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Connecting building density and vegetation to investigate synergies and trade-offs between thermal comfort and energy demand – a parametric study in the temperate climate of Germany

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Abstract. Climate change and increasing urbanization call for combined mitigation and adaptation measures. Therefore, this work shows a method to investigate affected aspects of urban space for their synergies and trade-offs. The focus lies on the interaction between building density and urban trees, as these are essential parameters for possible solutions. The combined, parametric simulation of indoor and outdoor spaces provides a more complete picture of the behavior of individual assessment aspects (e.g. indoor and outdoor thermal comfort, building energy demand). Overlaying the results allows us to identify interactions and to conclude on the effect of interventions such as building refurbishment. In this study, we apply the workflow to a generic neighborhood in Germany. Our results demonstrate a simultaneous behavior of indoor and outdoor thermal comfort, whereas there is a trade-off for heating energy demand. Increasing energy efficiency mitigated this trade-off in some density-green-space configurations. Our case study suggests the combination of green and gray interventions for achieving synergies that contribute to the sustainable transformation of the urban building stock. We conclude that during early planning phases, synergy potentials and trade-offs are already identifiable but context-specific, giving perspectives for further research in this area.

1. Introduction

Climate change mitigation and adaptation require an integrated approach to urban development [1, 2]. At the same time, growing population and urbanization call for an increase in urban density [3]. This implies rising sealed surfaces, increasing anthropogenic emissions, and high pressure on free urban plots. The associated acceleration of the urban heat island effect (UHI) can partly be compensated by preserving and adding vegetation such as trees in outdoor spaces [4, 5]. However, shading and evapotranspirative cooling can influence the energy demand of buildings depending on parameters such as building position and orientation relative to trees [6]. Thus, there is a need to investigate the dependencies causing trade-offs between the regarded aspects and to develop methodologies for identifying interventions with the potential for synergistic effects. In this paper, we focus on the relationship between building density and urban trees with regard to energy demand, indoor and outdoor thermal comfort. We present a parametric workflow for capturing interactions between buildings and the outdoor environment. By evaluating the results of this workflow, we aim to identify opportunities for minimizing trade-offs and enhancing synergies to optimize the performance of the building-outdoor system as a whole.

2. State of research

Most studies focus on single aspects of sustainability in the built environment [7]. For instance, low-carbon building design tends to neglect human health and comfort on the urban scale [8]. However, evaluating changes in building density should always consider the surroundings and the potential interactions and trade-offs to avoid negative consequences [9]. Felkner et al. showed a methodology to analyze different density configurations for urban areas regarding energy demand [10]. They found high density to be useful for reducing today's and future energy demands of buildings. Balancing building density and trees has been investigated by studies with focus on their interaction regarding outdoor thermal comfort [11] or their influence on energy demand of single buildings [12] and urban neighborhoods [13, 14]. Wong et al. showed variations of urban trees and urban morphology in Singapore, where they observed better performance in combined scenarios of increasing vegetation cover and building density [15].

For the Mediterranean climate of Tel Aviv, Natanian et al. showed the connection between the urban microclimate and the energy demand of buildings [16, 17]. They conducted building energy simulations for a single day to determine maximum cooling energy demands by obtaining urban weather conditions from simulations of the UHI effect. They mention a whole-year approach as a valuable next step for considering seasonal dynamics. The authors additionally name the issue of high computational costs as a constraint on the possible number of parametric simulations. Another parametric investigation of outdoor thermal comfort and building energy demand was done by Ibrahim et al. for the Egypt climate [18]. The results of their study showed that building density had a significant effect on both aspects. Fink et al. used a parametric workflow for the Key Performance Indicator (KPI) based evaluation of design scenarios [19]. They assessed KPIs for energy demand, indoor and outdoor thermal comfort separately and discussed their interrelations qualitatively.

Investigating the indoor-outdoor relationship in a combined approach implies the use of different tools and methods to connect the simulation components. In recent years, a number of tools have been developed to assess the urban heat island (UHI) effect. One of them is the *Urban Weather Generator* (*UWG*) [20]. The *UWG* allows accounting for various influences on urban climates such as surface types, building density, and vegetation coverage. It also calculates evapotranspiration and thus allows investigating the impacts of this predominantly outdoor effect on building energy demand. Additionally, this tool has the ability to simulate annual conditions, in contrast to microclimatic tools such as *ENVI-met*, which have high computational requirements [21]. Some of these detailed simulation tools also account for wind flows. In the case of *ENVI-met* a detailed Computational Fluid Dynamics (CFD) approach is used. This improves results but is hardly capable of a high number of parametric runs. Fast Fluid Dynamics (FFD) solvers, such as *GH Wind* [22], are able to provide a balance between accuracy and computational efficiency, although they do not offer the same level of detail as other approaches in simulating wind flow [23, 24]. Regarding building energy simulation, *EnergyPlus* (*EP*) is one of the most accessible tools, providing several interfaces to other software. One of these is the *Ladybug Toolbox* [25], which allows data exchange with *EP* through *Honeybee* and offers components for outdoor comfort calculation (*Ladybug*). The parametric environment *Grasshopper* for *Rhino 3D* allows to link the described tools and supports creating a parametric model, where simulations are automatically handled through plugins like *Colibri* [26]. The described approaches have been used to investigate several aspects of sustainable urban planning, but methodologies for systematically coupling information and evaluating the results in terms of synergies and trade-offs are yet to be developed [27, 28]. In this paper, we show a workflow for parametric KPI collection and evaluation of trade-offs and synergies, especially regarding urban trees and building density.

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3. Methodology

The aim of this investigation is to assess changes in indoor and outdoor thermal comfort due to different building densities and green configurations. The Universal Thermal Climate Index (UTCI) serves as KPI of outdoor thermal comfort [29]. In addition, building energy simulation is conducted to obtain heating and lighting energy demand (KPI: kWh/m^2.yr) and indoor thermal comfort (KPI: number of hours with Predicted Mean Vote (PMV) above a certain threshold). The results are analyzed with a visual multi-criteria approach to identify possible synergies and trade-offs. The methodology for coupling the necessary simulation components (see section 2) is outlined below and summarized in figure 1. The numbers in round brackets relate to the methodological steps in figure 1.

First, the parametric input parameters density and tree coverage (1) are used to initialize a generic neighborhood in the *Grasshopper* environment (2). In our model, we employ a 3x3 grid of buildings, resulting in a total of nine buildings. For tree placement, we initialize a 50m radius around the central building and create a 12x12m grid within this radius. We then remove grid points that intersect with streets or neighboring buildings, and randomly populate the remaining points with trees at the specified percentage to generate the final morphology. For instance, a 50% tree percentage means that trees are present at half of the remaining grid points, while the other half of the grid points is considered as grass-covered free space. Figure 2 provides a visualization of the morphology for an exemplary configuration of inputs. To evaluate the outdoor environment, we extract the parameters of building density, tree cover, and grass cover from the neighborhood model, as these have been shown to have a high level of sensitivity in *UWG* simulations [30]. The *UWG* simulation generates morphed weather data that contains UHI effects (3). This dataset of 8,760 hours is first screened for the hour with the maximum UTCI value over the year. Wind speed and direction during the identified hour serve as inputs for the FFD simulation (4). For the outdoor comfort calculation (5) we employ the described grid around the central building. Sky exposure at each point on the grid is simulated using the appropriate *Ladybug* component. The wind speeds are also determined for each grid point to account for local variations. The *UWG* weather file provides the input for air temperature and relative humidity. This workflow enables us to calculate the local UTCI for each grid point. The results are then averaged and represent the outdoor thermal comfort KPI for the whole neighborhood. In parallel, the *UWG* weather data serves as an input for the building energy and indoor comfort simulation (6). In this study, we only consider the central building. Shading from neighboring buildings as well as from trees (seasonal, see table 1 and section 4.2) is taken into account for the simulations. Finally, the obtained KPIs are analyzed visually to identify any synergies or trade-offs and to determine their relationship to the inputs (7).

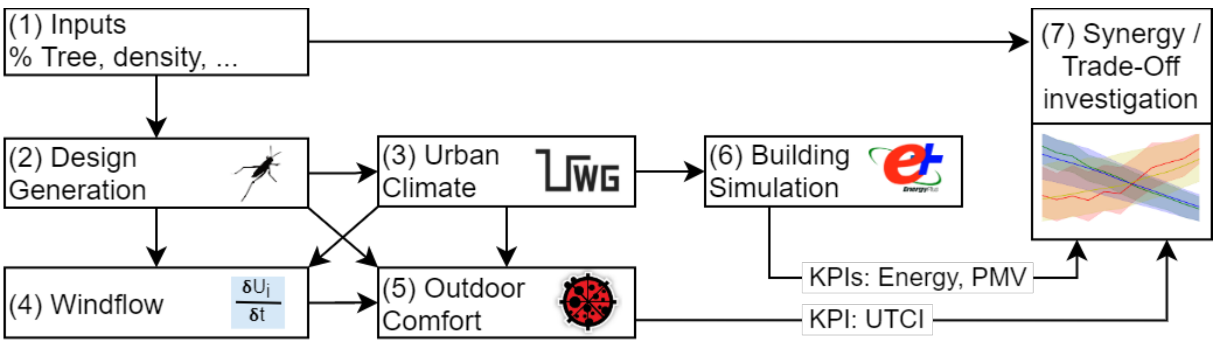

Figure 1. Summary of the parametric workflow within the *Grasshopper* environment.

4. Case study

We use a case study approach to show how our methodology allows investigating single objectives as well as the interactions of multiples. A generic residential neighborhood from the 1950s, located in Munich, Germany, is investigated. Spacing between neighboring buildings and percentage of trees around the central building are parameterized as described in section 3. Additionally, we consider a street width of 7m between the buildings. We use a typical urban tree in Germany (T. cordata) with an age of 50 years for this study. The dimensions of the tree and corresponding sources are given in 1. Section 4.1 gives the input parameters for our investigation, whereas section 4.2 explains the representation of trees in our simulations.

4.1. Input Parameters for the case study

The inputs for our parametric simulations are summarized in table 1. Figure 2 shows an example of a generated neighborhood with the surrounding buildings, streets, and trees for a certain input choice. For this study, we also analyze the impact of refurbishment on the synergies and trade-offs related to trees and building density. Thus, we also add the thermal properties of the envelope, represented by U-value sets for low and high energy standards, to the parameter space.

Table 1. Input parameters for the case study.

Simulation parameter	Input	Source
Building dimensions [m]	length: 40, width: 13, height: 17	-
Space between buildings [m]	[15, 95], stepsize: 8	-
Tree percentage [%]	[0, 100], stepsize: 10	-
U-Values [W/m^2.K] for	not refurbished: 1.3, 1.0, 1.0, 2.5	[31]
wall, roof, ground, window	refurbished: 0.15, 0.15, 0.15, 0.7	[32]
Window-Wall-Ratio | Operable	0.23 | 50%	[33]
Heating setpoint | Internal loads	20°C | 3.34 W/m^2	[34]
Anthropogenic heat $Q_{f,max}$ [W/m^2]	summer: 34.64, winter: 57.5	[35]
Tree dimension [m]	radius: 5.90, height: 14.2	[36, 37]
Tree crown transparency	summer: 0.1, winter: 0.55	[38]

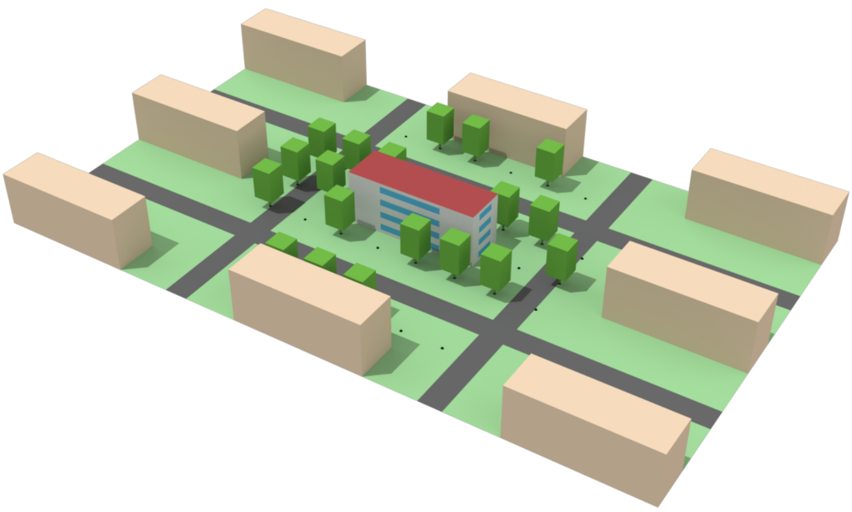

Figure 2. Simulation model for exemplary input parameters; space between buildings: 25m, tree percentage: 60%.

4.2. Representation of trees in simulation

The high number of parametric runs required for our investigation can be computationally intensive. This is particularly due to the need to integrate the seasonal variation in tree shading for deciduous trees in building energy simulations. One way to consider the seasonal changes is to use dynamic values for the tree crown transparency. This causes *EnergyPlus* to perform a detailed sky diffuse modeling [39] which results in simulation times of approximately 15 minutes per run with high tree percentages. Thus, we propose the integration of trees as simplified vertically split surfaces, whose ratios are set according to the transparency values chosen in table 1. This approach assumes that all surfaces are opaque (transparency=0%), allowing the use of a simplified sky diffuse model. Figure 3 shows the representation of summer and winter tree geometries in the energy simulation. We split the simulation into a summer and a winter simulation model to consider the seasonal geometries and simulate them separately for the respective months. After simulation, we recombine the results for the whole year. To test the accuracy of this assumption, we conducted a simplified experiment using the central building described in section 4.1 as the study subject. In this study, we systematically varied the tree percentage (ranging from 0 to 100%) at different distances (5, 10, 15, 20m) from the building. We conducted simulations for both the transparency schedule and for the split surfaces to evaluate their performance in terms of heating, lighting, and PMV.

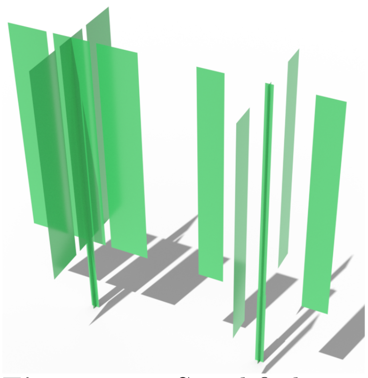

Figure 3. Simplified tree models; summer (left) and winter (right).

5. Results

This section explains our results, first regarding the tree representation in our simulations and second for the parametric runs. We separate the section for the different aspects (energy demand, indoor thermal comfort, outdoor thermal comfort) and their combined consideration.

5.1. Simplified tree representation

Figure 4 shows the results of the simplified tree representation approach. We observe high correlation and thus use the simplified representation of tree shading for further analysis. Hence, we reduce the energy simulation time to approximately 3 minutes per run. The PMV results (right plot in figure 4) indicate that the approach shows similar tendency as the detailed simulations. However, absolute results are not fully comparable.

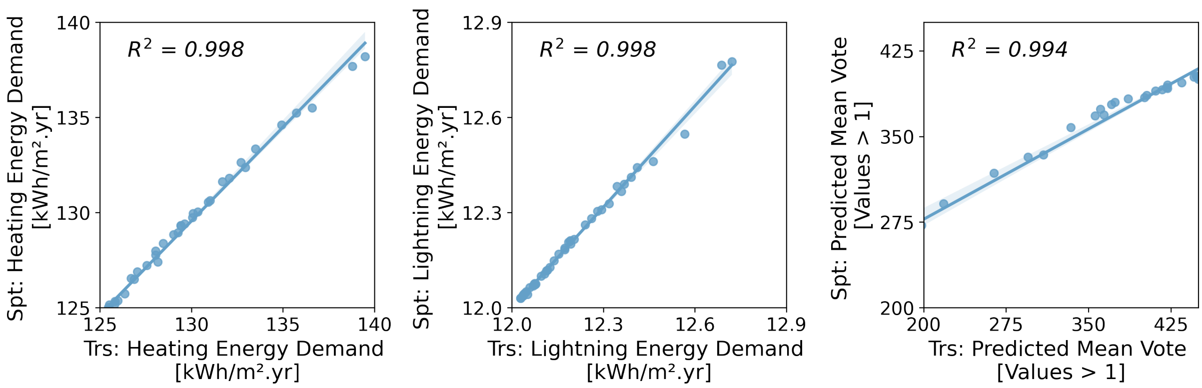

Figure 4. Validation of the shading simulation assumptions. Spt=Split surfaces approach, Trs=Transparent *EnergyPlus* schedule.

5.2. Building energy demand

Figure 5 shows the heating energy demand of the studied building, separated for the two energy scenarios (not refurbished, refurbished) in order to visualize the effects of space between buildings and tree percentages. Overall, trees affect heating energy demand up to maximum 10% for both energy standards. A constancy of the heating energy demand is observable for very low distances between buildings (equivalent to high building density), since tree placement is hardly possible in the area. As the distance between buildings increases, the influence of trees on heating energy demand becomes apparent. The presence of trees can lead to an increase in heating energy demand due to shading and evapotranspiration. The two scenarios exhibit different responses to this change. In the not refurbished scenario, there is a nearly linear increase in heating energy demand with increasing tree percentage. In contrast, the refurbishment scenario exhibits a slower initial increase, with a noticeable increase only observed at higher tree percentages.

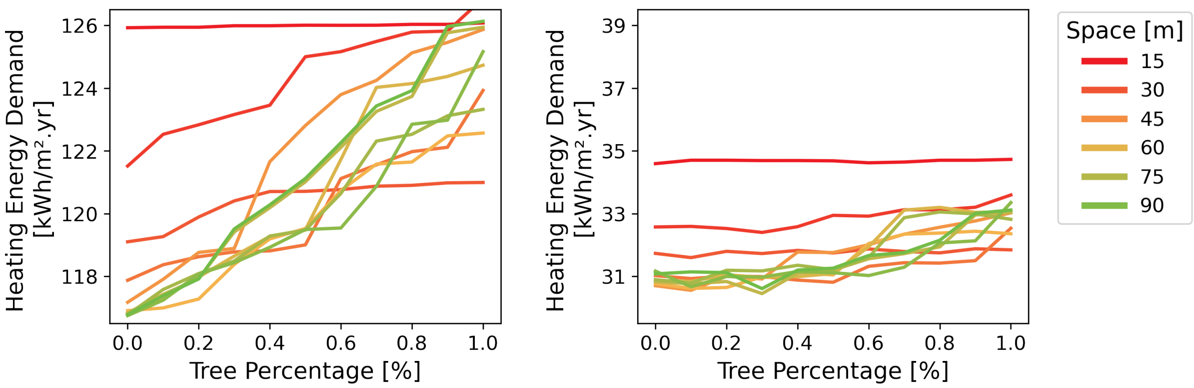

Figure 5. Heating energy demand for varying space between buildings (left: not refurbished, right: refurbished) depending on tree percentage.

5.3. Indoor thermal comfort

Figure 6 demonstrates that renovation can negatively impact indoor thermal comfort. This is due to the increased insulation, which reduces heat transmission to the outdoors and nighttime cooling. Mechanical ventilation has not been considered for this study. However, the addition of trees improves the median of PMV values more for the higher energy standard than for the non-refurbished scenario (26% compared to 21%). The low outliers in the data are likely due to high-density scenarios with limited opportunities for placing trees.

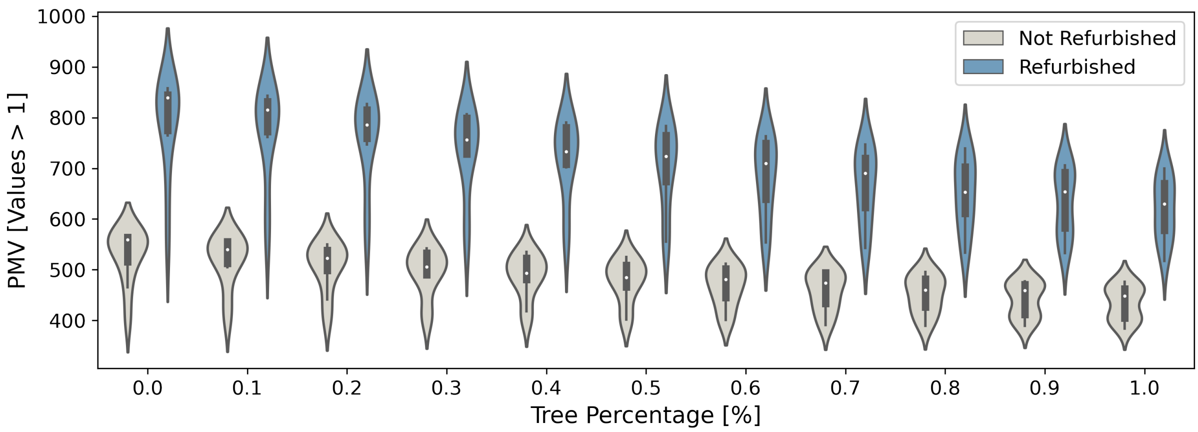

Figure 6. Spread of indoor thermal comfort for the two energy standards.

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5.4. Outdoor thermal comfort

For outdoor thermal comfort, we observe a consistent increase up to a certain building density due to the unavailability of free tree spots in the model for both refurbishment scenarios. In our case study, this is a spacing of approximately 35m. Further density reduction allows to add trees and has a significant effect on the UTCI results. UTCI continues to increase with increasing space between buildings when low tree coverage is applied. However, it stays constant or even decreases for high tree percentages (see figure 7). This is because the trees serve as shading objects in the low-density scenarios, where the shading from neighboring buildings does not cover the entire area. Additionally, the evapotranspirative cooling from the trees contributes to a further reduction of UTCI values. As a result, averaged UTCI can be reduced by up to 1.4K in the low-density scenarios of our case study.

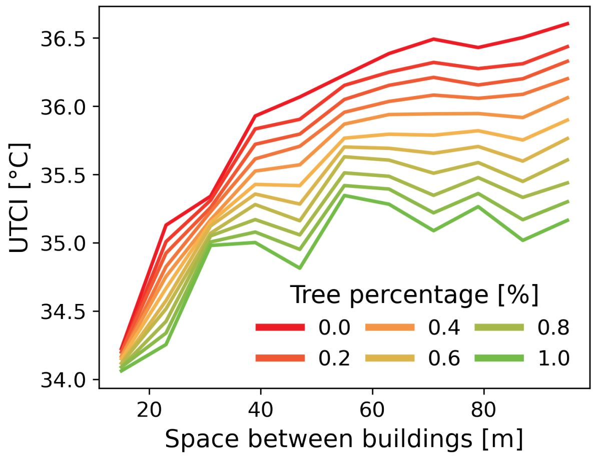

Figure 7. Outdoor thermal comfort; mean of the refurbished and not refurbished scenario.

5.5. Interaction on urban scale

For visualizing interactions and trade-offs between tree coverage and building density, figure 8 combines the means of heating/lighting energy demand and indoor/outdoor thermal comfort of the refurbished building. This illustrates the trade-off between the four aspects. While adding trees improves average comfort levels, it also leads to an increase in energy demand for the building. In addition, we observe a synergy between indoor and outdoor thermal comfort, with both metrics improving simultaneously as the tree percentage increases. It is important to mention that the intersection point of the lines is due to the scaling of the y-axes and cannot be interpreted as a break-even point that one should or should not exceed.

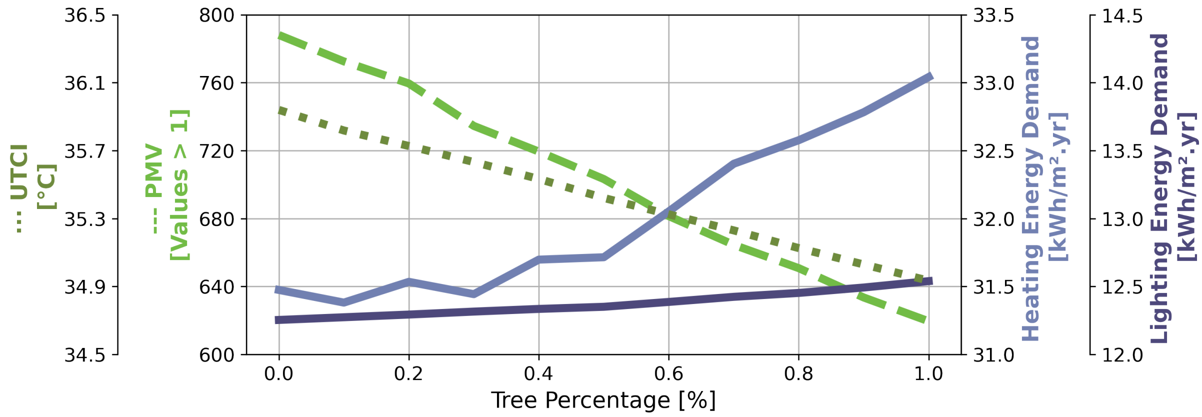

Figure 8. Dependence of mean heating/lighting energy demands and indoor/outdoor thermal comfort for the refurbished scenario on increasing tree percentage.

6. Discussion

In this section, we interpret the individual components and interactions in our results and compare them to previous research. We also discuss the limitations of our methodology.

6.1. Findings from the results

Regarding **tree seasonality in energy simulation**, we found the influence of the described modeling options for trees (transparency vs. split surfaces) on the simulation results to be acceptable. The simplification of surface shares instead of transparencies allows us to use a faster simulation setup, resulting in time savings for the simulations.This allowed us to expand the parameter space for our investigation and include more scenarios in the parametric run. In any case, it is important to consider trees in the energy modeling process, since we found notable deviations in the heating demand, especially for not refurbished buildings (up to 10%). An influence of trees in this order of magnitude is also noted by Pan et al. in the Canadian context [12]. The refurbishment options show significantly lower **heating energy demands** than the non-refurbished scenarios. Besides the general improvement of energy efficiency, the refurbishment reduces the deterioration in heating energy demand caused by trees. Thus, when trees are integrated into a neighborhood design, refurbishment can help to reduce the negative impact on heating energy demand. Trees enhance both refurbished and non-refurbished buildings in terms of **indoor thermal comfort**. Higher insulation levels tend to worsen indoor comfort results [40] but are necessary for reducing energy demands and thus achieving climate change mitigation goals [41]. Therefore, the integration of trees is a helpful measure, especially in the course of a renovation. Trees can reduce the deterioration in indoor thermal comfort coming from refurbishment and thus be an alternative to technical solutions. While high-density neighborhoods rarely allow the integration of trees, low-density neighborhoods profit from adding trees in terms of **outdoor thermal comfort**. This makes trees a suitable option for neighborhoods with high distances between buildings, as also suggested by other authors [19]. Additionally, scenarios with many trees lead to enhanced cooling through evapotranspiration. Our results suggest that a certain percentage of trees can prevent further deterioration of outdoor thermal comfort and even contribute to improvements in this aspect. The visualization of our results shows a clear **interaction on urban scale**. Improvements in outdoor thermal comfort also contribute to improving indoor thermal comfort. Nevertheless, there is a trade-off with heating and lighting energy demand. In our case study, this trade-off is small up to a certain tree coverage of about 50% for the refurbished scenario. Thus, a context-specific investigation is necessary to conclude on synergistic potential and to avoid trade-offs. This applies not only to the aspects considered in this study, but also to a much broader scope. For example, Fuso Nerini et al. observed this regarding interactions of energy development with the Sustainable Development Goals (SDGs) [42].

6.2. Limitations

The findings of our study are only applicable to temperate climates, such as those found in Germany. The simplified representation of trees in the energy model has only been compared with a transparency approach. Validation with measured data as well as comparison to other methodologies, e.g. shading coefficients as used in [43] should be done. Furthermore, the usage of the FFD solver for wind simulation is a balancing act between accuracy and computational costs. Its usability has been shown in urban environments before, but results may deviate from detailed CFD simulations [22]. Nevertheless, the usage in our case study can be justified, as wind flow is only used for the calculation of UTCI index, which shows minor sensitivity to low wind speed in warm outdoor conditions [29]. The consideration of evapotranspirational cooling from trees is simplified in the UWG, which leads to averaging over the whole neighborhood. This approach is acceptable for urban simulations as done here, but for local hot spot investigation, more detailed tools are necessary [44]. We considered 50-year-old, large-sized trees for the simulations. It is important to mention that implementing such large trees is not always possible in existing urban neighborhoods. Additionally, many of the ecosystem services (e.g. shading, transpiration, CO_2-removal) the trees provide increase with tree age [45]. Therefore, the benefits identified in this study may take time to fully develop, or may be reduced if a different tree species is selected due to a lack of space.

7. Conclusion

Urban neighborhoods represent highly interconnected systems. This study showed a combined approach for building and outdoor simulations to obtain insights into single aspects as well as interactive behaviors through parametric simulations. Our case study shows the connection of density and tree coverage in urban neighborhoods and how synergies and trade-offs for the considered aspects (building energy demand, indoor and outdoor thermal comfort) develop. The results demonstrate that these trade-offs and synergy potentials are already visible in early design phases. Thus, the evaluation of multiple-objectives in early design phases supports the development of a design space for further assessment of preferable options [46]. We highlight the importance of a context-specific investigation, as our study showed minor trade-offs for heating energy demand up to a certain tree percentage. Therefore, combined modeling of indoor and outdoor spaces is necessary to understand the holistic impact of interventions. Our case study shows the significant influence of trees on building heating energy demand (up to 10% increase) and thermal outdoor comfort (up to 1.4K averaged UTCI reduction). Indoor thermal comfort is improved for refurbished as well as not refurbished scenarios. Thus, considering trees in urban planning in the German context has high potential concerning the transformation of existing urban neighborhoods, where several interventions are necessary to achieve climate change mitigation goals while enhancing climate change adaptation.

To allow for more detailed accounting of Leaf Area Index (LAI) and blue infrastructure, future work should focus on modeling and simulation improvements such as the further development of *UWG*, as also proposed by Bi et al. [8]. Coupling wind and building energy simulation would also be valuable to account for model dependencies. Additionally, a systematic representation of the workflow inputs and outputs would facilitate collaboration with experts who may not be familiar with urban simulation environments like *Grasshopper*. Furthermore, methods for identifying and quantifying synergies and trade-offs between different aspects of the built environment, as demonstrated in this study, would be useful for both physical design and policy decision-making [1]. As a result, designers and policy makers should adopt a more systemic perspective on the built environment [27]. Our methodology intends to serve as a basis for investigating other neighborhood types and climates, thus enabling the identification of optimal configurations for the composition of density, vegetation, and building characteristics in specific contexts. However, identifying further connected aspects for integration needs to be done. The Socio-Ecological-Technical Systems approach might serve as a basis for this development [47]. Finally, integrating a life cycle perspective into investigating synergies and trade-offs is necessary to avoid neglecting long-term effects.

Acknowledgments

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