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Co-Creating Climate-Resilient Streets: Digital Twin-Based Simulations for Outdoor Thermal Comfort

Koldo Urrutia-Azcona [1,*], Valentina Bonetti [1], Mohammad Mizanur [1], Nele Janssen [2], Niall Buckley [1], Mark De Wit [1], Kieran Murray [1] and Niall Byrne [1]

[1] Integrated Environmental Solutions Limited, D01 A8N0 Dublin, Ireland
[2] Stad Leuven, Professor Roger Van Overstraetenplein 1, 3000 Leuven, Belgium
* Correspondence: koldo.azcona@iesve.com

Highlights

What are the main findings?

- A streamlined digital twin workflow enables rapid simulation of nature-based solutions and surface materials for outdoor thermal comfort in public spaces.
- Participatory, temporary interventions can significantly improve thermal comfort during extreme heat, with effects varying by season and location.

What are the implications of the main findings?

- The integrated approach supports evidence-based, participatory planning for climate adaptation in cities, making technical results accessible to planners and citizens.
- High-resolution, scenario-based analysis is essential for designing effective, context-sensitive urban interventions that enhance resilience and well-being.

Abstract

Rapid urbanization and climate change are intensifying heat exposure in cities, making effective adaptation strategies essential. This study presents a streamlined digital twin modeling framework for simulating the impact of nature-based solutions (NBSs) on outdoor thermal comfort, developed within the Intelligent Communities Lifecycle (ICL) software suite. The approach automates the import of urban geometry from OpenStreetMap and integrates geolocated weather data, enabling users to efficiently test scenarios involving NBSs and surface material modifications. Outdoor thermal comfort is quantified using the Universal Thermal Climate Index (UTCI), with results visualized through an interactive cloud-based 3D platform to support participatory urban planning. The methodology is demonstrated in Meunierstraat, Leuven (Belgium), where three planning alternatives are compared across seasonal extremes. Simulations show that targeted NBS interventions, particularly temporary participatory measures, can improve thermal comfort under extreme heat. However, the benefits are seasonally dependent and spatially heterogeneous, emphasizing the value of high-resolution, scenario-based analysis. This integrated workflow enhances both technical evidence and stakeholder engagement. While the tool is capable of linking outdoor comfort improvements with building energy performance and carbon emissions, the present paper focuses solely on the outdoor thermal comfort results, leaving indoor–outdoor coupling analysis as a direction for future work.

Keywords: digital twin; nature-based solutions; outdoor thermal comfort; UTCI

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1. Introduction

Scientific studies demonstrate that climate change is progressively altering living conditions around the globe, making speeding up mitigation and adaptation efforts critical. Regarding climate adaptation, this global challenge demands effective climate action deployment at the local level, placing urban environments at the heart of this effort. Currently hosting 4.2 billion people, cities are expected to reach over 6.7 billion urban inhabitants by 2050 (~70% of the global population), with urban communities—especially marginalized groups—suffering disproportionate economic, social, and environmental impacts from new climate patterns [1,2].

The latest IPCC report states that global warming and population growth in already-warm areas are the primary drivers of increased heat exposure for humans [1]. For example, Knowlton et al. project that rising temperatures in New York could increase mortality rates by 47% to 95% by 2050, compared to 2007 [3], equating to 3500 to 27,000 heat-related annual deaths in the US due to the combined global greenhouse effect and the urban heat island effect [4]. Accordingly, improving the outdoor thermal comfort of our cities is one of the key challenges in climate adaptation efforts, particularly for addressing localized heat exposure.

To achieve better microclimatic conditions in cities, climate-adaptive solutions need to be implemented. In particular, Sailor et al. identify a combination of NBSs and albedo enhancement as a highly impactful strategy for reducing heat-related mortality [5]. In support of such impact estimates, computational simulation tools can provide precise and comprehensive assessments of the effects of urban design and NBSs on microclimatic conditions, considering a wide range of scenarios and adaptation measures [6]. These physics-based tools are increasingly providing robust evidence to urban planners, developers and local authorities and must become a cornerstone in public-space planning for thermal comfort. Within a virtual environment, such tools enable decision-makers to maximize the efficiency of deployed resources and the impact of real-world actions.

Over the last decade, advances in computational simulations have enabled quantitative analysis of outdoor thermal comfort using techniques like computational fluid dynamics (CFD) [7] combined with improved 3D interfaces that allow a better understanding of local microclimate impacts [6,8]. State-of-the-art tools for assessing outdoor thermal comfort have significantly advanced our understanding of urban microclimates [9–13], but they often require high-fidelity data, complex workflows, and have a lack of integration with indoor thermal performance.

This study introduces a streamlined modeling framework within the iCD software (version 2025.2) —well recognized for its capabilities in energy efficiency and decarbonization— that automatically retrieves building geometries from OpenStreetMap and selects geolocated weather files for outdoor thermal comfort simulations. This automation allows users to concentrate on impactful interventions such as NBSs and surface material adjustments. Furthermore, results are delivered through interactive, cloud-based 3D visualizations, enabling intuitive communication with planners, stakeholders, and citizens—an essential step for participatory urban design. The primary advantage lies in usability and accessibility. Importantly, the approach addresses the key gaps in existing research by simplifying the workflow and actively involving community participation, thereby innovating beyond prior studies that often lack practical integration with stakeholder engagement or focus narrowly on technical aspects. The novel contribution of this work is combining a simplified digital twin workflow with participatory planning support to co-create climate-resilient designs.

Following this introduction, Section 2 outlines the key aspects of the software development and provides a description of the workflow. Section 3 applies this workflow to the case study of the Leuven municipality (Belgium), presenting simulation results for various planning alternatives. Section 4 discusses these results, evaluates the capabilities of the proposed tool, and offers context for interpretation. Finally, Section 5 summarizes the main findings and their implications.

2. Materials and Methods

Our society's trend toward digitalization is influencing how we plan and operate cities. Digital twin technology is establishing itself as one of the most effective approaches to tackle these tasks, especially in construction and energy domains, since it can represent key elements of the real world and offers simulation capabilities for planning, as well as real-time reporting for optimized operation [14–17]. The authors of this research assert that digital twin technology is applicable to configuring public spaces and NBSs, specifically for analyzing outdoor thermal comfort. Accordingly, a combination of tools from the Intelligent Communities Lifecycle (ICL) suite (developed by Integrated Environmental Solutions, IES), was chosen for the study [18].

The methodology is structured in three parts: (1) development and integration of the outdoor thermal comfort calculation functionality in the ICL environment; (2) the simulation process followed within the software to obtain the results, including the steps of modeling the urban environment, simulating outdoor comfort, and visualizing the results; (3) the case study application in Meunierstraat, Leuven.

2.1. Integration of Outdoor Thermal Comfort Calculation into the Engine

The Universal Thermal Climate Index (UTCI), as defined by COST Action 730, is used as the metric for outdoor thermal comfort [19]. The UTCI is defined as the equivalent temperature of a reference environment (50% relative humidity, no wind, radiant temperature equal to the air temperature) that elicits the same physiological response of the actual environment. UTCI is computed from four inputs: dry-bulb air temperature, humidity, wind speed and mean radiant temperature (MRT).

In this first implementation of UTCI calculations integrated into IES tools, a simplifying assumption is applied: dry-bulb air temperature, humidity and wind speed (at 10 m high) are taken directly from the weather data and considered uniform over the entire model domain. Instead, the mean radiant temperature is calculated for each point of a model grid using the algorithm described below, which combines longwave and shortwave radiation contributions from the surroundings.

The first step in computing MRT for a specific point is obtaining the contribution from longwave radiant heat exchanges (MRT_{lw}). This is a weighted average based on "view factors", defined here as the fraction of spherical view occupied by each surrounding surface "*i*" as seen by the point where UTCI is calculated. A ray-tracing solution establishes the view factors of the sky, ground, and other surfaces visible from that point. Then, averaging over all N surfaces yields:

$$MRT_{lw} = \left[\sum_{i=1}^{N} F_i {T_i}^4 \right]^{\frac{1}{4}}$$

where F_i is the view factor of surface i and T_i is the temperature of surface i, including ground surfaces. In this calculation, all surfaces are treated as black bodies (no reflection), and the sky is also approximated as a black body using the same sky temperature model used by IES Apache [20]. The surface temperatures could be extracted from dynamic building simulations, but by default they are set equal to the ambient air temperature in this study. This simplification was initially adopted to reduce complexity; however, the authors acknowledge that it limits realism and discuss its implications in Section 4 (i.e., potential underestimation of surface material effects).

The second step computes the delta T caused by shortwave radiation reaching a person (approximated at the point on the model grid, either on the ground or a roof area). The "SolarCal" model (from ASHRAE-55 Standard [21]) is used to obtain the effective radiant field (ERF, the shortwave radiation on the body, in W/K), including shading and ground reflectance [9]. A ray-tracing method determines whether each point is sunlit or shaded for a given hour. The ERF is then used to calculate an increase in MRT due to solar gain. The final MRT used in the UTCI equation is:

$$MRT = MRT_{lw} + \frac{ERF}{f_{eff} h_r}$$

where f_{eff} is the fraction of the body's surface that can radiate heat (0.725 for a standing position) and h_r is the radiative heat transfer coefficient (here a default of 0.6012 W/m^{2}K).

Regarding model resolution, the simulations use a high-resolution grid, with points spaced approximately 1 m apart in plan view across the study area (covering the sidewalks and street). For longwave radiative exchange, each grid point samples 1000 rays per hemisphere using a ray-tracing algorithm with one diffuse bounce (first-order interreflection). These values for grid density and ray-tracing configuration were selected to balance geometric detail and computational feasibility. Sensitivity tests using coarser spatial grids indicated that key UTCI outcomes varied by no more than 0.1 °C, suggesting the results are robust to small changes in resolution.

2.2. The Outdoor Thermal Comfort Simulation Process

Once the algorithms are integrated into the simulation engine, the workflow begins by automatically importing the urban geometry from OpenStreetMap and selecting an appropriate geolocated weather file for the site. These inputs, together with user-defined NBS configurations and surface albedo properties, are processed to compute radiation fluxes and surface temperatures, and the resulting spatial UTCI patterns are visualized through an interactive 3D web interface for intuitive interpretation:

- Modeling in iCD (version 2025.2): The model is developed by combining the automatic urban geometry import from OpenStreetMap with NBS and public-space planning details obtained from Leuven municipality.
- UTCI simulation: After finalizing the model, the simulation is launched via a dedicated dialog where users select a date/time and optionally restrict the analysis to a sub-area. Progress can be monitored and canceled if needed. Once complete, the results are automatically displayed on the 3D model for immediate interpretation. By iterating between modeling and simulation, the tool allows users to explore the influence of trees, landscaping, and building orientation on thermal comfort and identify optimal design solutions.
- Results visualization: The tool supports exporting results for advanced visualization and online access. For instance, simulation outputs can be saved as a .glb file and imported into the iCIM platform (via Analysis > UTCI Visualization) to enable comparative analysis across scenarios in a web-based 3D viewer. For detailed quantitative evaluation, the retained simulation data can be opened in external software like ParaView [22] (version 6.0.1, see Figure 1), which allows inspection of spatial variations and side-by-side comparison of planning alternatives (i.e., winter vs. summer conditions).

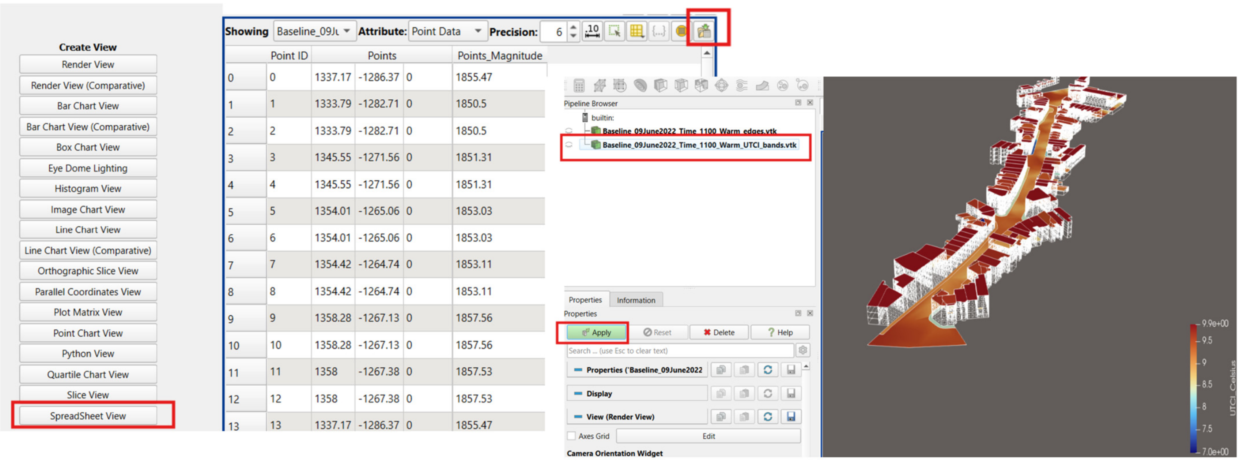

Figure 1. Caption of results processing in ParaView.

2.3. Case Study: Meunierstraat, Leuven

To demonstrate the workflow in a real planning context, this study focuses on Meunierstraat, a street in Leuven, Belgium, where outdoor thermal comfort simulations supported a collaborative planning process. The objective is to compare three planning alternatives with different configurations of NBSs and surface properties (i.e., albedo, emissivity) to evaluate their impact on outdoor thermal comfort. By providing evidence through simulations, planners can make informed decisions between alternatives using an intuitive 3D environment, which can also be showcased during citizen workshops as a communication and discussion tool.

Figure 2 shows a Google Earth view of the pilot site. The planning alternatives for Meunierstraat are structured in three stages of street renovation and renaturalization (Figure 3 shows pictures from the co-creation process):

- Baseline (pre-2023): The original street configuration, characterized by asphalt surfaces and minimal NBSs (little to no greenery).
- Planning alternative 1 (A1, 2024–2025): A quick participatory temporary intervention, introducing new NBSs, reducing car-parking areas, reusing construction materials, and implementing environmental monitoring. In quantitative terms, A1 added several street trees in large planters (approximately 58 trees and bushes), removed approximately half of the on-street parking spaces to create space for green features, and installed inexpensive sensors for ongoing microclimate monitoring.
- Planning alternative 2 (A2, planned for 2026): A comprehensive permanent redesign informed by the A1 pilot, continuing the participatory approach for a finalized street layout [23]. A2 includes permanent planting of additional trees (approximately 79 trees and bushes), replacement of most asphalt with high-albedo or permeable materials, and embedded infrastructure for long-term environmental monitoring.

The entire process is supported by the digital twin of the street, with outdoor thermal comfort simulations for each planning alternative following the UTCI standard. Weather data are derived from typical meteorological year files (EPW format). For each alternative, three scenarios are simulated to represent seasonal extremes: the hottest day (11 August at 15:00), the coldest day (13 February at 12:00), and a mild day (9 June at 11:00), based on hourly temperature extrema from the weather file. Local sensor data are used to validate the simulations and ensure the results are meaningful and reliable [24]. Specifically, four temperature/humidity sensors were deployed along Meunierstraat (at 1.5 m height) logging data every 10 min over the year. These field measurements indicate that the simulated baseline UTCI values (Supplementary File) align with observations to within approximately 1–2 °C during the chosen hours, providing confidence in the model's accuracy (see Section 4 for validation reflections).

Figure 2. Google Earth overview of Meunierstraat pilot, Leuven.

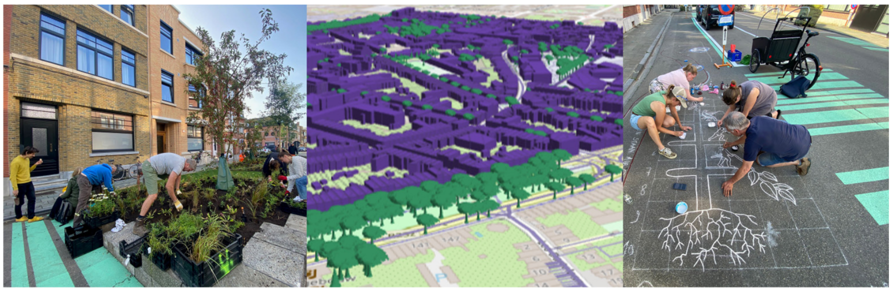

Figure 3. Co-creation process in Meunierstraat, including 3D modeling as a participatory tool.

The analysis of outdoor thermal comfort improvements between planning alternatives is based on simulated UTCI data. For each scenario (cold, mild, hot), the analysis compared baseline conditions with the two planning alternatives (A1, A2) by evaluating (i) absolute UTCI values; (ii) the distance to the comfort band (defined as 9–26 °C UTCI); (iii) changes in UTCI stress categories; (iv) extreme values; and (v) the share of points improved versus worsened. Statistical significance of differences was assessed using the Wilcoxon signed-rank test on the distance-to-band metric [25]. This comprehensive approach quantifies both the magnitude and significance of thermal comfort changes attributable to the proposed interventions, providing robust evidence for the municipality's planners to inform urban climate adaptation strategies.

3. Results

After applying the simulation process described in Section 2.2 to the case study (Section 2.3)—comparing the baseline, A1, and A2—a comprehensive dataset of UTCI values was obtained. The analysis systematically compared baseline conditions with both planning alternatives across three seasonal scenarios, enabling a detailed investigation of how each intervention affected outdoor thermal comfort.

3.1. UTCI Values Under Different Scenarios

Across all seasons, the baseline UTCI values differed notably from those under the planning alternatives. In cold conditions, the baseline median UTCI was 6.39 °C, with A1 yielding 6.35 °C and A2 dropping to −1.72 °C. In the mild scenario, the baseline median was 8.96 °C, A1 was 8.92 °C, and A2 was 8.61 °C). Notably, this "mild" scenario median of ~9 °C is just at the lower comfort threshold, effectively making it a cool scenario in terms of comfort –the term mild is kept for consistency with the chosen day but acknowledged it was a relatively cool day. In hot conditions, the baseline median was 33.9 °C, with A1 and A2 reducing this to 31.6 °C and 31.7 °C, respectively. These results indicate that while the mild scenario showed negligible changes, the hot scenario demonstrated meaningful cooling benefits from both interventions (especially A1), and the cold scenario revealed a substantial cooling effect for A2 that actually pushed conditions further from comfort.

3.2. Distance to Comfort Band

Analysis of the distance to the 9–26 °C comfort band revealed that both the cold and hot scenarios remained far from optimal comfort, whereas the mild scenario was near the lower comfort bound. In cold conditions, the mean distance to the comfort band increased under both alternatives (due to already cold conditions becoming colder with interventions). In hot conditions, A1 reduced the mean distance by 0.23 °C (median improvement of +0.10 °C), indicating a small but tangible shift toward comfort, whereas A2's reduction was marginal (virtually the median change). Mild conditions showed only minor changes (of the order of a few hundredths of a degree). While these numbers may seem small in absolute terms, even fractional UTCI improvements can indicate heat mitigation in localized spots. However, changes under ~0.5 °C are likely below typical human perceptibility for thermal stress, so such small improvements may not translate to noticeable comfort differences.

3.3. Changes in UTCI Stress Categories

Transitions between UTCI stress categories (i.e., from "moderate heat stress" to "no thermal stress") were infrequent. In cold scenarios, no points moved into a warmer stress category (no stress improvement), and indeed some points shifted to worse categories (colder stress) with interventions: A1 saw 11.7% of points worsen by at least one category, and A2 saw 25.5% worsen (consistent with the overall cooling effect of added trees in winter). In the mild scenario, conditions were near the edge of the comfort band, so category changes were minimal. In hot scenarios, some improvements were observed: under A1, about 3.9% of points improved by one UTCI stress category (i.e., from "strong heat stress" down to "moderate heat stress"), compared to 2.6% under A2. These modest category shifts reflect that most areas remained in heat stress categories even after intervention, although the severity was slightly reduced.

3.4. Extreme Values and Variability

Analysis of the extreme values highlighted substantial local variability in outcomes. In the cold scenario, the differences in UTCI at individual points (A1 minus baseline) ranged from −10.74 °C (a point that became much colder under A1, a shaded area) to +6.24 °C (a point that became warmer, perhaps due to reduced wind or radiation trapping). Under A2 in the cold scenario, the extremes were even more pronounced (consistent with its stronger interventions). In the hot scenario, the largest localized cooling was −3.3 °C under A1 (i.e., a specific location experienced a 3.3 °C drop in UTCI compared to the baseline), and some spots showed local warming up to +2.3 °C (areas where an intervention might have reduced airflow or reflected heat toward a point). A2 exhibited the largest cooling of −3.5 °C and warming up to +2.2 °C at individual points. These extremes underscore the spatial heterogeneity of intervention impacts: even within the same street, some locations benefit while a few may slightly worsen, depending on the micro-scale interplay of shade, wind, and surface changes.

3.5. Share of Points Improved vs. Worsened

Defining "improvement" as a reduction in distance to the comfort band (i.e., conditions moving closer to the 9–26 °C range), A1 outperformed A2 across all scenarios in terms of fraction of area improved. In the hot scenario, 89.5% of points showed improved comfort under A1, versus 37.7% under A2). In cold conditions, paradoxically, many points moved away from the comfort band (because added NBS further cooled an already cold environment): only 63.2% of points improved under A1 (implying 36.8% worsened), and 44.9% improved under A2 (meaning over half got colder relative to comfort). In the mild scenario, the baseline was so close to comfort that changes were marginal; thus, the share improved was not meaningful to report (virtually 50/50 within rounding error). The notably higher percentage of points improved with A1 in the hot scenario suggests that the temporary interventions in A1 were very effective at broadly mitigating heat, whereas the final design (A2) had a mix of cooling and some unintended warming spots, leading to a lower net fraction of improvement.

3.6. Seasonal Context and Statistical Significance

Seasonal analysis confirmed the most pronounced benefits of NBSs occurred in the hot scenario, whereas the mild scenario showed negligible change and the cold scenario could incur negative effects. A1 consistently delivered broader and more significant gains in thermal comfort than A2 in hot conditions, while in cold conditions A1 had a smaller negative impact than A2. The Wilcoxon signed-rank tests (applied to the distributions of distance-to-comfort for each pair of scenarios) indicated statistically significant improvements for A1 in both cold ($p \approx 2.4 \times 10^{-6}$) and hot ($p \ll 0.001$) scenarios (relative to the baseline), and for A2 in the hot scenario ($p \ll 0.001$). Changes in the mild scenario were not statistically significant ($p \approx 1.0$) [25]. It should be noted that the grid points used in these tests are not independent samples—there is spatial correlation of the UTCI values over the street—so the significance levels (p-values) may be overly optimistic. In other words, the Wilcoxon test here might exaggerate the statistical significance due to spatial autocorrelation. The authors acknowledge this limitation and interpret the statistical results with caution.

3.7. Summary of Key Differences

To visualize the overall impact of each intervention scenario on thermal comfort, Figure 4 presents the median UTCI in each scenario for the baseline, A1, and A2. As shown, in the hot scenario, both A1 and A2 yield substantially a lower median UTCI than the baseline (improved comfort), whereas in the cold scenario A2's median UTCI is dramatically lower than the baseline (indicating much colder perceived conditions), with A1 roughly equal to the baseline. The mild scenario shows almost no difference among the three cases.

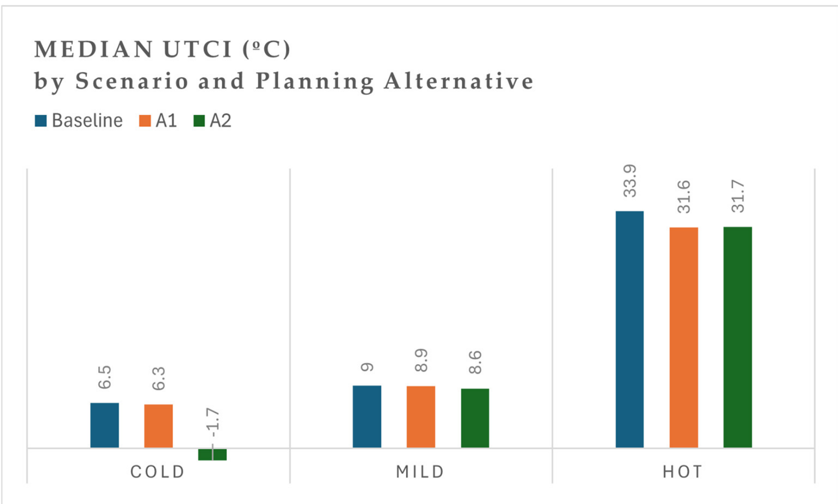

Figure 4. Median UTCI by scenario and planning alternative (baseline vs. A1 vs. A2).

The simulation results demonstrate that temporary, participatory NBS interventions (A1) can offer substantial improvements in outdoor thermal comfort during extreme heat events. These interventions not only facilitate stakeholder engagement and co-creation but also deliver statistically significant reductions in UTCI values, with up to 89.5% of spatial points moving closer to the comfort band in hot conditions under A1. This dual benefit highlights the effectiveness of temporary measures as both technical solutions and platforms for participatory urban design.

However, the analysis also reveals pronounced spatial heterogeneity in NBS impacts (see Figures 5 and 6). While most areas experience cooling, some localized points show slight warming, even within the same intervention scenario. This variability underscores the necessity of high-resolution simulations to accurately capture the nuanced effects of urban interventions. It also suggests that blanket statements about "NBS always cooling urban areas" do not hold uniformly; site-specific factors matter.

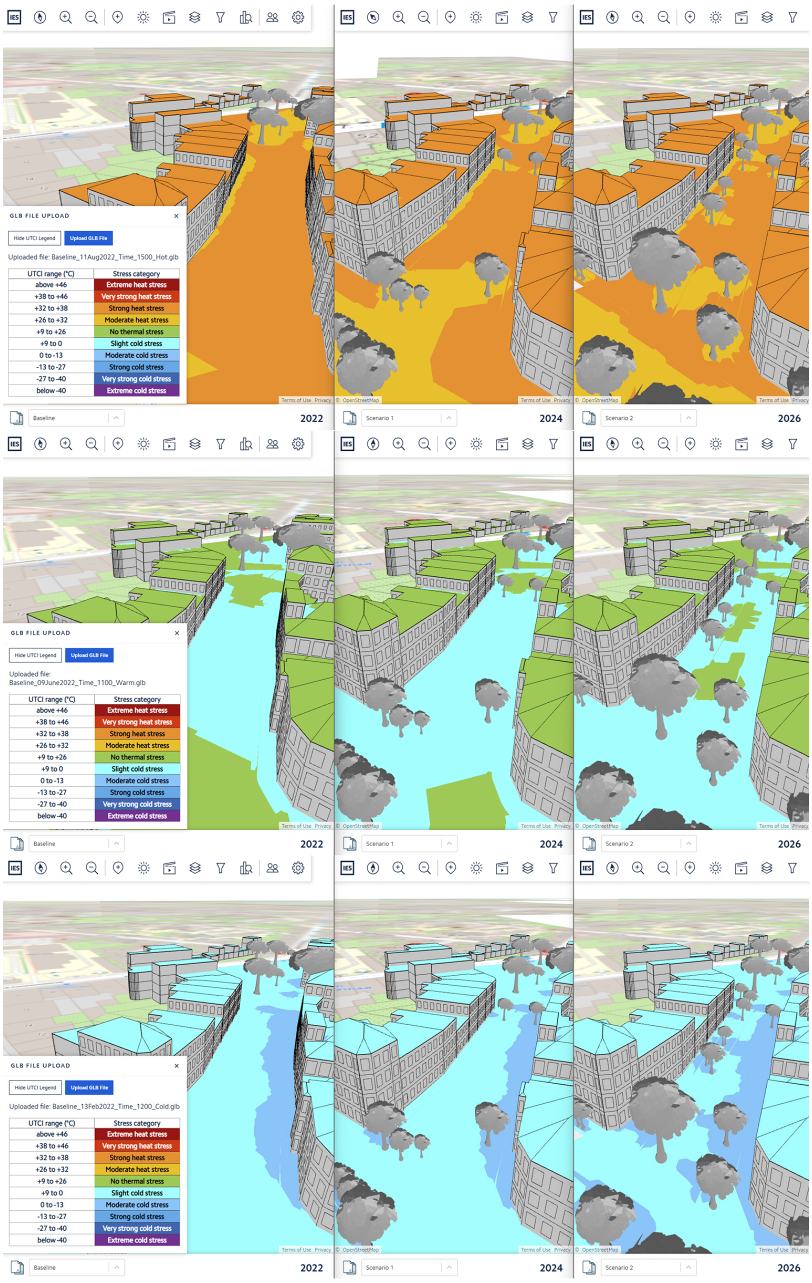

Figure 5. UTCI simulations for hot (1st), mild (2nd) and cold (3rd) scenarios. Within each figure, from left to right, *baseline*, *A1*, *A2* planning alternatives.

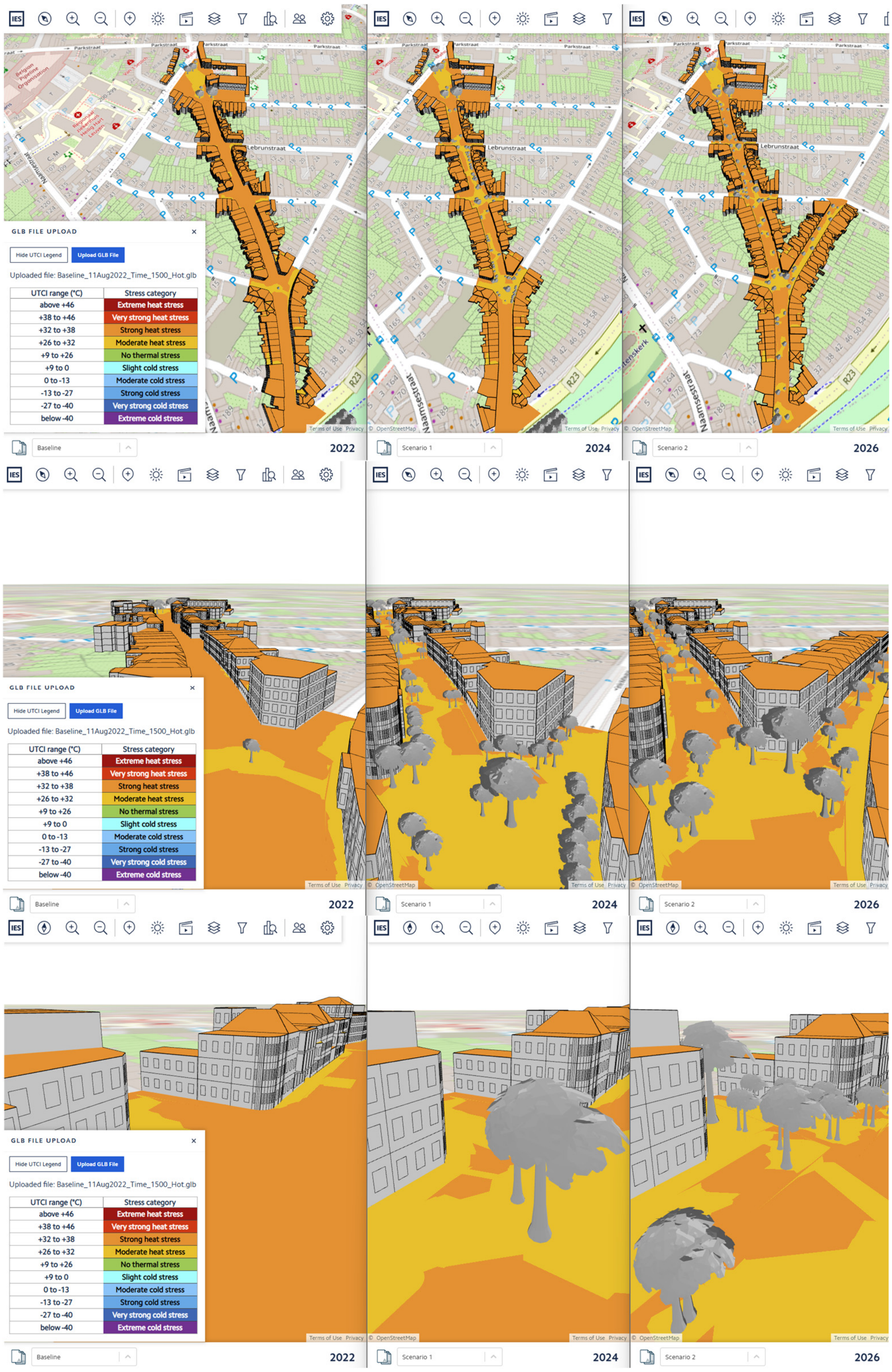

Figure 6. UTCI simulations for the hot scenario, displaying results over specific spots of Meunierstraat, Leuven. Within each figure, from left to right, *baseline*, *A1*, *A2* planning alternatives.

Seasonal dependence is another critical finding: NBS benefits are most pronounced in the hot scenario, marginal in mild conditions, and in cold scenarios certain interventions can actually reduce thermal comfort (by making an already cold environment feel colder). For example, additional tree shading in winter (A2) led to further decreases in UTCI, moving conditions farther from the comfort band. This highlights a trade-off: measures that improve summer comfort might negatively affect winter comfort. Planners should carefully weigh these trade-offs, perhaps by implementing seasonal strategies (i.e., deciduous trees that provide summer shade and winter sun).

Overall, the results indicate that temporary, low-cost interventions can serve as "living laboratories", enabling real-world testing and participatory engagement while providing immediate microclimate benefits. The combination of robust quantitative analysis and community co-design ensures that urban climate adaptation strategies are both effective and publicly accepted.

4. Discussion

The discussion builds on the insights gained from the Meunierstraat case study, where outdoor thermal comfort simulations supported a collaborative planning process with multiple stakeholders. This section examines how the integration of technical evidence (through UTCI-based simulations) with participatory approaches can inform design decisions across different planning alternatives. Broader implications of using interactive 3D visualizations as communication tools are also considered, as they enable planners and citizens to engage with climate adaptation strategies intuitively. Finally, the discussion reflects the workflow's usability relative to existing solutions and identifies areas for improvement to enhance its role in integrated urban planning.

4.1. Balancing Technical Performance and Community Preferences

Temporary, low-cost interventions—such as the "temporary renovation" scenario A1, which introduced vegetation and reflective materials—can significantly improve outdoor thermal comfort by mitigating heat accumulation through shading and evapotranspiration (even though the latter was not explicitly measured). Results showed that even modest changes (i.e., a few trees or a slight increase in surface albedo) can reduce mean radiant temperature and perceived heat stress during critical hot periods, providing immediate benefits for pedestrians while informing long-term design strategies. These interventions serve as "living laboratories", allowing citizens to contribute and feel the benefits, and allowing planners to test and monitor real-world effects before committing to permanent solutions.

From a collaborative planning perspective, temporary measures foster participatory engagement by making climate adaptation tangible and visible. Citizens and stakeholders can experience the proposed strategies in situ, which strengthens trust and co-creation in the decision-making. Coupled with simulation-based evidence and interactive visualization tools, these interventions provide a feedback loop aligning technical performance with community preferences, ensuring that final designs are both effective and socially accepted.

However, the differing outcomes of A1 vs. A2 highlight an important discussion point: the degree of intervention and its timing can influence both technical results and public reception. A1's temporary nature might have been more publicly palatable, and it showed strong technical performance in summer without major drawbacks in winter. A2, being permanent and more intensive (more trees and reflective surfaces), slightly eclipsed A1's cooling in some hot spots but at the cost of winter comfort—something the community might notice (colder winds, more shade in winter). This suggests the need for flexible, context-sensitive application of NBSs: perhaps implementing deciduous planting, adjustable shading structures, or other measures that can be tuned seasonally.

4.2. Enhanced Communication Through Visualization

In line with the importance of social acceptance, beyond computational efficiency, the solution introduces an intuitive visualization capability by publishing outdoor thermal comfort results through interactive 3D web links. This feature transforms technical outputs into accessible, visually engaging representations that can be shared widely. In the Meunierstraat case, the ability to walk through a virtual 3D model of the street under different scenarios helped stakeholders and residents literally "see" the difference an extra tree or a lighter pavement could make. This fosters an informed dialog around urban heat resilience strategies and ensures transparency in the planning process. Such visual and transparent communication is critical for participatory planning and building consensus on adaptation measures.

4.3. Simplified Workflow and Accessibility

Compared to other market alternatives that require extensive manual input and detailed urban geometry modeling, the approach of this research leverages automated data acquisition to streamline the process. By integrating building geometries directly from OpenStreetMap and auto-selecting weather files, the model minimizes the technical burden on users. This allows practitioners to focus on impactful design interventions—introducing NBSs, modifying surface materials, adjusting albedo—rather than spending effort on tedious data preparation. This simplification lowers the barrier for urban planners and researchers, enabling faster scenario testing in early planning stages and broader adoption in real projects.

Despite the strengths, several enhancements could make the tool more intuitive and powerful for planners and stakeholders. First, integrating a side-by-side visualization of the 3D model with numerical results (graphs or gauges) would improve interpretability—i.e., clicking a point on the map could pull up its UTCI time series or comfort trend. Second, incorporating real-time sensor data feeds into the simulations (or at least model calibration) would strengthen accuracy and trust in the results; the validation used static data post-simulation, but a live integration could allow continuous improvement of the model. Third, expanding the analysis beyond single hours to consider longer periods (daily average UTCI or frequency of extreme stress hours over a summer) would offer a more comprehensive performance evaluation; a single hour snapshot may miss cumulative exposure effects. Fourth, an "exploratory mode" in the tool that gives quick feedback during design tweaks (even if less precise) could accelerate the iterative process and creativity in workshops.

It is also worth discussing the limitations of the modeling assumptions. The assumption of spatially uniform meteorological inputs (air temperature, humidity, wind) means micro-scale differences are not captured. In reality, urban microclimates can vary significantly over short distances. This research case assumes that the relative performance of A1 vs. A2 would remain similar even if micro-variations were considered (i.e., if a more advanced model with spatially varying inputs were used, we expect A1 would still outperform A2 in hot conditions, and A2 would still cause more winter cooling). Nevertheless, this is a hypothesis that warrants future testing via sensitivity analysis. This research did not conduct a full sensitivity analysis on the input parameters (like varying wind or adding/removing sensors), which is a limitation of this study. Future work should test how robust the conclusions are if, for example, the wind was 2 m/s higher or if a building facade was 5 °C warmer than ambient. This would directly address the question of whether the "relative superiority" of different schemes stays stable under less simplified conditions. In this regard, technological progress associated with improvements in simulation will enable more complex studies.

While the current workflow demonstrates strong capabilities for outdoor thermal comfort assessment, implementing the above enhancements and addressing model limitations will further improve its utility. The authors plan to incorporate many of these in future development cycles. For instance, enabling the simulation of multiple hours or an entire hot day could allow calculation of metrics like "hours of heat stress avoided" by an intervention, which may resonate more with public health outcomes.

As a final point in this discussion, it is useful to place this work in the larger context of urban climate adaptation tools. This study extends iCD's established strengths in building energy and CO_2 analysis by adding outdoor thermal comfort functionality. By integrating these features within a single ecosystem (using iCD for modeling/simulation and iCIM for visualization), there is potential for combined analyses: cities could simultaneously evaluate outdoor comfort, building energy performance, and emissions, all while engaging stakeholders with immersive visualization. This holistic approach supports the complex cross-sector strategies needed for climate action in cities. Building on these results, a logical next step is to execute a combined analysis in a district-scale project, examining trade-offs and co-benefits between outdoor comfort improvements and building energy savings or carbon reductions. Such integrated assessments will further ensure that interventions like the ones in Meunierstraat not only make a single street more comfortable but also contribute to broader sustainability goals.

5. Conclusions

This research presents a case study of co-creating climate-resilient streets using a digital twin-based simulation workflow for outdoor thermal comfort. The revised analysis addresses key concerns raised by reviewers and leads to several conclusions and takeaways:

- Effectiveness of participatory NBS: Quick, low-cost interventions developed through a participatory process (such as adding greenery and reflective surfaces) can significantly reduce heat stress on urban streets during extreme heat events. In this case, the temporary intervention (A1) reduced the median UTCI by about 2.3 °C on a hot summer day and improved thermal comfort at nearly 90% of the locations in the study area. These improvements, while technical in nature, were achieved in tandem with community engagement, underscoring the value of participatory design for climate adaptation.
- Seasonal trade-offs: Not all interventions are beneficial year-round. We found that the permanent design (A2), which maximized cooling features, provided heat relief similar to A1 in summer but caused a notable decrease in winter thermal comfort (a median UTCI ~8 °C lower than baseline on a cold day due to shading). This reveals a trade-off: measures that improve summer conditions can exacerbate winter cold. Future resilient design should strive for solutions that balance seasonal needs—such as using deciduous plants or adjustable shade structures to mitigate extreme heat while minimizing winter discomfort.
- Spatial heterogeneity: The impact of the interventions varied spatially. Even with uniform meteorological inputs, the model showed micro-scale differences (some spots warming slightly while most cooled). This highlights that high-resolution analysis is essential; averages alone could obscure hot spots or cool spots. Urban comfort assessments should include detailed spatial results and visualization so planners can identify where exactly an intervention works or if any unintended adverse zones appear.
- Modeling limitations and validation: Our approach involved certain simplifications (i.e., uniform air temperature and wind, treating all surfaces as black bodies, no explicit evapotranspiration modeling). While these assumptions enabled a faster workflow, they also limit physical accuracy. Through added validation with field measurements, the study gained confidence that the model's baseline predictions were reasonable (within 1–2 °C of measured UTCI). However, future work should incorporate microclimate variations and conduct sensitivity analyses to ensure conclusions hold

under different conditions. Additionally, acknowledging statistical limitations (spatial autocorrelation affecting significance tests) is important for rigorous interpretation of results.

- Implications for urban planning practice: The integrated digital workflow proved to be a useful decision-support tool for the municipality of Leuven, bridging technical analysis and stakeholder communication. By automating data input and providing interactive 3D outputs, it lowered the barrier for scenario exploration. The combination of quantitative evidence and community co-design helped justify specific interventions in the eyes of both experts and residents. This approach can be generalized to other urban projects where climate adaptation measures need to be evaluated quickly and communicated clearly. The authors recommend that urban planners consider such tools to test interventions (virtually) before implementation, and to use visualizations to build public support for climate resilience measures.

In summary, co-creating climate-resilient streets requires both robust data and community buy-in. The study demonstrates a framework to achieve both: leveraging a digital twin for detailed thermal comfort simulation and using it as a platform for participatory planning. The outcome is a design that not only performs well in simulations but is also shaped and supported by its future users. The authors foresee that incorporating the mentioned future improvements (i.e., richer microclimate modeling, longer-term simulations, and broader impact metrics) will further enhance the value of this approach in the ongoing fight against urban heat challenges.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/smartcities9020039/s1, Excel file with the UTCI values result of the outdoor thermal comfort simulations.

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Abbreviations

The following abbreviations are used in this manuscript:

NBSs	Nature-Based Solutions
UTCI	Universal Thermal Climate Index
CFD	Computational Fluid Dynamics
JTBDs	Jobs-To-Be-Done
MRT	Mean Radiant Temperature
ERF	Effective Radiant Field
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
.epw	EnergyPlus Weather File Format
IPCC	Intergovernmental Panel on Climate Change
PET	Physiological Equivalent Temperature

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