considering both the building and its surroundings. Consequently, an optimization based on the energy performance of the building, indoor and outdoor comfort should be carried out to find the best fitting solution.

The results demonstrated that in a first iteration of the method building density, tree and grass coverage of the urban district had the highest sensitivity regarding the cooling demand. However, the effects are just based on the morphed UWG weather data. The limitation of our work is that the shadowing effect of higher building density or tree coverage on the energy performance of the BEM was not investigated. Furthermore, a more detailed investigation is required that allows parameter changes both in UWG and BEM. For instance, changing the albedo value of the buildings requires modification in both the BEM and UWG models. Another limitation of our approach is that the consideration of evapotranspiration effects in UWG is limited to the outside temperature. This could be adressed by using the recently developed Vertical City Weather Generator (VCWG) (Moradi et al., 2022). The same approach can be utilized by the VCWG tool to get more robust results considering the evapotranspiration effects.

6. Conclusion and future work

In this paper, we introduced a workflow for investigating the influence of different building and outdoor parameters on the energy performance and indoor comfort of buildings in the early design stages of urban districts through a Monte Carlo based SA and UA. The methodology was tested on a case study in Kempten, Germany. The results showed the importance of building density and green infrastructure in the first iteration of the design.

This study aimed to implement the insights and the approach in CDP. The microclimate simulations through UWG are not computationally expensive. However, the interdependence on building energy simulation and the UWG computation hinders real-time feedback to the decision-makers on the CDP. For future work, we aim to train a surrogate or meta-model of the BEM based on the microclimatic insights to deliver real-time simulation results. The meta-model will be based on different building parameters and variables from the surrounding environment. With this approach, a coupled simulation of building and the microclimate should be feasible.

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