SimBuild
2024

Eleventh National Conference of IBPSA-USA
Denver, Colorado
May 21 – 23, 2024

Façade Greening Strategies: Integrating Life Cycle Assessment and Microclimatic Analysis for Sustainable Urban Planning

Bernadette Lang-Eurisch[1] and Nadja Bishara[1]
[1] Institute of Structural Mechanics and Design, Technical University of Darmstadt, Darmstadt, Germany

Abstract

This research investigates the ecological and microclimatic implications of implementing green façade systems in a residential district. The evaluation is grounded in a Life Cycle Assessment (LCA) that scrutinizes greenhouse gas emissions, encompassing both the material life cycle and transportation aspects. Complementarily, the study employs a Microclimatic Analysis utilizing the Universal Thermal Climate Index (UTCI) to elucidate microclimatic conditions, considering the variations in plant and construction selections. The findings show that certain green façade configurations contribute to a reduction in emissions and an enhancement of microclimatic conditions, thereby suggesting a potential for synergistic integration within urban planning frameworks. This investigation underscores the efficacy of green façade applications in fostering urban sustainability and accentuates the necessity of harmonizing environmental considerations with microclimatic factors in urban planning decision-making processes.

Introduction to Life Cycle Assessment and Microclimatic Analysis

In an era marked by rapid urbanization (Halder et al. 2021) coupled with escalating environmental concerns (IPCC, 2018), this study delves into the detailed interplay between microclimatic conditions and LCA within urban environments.

As a critical tool for evaluating the environmental footprint of products, processes, or systems throughout their lifecycle, LCA is highly relevant in the context of urban sustainability (Rüter and Diederichs 2012). LCA enables a comprehensive analysis of urban areas, focusing especially on understanding the ecological consequences of façade greening initiatives (Chàfer et al. 2021). The LCA process begins with the Goal and Scope Definition phase, setting precise objectives and boundaries to ensure methodological focus and relevance. The subsequent Life Cycle Inventory stage involves detailed data collection across the project's lifecycle. The Life Cycle Impact Assessment quantifies environmental impacts, leading to data analysis that offers a holistic view of the project's environmental performance (Hauschild et al. 2018, ISO 2006a; 2006b). In the context of urban heat islands, increasing energy usage, and a growing preference for eco-friendly and healthier urban spaces, façade greening projects have garnered significant attention (Halder et al. 2021). LCA emerges as a powerful tool for analyzing the ecological and social impacts of such projects (Ketterer und Matzarakis 2015; Pioppi et al. 2020). This methodology provides objective criteria for stakeholders to evaluate the sustainability and ecological impacts of their initiatives (Zihlmann Sánchez 2023). As urbanization continues to accelerate and environmental challenges intensify, examining façade greening through LCA becomes increasingly pivotal in sculpting sustainable urban landscapes (Ottelé et al. 2014; Shamsuddeen Abdullahi 2016; Salonen et al. 2022). However, microclimatic analysis is also instrumental in urban environmental research, examining localized climate conditions within cities (Bherwani et al. 2020). This analysis, often conducted through simulations, involves the detailed assessment of various environmental factors

Figure 1: North View of the Case Study Area

such as temperature, humidity, wind speed, solar radiation, and air quality. These simulations utilize data collected via sensors and remote sensing technologies (Yudina 2017; Motazedian et al. 2020). These computational modeling and simulation techniques enable predictions of how urban elements, such as façade greening, influence the microclimate, factoring in variables like seasonal vegetation behavior and material characteristics (Mughal et al. 2021; Pioppi et al. 2020; Toparlar et al. 2017). Contemporary research emphasizes evaluating urban interventions, focusing on the direct effects of façade greening (Ottelé et al. 2014; Teichmann et al. 2022; Peng et al. 2020). These interventions have the potential to mitigate the urban heat island effect, reduce energy consumption, and enhance urban comfort (Manso et al. 2021). This approach yields insights into how these initiatives transform the local climate and improve the quality of life for urban residents (Santos et al. 2019). In the evolving field of building façade greening, researchers increasingly rely on microclimatic analysis to investigate the effects of green façades (Alsaad et al. 2022; Teichmann et al. 2022). Recent research involves detailed analyses considering variations in plant species, façade design, and maintenance practices (Toparlar et al. 2017; Chew et al. 2019; Ascione et al. 2020; Ling 2022; Oquendo-Di Cosola et al. 2022). The aim is to unravel the complex interactions by which nuances in green façade execution impact microclimatic conditions. Furthermore, current studies explore incorporating microclimatic data into broader urban sustainability frameworks, addressing key issues related to the scalability of façade greening and its contributions to overarching environmental and societal objectives, such as reducing energy consumption and improving urban resilience (Alonso und Renard 2020; Bherwani et al. 2020; Stavrakakis et al. 2021; Irga et al. 2023; Elliott et al. 2020; Bakhshoodeh et al. 2022). In Summary, the intersection of LCA and microclimatic analysis represents a paradigm of complementary methodologies, each vital in addressing the exigencies posed by the climate crisis within urban environments. Working towards a sustainable and resilient future necessitates the fusion of these analytical instruments with in-depth research, playing a critical role in the sustainable development of our urban landscapes and in addressing the challenges of the prevailing climate crisis.

This study establishes a connection between microclimatic factors and LCA outcomes, revealing potential synergies and trade-offs essential for urban planning and sustainability strategies. The case study conducted in central Germany (see Fig. 1) analyzes five distinct façade greening concepts. An overview of their construction and material aspects is provided in Table 1. Façade greening scenarios are categorized into three groups, as outlined in Table 2. The first, labeled 'Ref.,' scenarios are examined without façade greening, establishing this group as the baseline for comparison. The second group, labeled 'G.,' assesses ground-based greening designs, designated as 'G.D.' for direct green, where plants grow directly on the facade's surface, and

Table 1: Components and Materials for Exterior Façade Greening System. Abbreviations: TAG Lathing (Tongue and Groove Lathing with Pre-Aged Larch, Support, and Counter Lathing); WS Construction (Wooden Stand Construction).

Type	**Ground Based System**		**Façade Bound System**		
Façade greening components	Direct Green	Indirect Green	Planter Box Installation	Modular Construction	Felt System
Exterior wall	WS Construction	WS Construction	WS Construction	WS Construction	WS Construction
Air cavity	5cm	5cm	5cm	5cm	5cm
Wood curtain façade	TAG Lathing	TAG Lathing	TAG Lathing	-	-
Structural support system	-	Steel mesh	Steel profile	Steel profile	Steel profile
Supporting system	-	-	Steel boxes	Steel grid box	PVC foam plate
Inner layer	-	-	-	-	White fleece
Growing material	Terrestrial soil	Terrestrial soil	Potting mix	Potting mix	Potting mix
Vapor Barrier	-	-	-	-	PE film
Outer felt layer	-	-	-	-	Black fleece
Irrigation system	-	-	PP pipes	PP pipes	PP pipes
vegetation	Hedera helix (20cm)	Hedera helix (30cm)	Hedera helix (30cm)	Carex divulsa (25cm)	Carex divulsa (25cm)

'G.I.' for indirect green, which employs a support structure for plant growth. F.', the third group, delves into greening options bound to façades, such as Planter Box Installation ('F.P.'), Modular Construction ('F.M.'), and the Felt System ('F.F.'). Each category is further analyzed across four levels of façade greening intensity on the exterior wall, defined as V1=100% greening, V2=75%, V3=50%, and V4=25%, as depicted in Figure 2. This approach allows for a nuanced evaluation. The aim is to illuminate the relationship between environmental impact and microclimatic effects, thus identifying beneficial synergies and necessary trade-offs.

Methodology and Simulation

Life Cycle Assessment

The principal aim of this LCA is to conduct a thorough evaluation of the ecological performance of the urban district, with a special emphasis on the effects of façade greening, thereby identifying environmentally beneficial scenarios that contribute to the reduction of CO_2 emissions and address significant environmental concerns. The study focuses on a comprehensive 50-year LCA of an urban district in the case study, encompassing the complete cradle-to-cradle life cycle. This includes phases such as raw material extraction, transportation, construction, maintenance, end-of-life scenarios, and potential for recycling. In the urban district, the inventory analysis comprehensively assesses the entire area, with a specific focus on the exterior wall and façade greening strategies. The Global Warming Potential (GWP) metric is employed to evaluate the scenarios, providing quantitative insights into emission reductions achieved through greening initiatives compared to the reference scenario. This comprehensive assessment necessitates the quantification and appraisal of all relevant building elements, focusing particularly on their greenhouse gas emissions.

The inventory analysis is grounded in detailed architectural specifications to ensure an accurate assessment. In the absence of specific material information, secondary data from similar projects or reliable sources are incorporated. This analysis identifies certain constraints, notably the exclusion of elements such as the energy system, interior fixtures, railings, and light and ventilation shafts. These omissions, along with uncertainties stemming from incomplete data on building specifications and materials, are mitigated through an uncertainty classification system.

The methodology of this study incorporates a multi-stage approach using openLCA software and the ecoinvent 3.9.1 database, distinguished for its robust implementation and transparent, comprehensible data structure. This choice ensures the analysis is grounded in advanced tools coupled with a data source that demystifies complex environmental impacts, rendering them accessible and interpretable for comprehensive understanding (Hildebrand et al. 2022; Najjar et al. 2022; Battisti et al. 2019; Bahramian und Yetilmezsoy 2020). Manufacturing processes for each component are established, and transport processes are developed for delivering these components to the planning area. The product system of each scenario considers all components in their transported form as input streams, culminating in the new development area as the output. Sensitivity analyses and scenario modeling are employed to address uncertainties related to database materials, material lifetime and transportation routes.

To ensure transparency, this study acknowledges and addresses the inherent limitations in the LCA, arising from incomplete or inaccurate component details and the assumptions necessitated by practical constraints, particularly concerning material transportation and usage. The uncertainty classification system in the material databases provides information on the

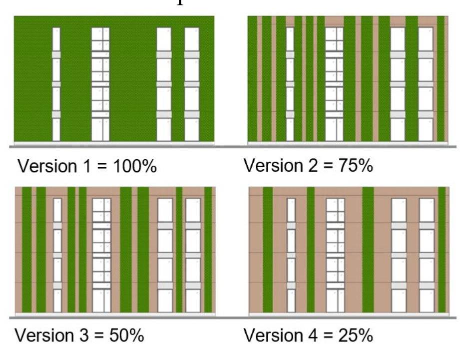

Figure 2: Overview of the facade greening versions

Table 2: Scenario Development

Façade greening main groups	**Reference**	**Ground Based System**		**Façade Bound System**		
Façade greening subcategories	Without greening	Direct Green	Indirect Green	Planter Box Installation	Modular Construction	Felt System
Scenario overview	Ref.	G.D.V1	G.I.V1	F.P.V1	F.M.V1	F.F.V1
		G.D.V2	G.I.V2	F.P.V2	F.M.V2	F.F.V2
		G.D.V3	G.I.V3	F.P.V3	F.M.V3	F.F.V3
		G.D.V4	G.I.V4	F.P.V4	F.M.V4	F.F.V4

uncertainty of transportation distances, material lifetimes, and replacement quantities, forming the basis for the sensitivity analysis. Additionally, the choice of a 50-year assessment period significantly influences the results, with variations in timescales potentially yielding different outcomes due to advances in recycling and material lifespan effects. The assessment may also not fully capture the spatial and temporal variability of environmental conditions across different geographic locations and time periods. Furthermore, this study examines the environmental implications of different types of façade greening designs through the LCA of the case study. This analysis begins by evaluating the GWP across all stages of the scenarios, focusing on the impact of various façade greening designs on exterior walls.

Microclimatic Analysis

The primary goal of this microclimatic analysis is to identify the green façade design scenario that maximizes thermal outdoor comfort within the case study area. The analysis involves a detailed evaluation of various scenarios for the 1st of July, with temperature ranges from 17°C to 35°C. The alignment with the LCA scenarios facilitates comparative analysis. The study site, approximately 100x100 meters as depicted in Figure 1, is situated in a distinctive urban context, bordered by urban developments to the south and west, and natural landscapes to the north and east. The size, shape, and orientation of the buildings within the district, comprising six distinct buildings, green spaces, trees, roads, and pathways, are crucial in assessing their microclimatic impact. Building variations include wooden façades and green rooftops, with wall and roof systems remaining consistent across scenarios, except for the variations introduced by different façade greening systems. For this analysis, the study employs an Envi-met model, integrated with a Simple Forcing System for meteorological input settings, due to its widespread recognition as both the most utilized and most reliable tool in this field. This model's robustness in simulating

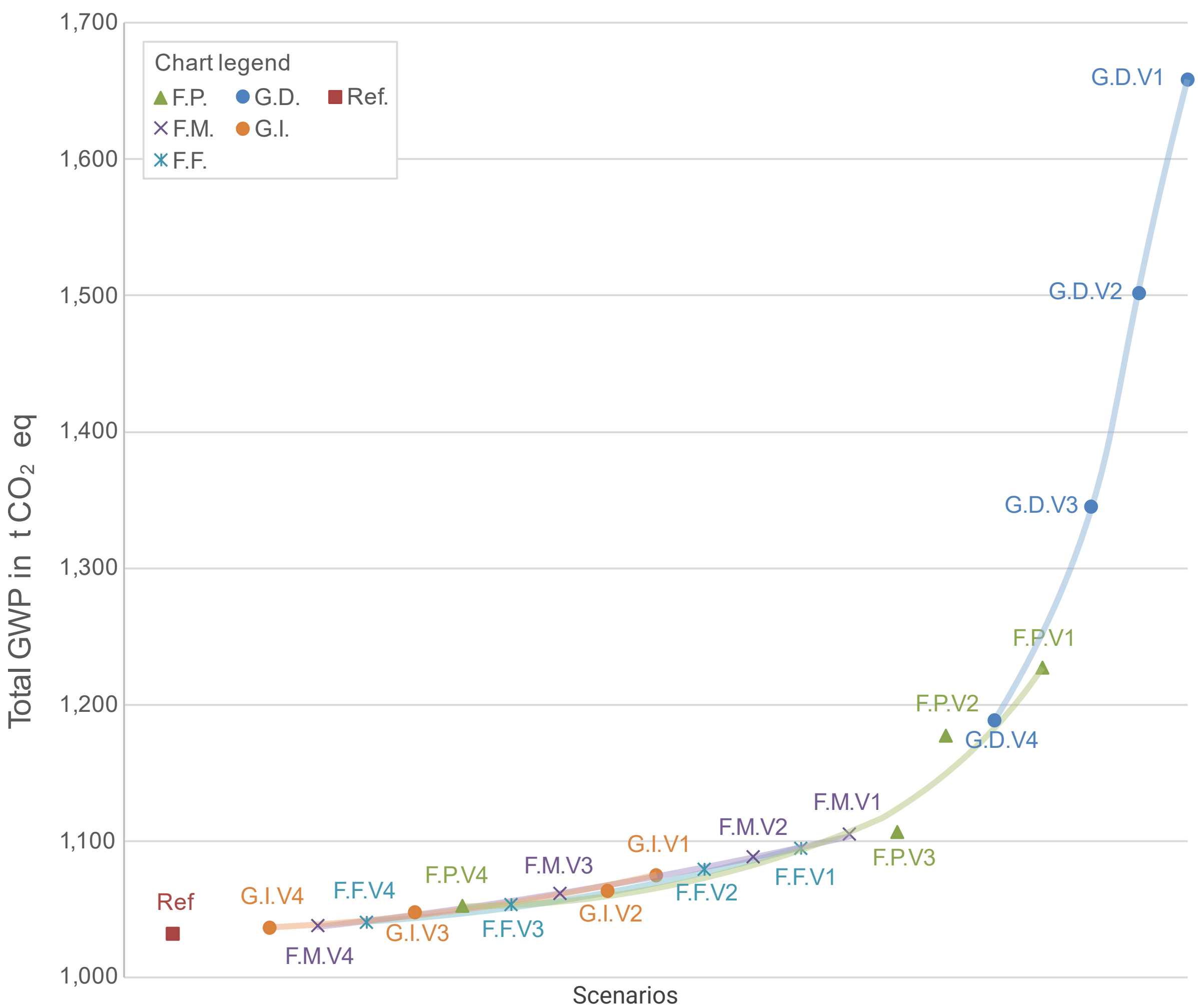

Figure 3: Total GWP – incl. Life Cycle Phases A, B, C, D

microclimate conditions make it an asset for the microclimatic analysis, offering detailed insights that are essential for environmental analysis (Detommaso et al. 2021; Perera et al. 2022; Eingrüber et al. 2022; Jänicke et al. 2021). The simulation covers a continuous 24-hour period, allowing for the monitoring of temperature and humidity variations and their effects on indoor temperatures. In this analysis, UTCI is employed using site-specific climate data, making it essential for microclimatic analysis and the assessment of thermal comfort. It incorporates key factors such as air temperature, humidity, wind speed, and radiation, facilitating an effective characterization of urban microclimates and human comfort. This is essential in evaluating the impact of façade greening systems on sustainable urban planning and human well-being.

Prioritization of the Analysis Methods

In assessing the roles of LCA and microclimatic analysis in sustainable urban planning, this research raises an essential question: In the context of the current climate crisis, should these two methods be given equal weight in decision-making processes, or does one outweigh the other in importance?

LCA plays a crucial role in understanding the dynamics of climate change. It does this by analyzing carbon emissions across the lifecycles of products and processes, thereby identifying and mitigating the root causes of climate change. This approach lays the groundwork for long-term sustainability and carbon neutrality. In contrast, microclimatic analysis addresses the immediate challenges posed by climate change, such as extreme heat in urban areas. It emphasizes the urgent need to build resilient cities capable of withstanding these challenges and highlights the importance of quick adaptation strategies. Despite their different focuses, both methodologies are vital. LCA provides a strategy for reducing CO_2 emissions and guiding us towards a sustainable future. Meanwhile, microclimatic analysis enhances urban resilience and improves the quality of

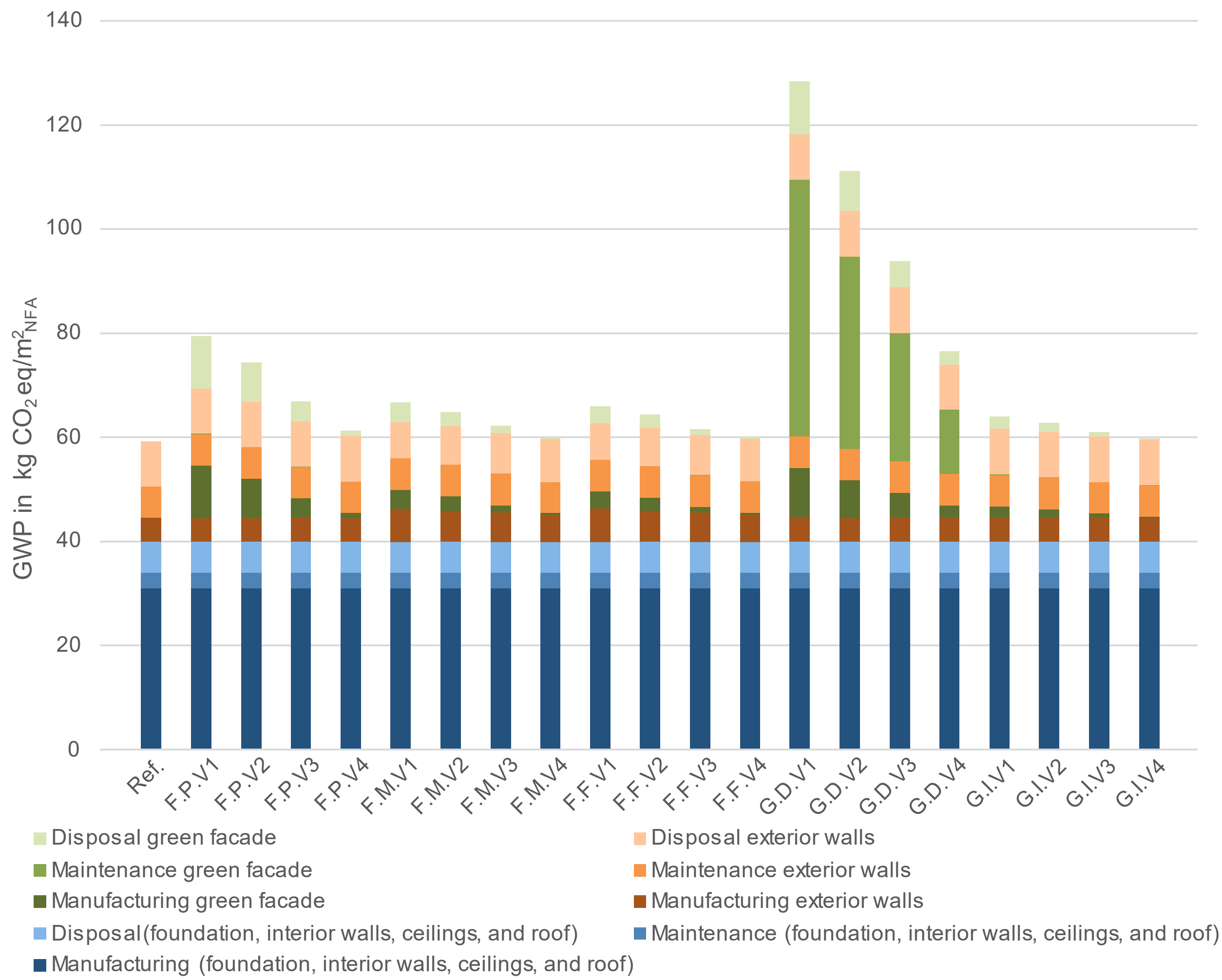

Figure 4: GWP of building components

life in cities by addressing the immediate effects of climate change. In this study, LCA assesses the urban district's overall environmental impact, particularly the exterior wall with green façade, examining the GWP of construction materials and the CO_2 absorption capacity of biomass layers throughout its lifecycle. However, microclimatic analysis focuses on local atmospheric conditions, particularly those affecting human comfort. Ultimately, the integration of LCA and microclimatic analysis is key in environmental studies. While each has its distinct area of focus, their combined application offers a more comprehensive approach to environmental analysis in the realm of urban sustainability. To further elucidate the relationship between CO_2 emissions and microclimatic effects, this study introduces a direct correlation analysis. This involves examining how reductions in CO_2 emissions correlate with improvements in microclimatic conditions. Such analysis can uncover valuable insights into the effectiveness of façade greening strategies, illustrating the benefits of these environmental interventions. The study balances quantitative measurements, such as GWP reduction and temperature changes, with qualitative assessments, including comfort considerations. This dual approach ensures a comprehensive understanding of façade greening's impacts.

Result Analysis and Discussion

Life Cycle Assessment

The analysis of total greenhouse gas emissions and building components across various scenarios indicated a range from approximately 1,032 to 1,658 tons of CO_2-equivalent. These findings are visually represented in Figure 3. The scenario without green façade design, Ref., resulted in the lowest greenhouse gas emissions, attributable to the reduced processes and materials involved. Scenarios such as F.M.V4, G.I.V4, and

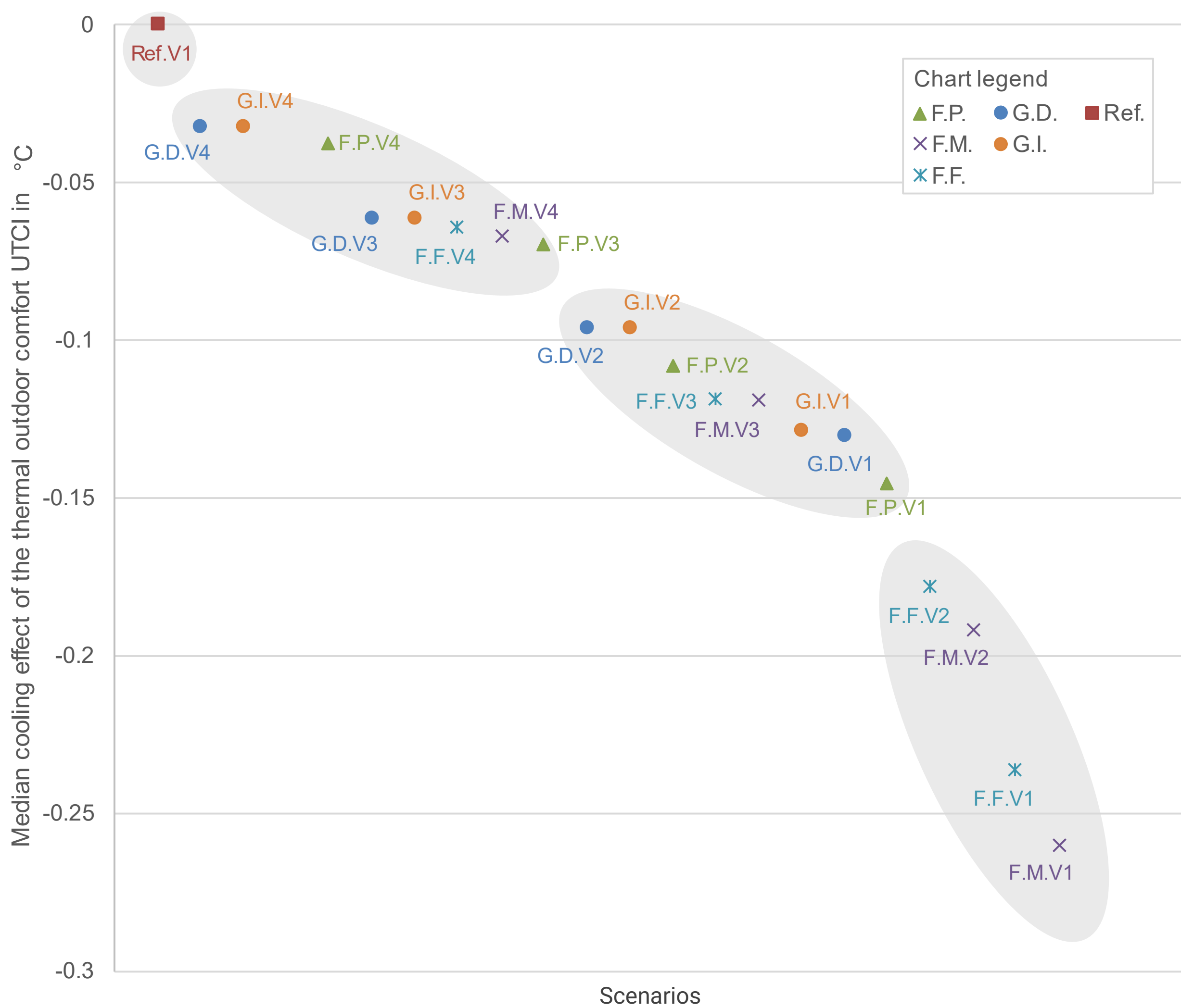

Figure 5: Median cooling effect UTCI compared to reference scenario (Ref.)

F.F.V4, which all feature reduced façade greening, demonstrate promising greenhouse gas reductions compared to the other greening scenarios. It is observed that scenarios with minimal material usage tend to exhibit better performance. A thorough analysis comparing component weight and GWP reveals significant differences; notably, scenarios in the G.D. group, despite having a total component mass akin to that of Ref., demonstrate a higher GWP. To understand these disparities, a thorough examination of building components is essential. The exterior wall component, which includes greening façades, emerges as the most environmentally significant. From the data presented in Figure 4, it becomes evident that the consistency in GWP values across each scenario group for the foundation, interior walls, ceilings, and roofs is due to the lack of changes in these components across the various scenarios. This consistency is attributed to the fact that these building components remain unchanged across the various scenarios. However, since the setup of the exterior wall changes with the different green façade scenarios, it also has different values, introducing a variable factor in the overall environmental impact assessment. In examining the CO_2 equivalent emissions across various façade greening scenarios, distinct patterns emerge. For the G.D. scenarios, the highest emissions are noted during maintenance, contrasting with other scenarios where the peak occurs during construction. This is based on the premise that the façade greenery in G.D., growing on the wooden curtain wall, necessitates replacement every 10 years. Regarding exterior walls, the GWP values remain consistent at 4.56 kg CO_2-eq./m^2_{NFA} for both Reference (Ref.) and ground based (G.) scenarios. However, a decrease in emissions is observed from V1 to V4 in façade bound (F.) scenarios, attributed to a reduction in wooden curtain wall usage. A downward trend is also apparent in all scenarios from V1 to V4, reflecting material use and process reduction. Significant variation in the maintenance phase of façade greening is observed across scenarios, with a general trend of decreasing emissions from V1 to V4. Disposal emissions are consistent for F.P., and G. scenarios, while F.M. and F.F. scenarios show a gradual increase. The study also reveals stable recycling potential for exterior walls in Ref., F.P., G.D., and G.I. scenarios, with a minor decrease from V1 to V4 in F.M. and F.F. scenarios due to the high recyclability of the wood structures. Conversely, façade greening demonstrates substantial recycling potential variations, with most scenarios showing an increasing trend from

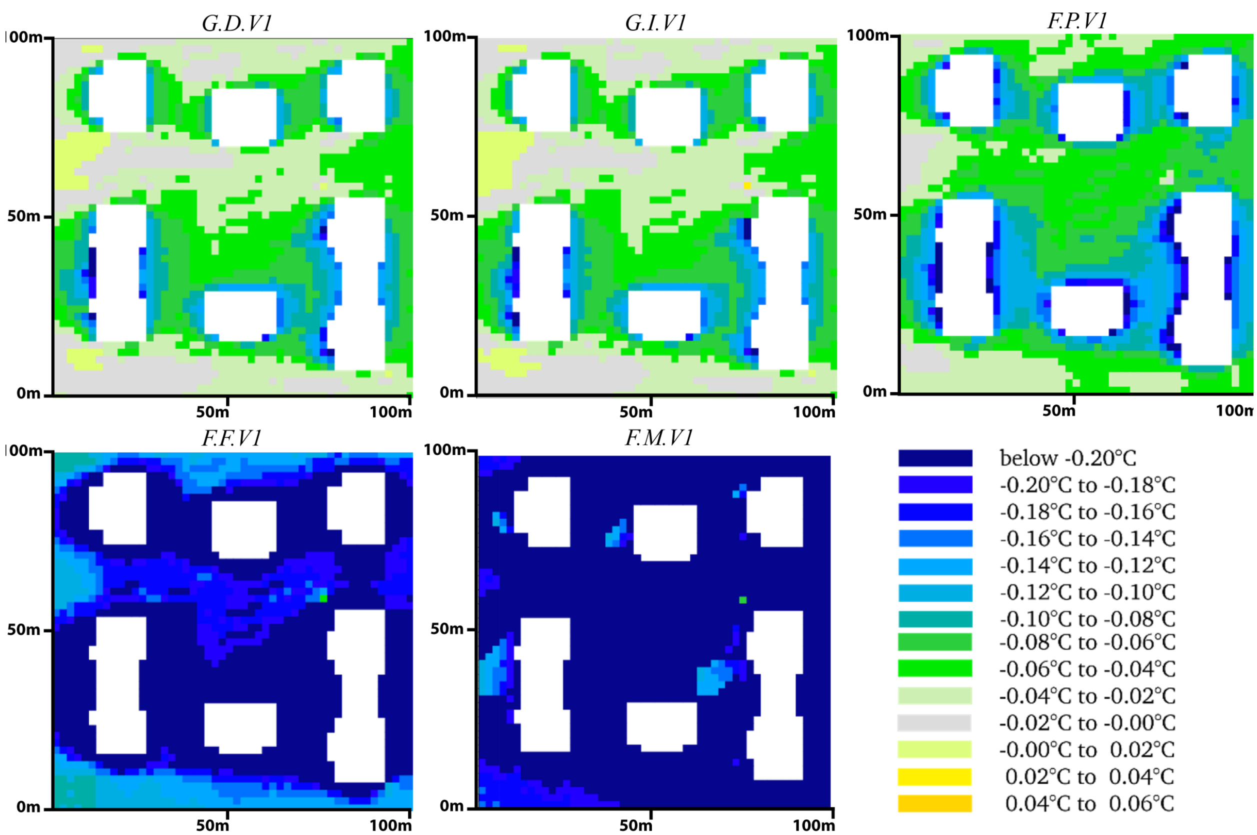

Figure 6: Site plan: UTCI comparison of variants to the reference scenario at the hottest time of the 1st of July

V1 to V4, indicating a reduction in negative recycling potential. However, G.D. scenarios maintain a constant recycling potential of 0 across V1 to V4, attributed to the decomposition of wood structures in these designs.

This is further corroborated through a biomass analysis. All scenario groups exhibit a decline in biomass quantity from V1 to V4, with variations attributable to different plant species and vegetation layers. The G.I. series displays the highest biomass, followed by G.D., F.F., F.M., and F.P., while the Ref. scenario shows minimal biomass due to limited planting. In terms of the CO_2 binding capacity of façade greening, trends like the previous analysis are observed. While these numbers provide a useful basis for comparing scenarios, caution is advised due to the inherent uncertainties in quantifying CO_2 absorption in biological processes.

The LCA results for green façade design systems reveal significant disparities in environmental impacts arising from material selections and replacement frequency. Indirect green systems generally exhibit a lower environmental impact owing to reduced material requirements, whereas systems using more material like metal or felt show higher environmental footprints. The G.D. scenario, necessitating the complete replacement of the outer façade layer, demonstrates particularly high impacts. These findings underscore the importance of selecting eco-friendly materials and design choices in such initiatives. Although living wall systems offer rapid coverage, they are associated with a higher environmental burden.

Microclimatic Analysis

The outcomes of the microclimatic analysis are assessed using two Envi-met software tools: 'Bio-met' and 'Leonardo.' 'Bio-met' calculates the UTCI for a standard person, while 'Leonardo' examines factors like comfort, air temperature and relative humidity. By excluding less consistent variables such as wind flow and pollutant concentrations, the analysis focuses on comparing results to the reference scenario without façade greening. It is important to acknowledge the limitations of the Envi-met model. The model's accuracy is less reliable for larger areas, and the precision of results may be influenced by simplifications in the simulation process and uncertainties in input data (Liu et al. 2023; Yang et al. 2021; Faragallah und Ragheb 2022). Understanding these limitations is crucial for interpreting the microclimatic analysis findings.

The study examined the impact of various façade greening scenarios on outdoor thermal comfort, using the Ref. scenario as a baseline. Results indicate a general cooling effect across all scenarios, as seen in Figure 5. Cooling effects were observed in the G.D.V1, G.I.V1, F.M.V1, F.P.V1, and F.F.V1 scenarios. The G.D.V1 and G.I.V1 scenarios demonstrated a peak cooling of 0.27°C and an average reduction of 0.13°C, likely due to similar construction and plant choices. The F.M.V1 scenario recorded the most pronounced cooling, with a maximum reduction of 0.51°C and an average decrease of 0.26°C, suggesting its potential for enhancing outdoor thermal comfort. The F.P.V1 scenario showed a peak cooling of 0.29°C, averaging 0.15°C, while the F.F.V1 scenario demonstrated a peak reduction of 0.39°C and an average decrease of 0.24°C. Interestingly, the F.M. scenario proved more effective at night, while the F.F. scenario showed better performance during the day, a difference attributable to the F.M. scenario's higher soil mass. The F.M. scenario emerged as the more efficient system overall, offering greater median thermal comfort.

The interpretation and sensitivity analysis within this section are essential. Limitations in simulation time affect the variation in thermal comfort among scenarios, though all consistently show high comfort levels. Figure 6 illustrates temperature variations and the spatial distribution of cooling effects, respectively, across different green façade scenarios. The F.F.V1 and F.M.V1 scenarios exhibit the greatest cooling effects. Scenarios with 25% façade greening provide lesser thermal comfort than those with 100% greening.

In summary, green façades consistently enhance the microclimate compared to non-green façades, with the F.M. and F.F. scenarios providing enhanced thermal outdoor comfort. A notable observation is the formation of a cooling circle around buildings, more pronounced in scenarios with extensive green façade coverage, indicating that comprehensive façade greening leads to better thermal comfort results.

Result Comparison: Integrating LCA and Microclimatic Analysis in Urban Sustainability

As the scenario developments progress, as depicted in Figure 7, there is a general trend towards decreasing values of GWP, while the positive effect on thermal comfort tends to diminish. F.M. and F.F. scenarios exhibit comparable patterns, with higher versions offering enhanced thermal comfort but lower environmental efficiency. F.P. scenarios strike a balance between environmental efficacy and thermal comfort enhancement. G.I. and G.D. scenarios have the most significant environmental impact without causing a substantial reduction in thermal comfort. When considering both environmental efficiency and thermal comfort, the F.M. and F.F. scenarios seem to maximize immediate cooling benefits, despite their higher environmental impact. Conversely, G.D. scenarios prioritize environmental impact but have less of an effect on the microclimate than G.I. and F.P. scenarios. Ref. ranks as the best choice from an LCA perspective due to its minimal CO_2 emissions; Nevertheless, F.M.V1 distinguishes itself by providing the most substantial enhancements in microclimate, highlighting its potency as a solution from a microclimatic perspective. Establishing the optimal scenario demands adopting a comprehensive strategy that prioritizes a minimal GWP and effective cooling. In this context, the F.M.V3 stands out as a noteworthy option for achieving a balance between environmental efficiency and a significant cooling effect. Despite producing more emissions of CO_2 than the reference scenario, F.M.V3 yields considerable enhancements to the microclimate, rendering it a promising solution for sustainable urban design in the case study. This solution addresses the needs of both sustainability and the microclimate, showcasing its potential for implementation in urban planning. As a result, when comparing and interpreting the results of both LCA and microclimatic analysis, several patterns emerge across different scenarios. These findings not only provide a clearer understanding of the individual and combined impacts of these methodologies but also offer valuable guidance for future sustainable urban planning strategies.

This comparison highlights the importance of integrating LCA and microclimatic analysis as essential instruments for informed decision-making in the realm of sustainable urban planning. The proposition at hand is not a matter of choosing one over the other; rather, it is about recognizing and leveraging the synergistic potential inherent in the confluence of these methodologies. Addressing emissions at their source is a key step in making significant progress toward forestalling impending climate crises. Concurrently, microclimatic analysis accentuates the immediacy of adapting to the extant challenges surrounding urban areas. The equilibrium between addressing the foundational causes

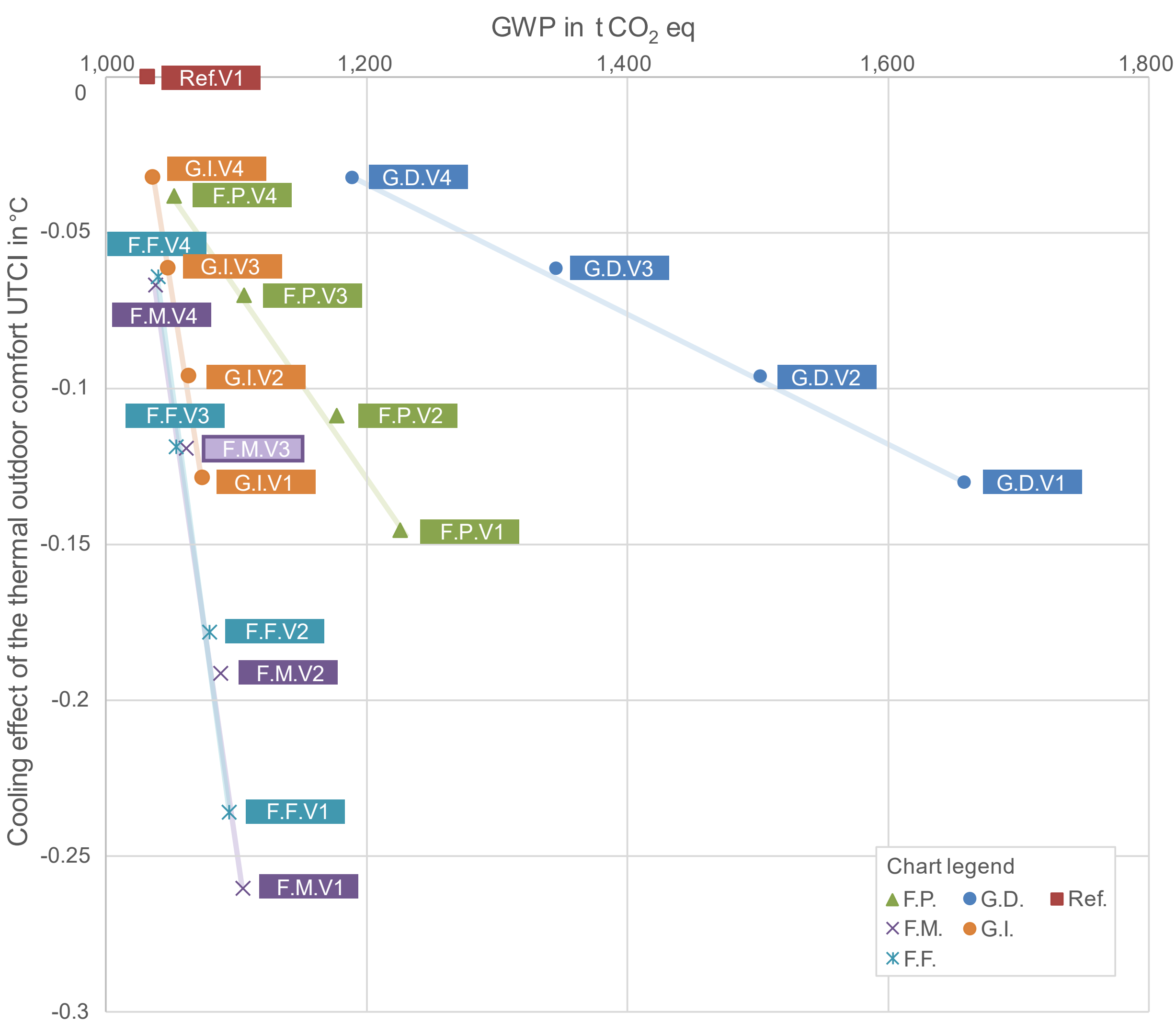

Figure 7: Result Comparison: LCA and Microclimatic Analysis

of climate change and adapting to its ongoing effects is a critical component of sustainable urban development. An integrated methodology that encompasses both LCA and microclimatic analysis is therefore indispensable. It empowers them to devise strategies that are not only emission-mitigative but also conducive to enhancing urban resilience and ameliorating the quality of life for city inhabitants.

Conclusion

This study thoroughly investigates the ecological and microclimatic impacts of green façade systems in urban districts, applying an integrated approach of LCA and microclimatic analysis. The principal findings reveal that green façade configurations, especially in the F.M.V3, G.I.V1, and F.F.V3 scenarios, effectively reduce CO_2 emissions and improve microclimatic conditions. This highlights the significant role green façades play in enhancing urban sustainability by balancing environmental effects with thermal comfort improvements. Based on these results, it is crucial for urban planning to incorporate both LCA and microclimatic analysis, ensuring environmentally sustainable and climatically favorable designs. Urban policies and development guidelines should be designed to incentivize projects that deliver verifiable benefits in terms of CO_2 reduction and microclimatic enhancements. The research also highlights challenges in achieving optimal cooling effectiveness of green façade systems, particularly in terms of identifying the most efficient approaches for their long-term implementation. This points to the need for further research, into diverse greening strategies and their broader implications. Such research will contribute to a more comprehensive understanding of the effectiveness of the cooling of green façades in urban environments.

Future studies will focus on a wider variety of greening scenarios, examining their long-term environmental impact. This approach will help refine the integration of LCA and microclimatic analysis, demonstrating its application in effective urban planning and the promotion of sustainable urban landscapes.

Acknowledgment

Thank you to the Energy Efficient Construction research team of the Institute for Structural Mechanics and Design for their dedicated support.

References

Alonso, Lucille; Renard, Florent (2020): A New Approach for Understanding Urban Microclimate by Integrating Complementary Predictors at Different Scales in Regression and Machine Learning Models. In: *Remote Sensing* 12 (15), S. 2434. DOI: 10.3390/rs12152434.

Alsaad, Hayder; Hartmann, Maria; Hilbel, Rebecca; Voelker, Conrad (2022): The potential of facade greening in mitigating the effects of heatwaves in Central European cities. In: *Building and Environment* 216, S. 109021. DOI: 10.1016/j.buildenv.2022.109021.

Ascione, Fabrizio; Masi, Rosa Francesca de; Mastellone, Margherita; Ruggiero, Silvia; Vanoli, Giuseppe Peter (2020): Green Walls, a Critical Review: Knowledge Gaps, Design Parameters, Thermal Performances and Multi-Criteria Design Approaches. In: *Energies* 13 (9), S. 2296. DOI: 10.3390/en13092296.

Bahramian, Majid; Yetilmezsoy, Kaan (2020): Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). In: *Energy and Buildings* 219, S. 109917. DOI: 10.1016/j.enbuild.2020.109917.

Bakhshoodeh, Reza; Ocampo, Carlos; Oldham, Carolyn (2022): Thermal performance of green façades: Review and analysis of published data. In: *Renewable and Sustainable Energy Reviews* 155, S. 111744. DOI: 10.1016/j.rser.2021.111744.

Battisti, Alessandra; Persiani, Sandra G. L.; Crespi, Manuela (2019): Review and Mapping of Parameters for the Early Stage Design of Adaptive Building Technologies through Life Cycle Assessment Tools. In: *Energies* 12 (9), S. 1729. DOI: 10.3390/en12091729.

Bherwani, Hemant; Singh, Anju; Kumar, Rakesh (2020): Assessment methods of urban microclimate and its parameters: A critical review to take the research from lab to land. In: *Urban Climate* 34, S. 100690. DOI: 10.1016/j.uclim.2020.100690.

Chàfer, Marta; Pérez, Gabriel; Coma, Julià; Cabeza, Luisa F. (2021): A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate. In: *Energy and Buildings* 249, S. 111236. DOI: 10.1016/j.enbuild.2021.111236.

Chew, Michael Y. L.; Conejos, Sheila; Azril, Fikril Hakim Bin (2019): Design for maintainability of high-rise vertical green facades. In: *Building Research & Information* 47 (4), S. 453–467. DOI: 10.1080/09613218.2018.1440716.

Detommaso, Maurizio; Costanzo, Vincenzo; Nocera, Francesco (2021): Application of weather data morphing for calibration of urban ENVI-met microclimate models. Results and critical issues. In: *Urban Climate* 38, S. 100895. DOI: 10.1016/j.uclim.2021.100895.

Eingrüber, Nils; Korres, Wolfgang; Schneider, Karl (2022): Microclimatic field measurements to support microclimatological modelling with ENVI-met for an urban study area in Cologne. In: *Adv. Sci. Res.* 19, S. 81–90. DOI: 10.5194/asr-19-81-2022.

Elliott, Helen; Eon, Christine; Breadsell, Jessica K. (2020): Improving City Vitality through Urban Heat Reduction with Green Infrastructure and Design Solutions: A Systematic Literature Review. In: *Buildings* 10 (12), S. 219. DOI: 10.3390/buildings10120219.

Faragallah, Riham Nady; Ragheb, Riham A. (2022): Evaluation of thermal comfort and urban heat island through cool paving materials using ENVI-Met. In: *Ain Shams Engineering Journal* 13 (3), S. 101609. DOI: 10.1016/j.asej.2021.10.004.

Halder, Bijay; Bandyopadhyay, Jatisankar; Banik, Papiya (2021): Evaluation of the Climate Change Impact on Urban Heat Island Based on Land Surface Temperature and Geospatial Indicators. In: *Int J Environ Res* 15 (5), S. 819–835. DOI: 10.1007/s41742-021-00356-8.

Hauschild, Michael Z.; Rosenbaum, Ralph K.; Olsen, Stig Irving; Hauschild, Michael; Rosenbaum, Ralph (Hg.) (2018): Life Cycle Assessment. Theory and Practice. Cham: Springer International Publishing; Imprint: Springer. Available online at https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=6312187.

Hildebrand, Linda; Tran, Kim; Zirwes, Ina; Kretschmer, Alina (2022): Life cycle assessment in façade design. In: Rethinking Building Skins: Elsevier, S. 495–517.

IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Irga, Peter J.; Torpy, Fraser R.; Griffin, Daniel; Wilkinson, Sara J. (2023): Vertical Greening Systems: A Perspective on Existing Technologies and New Design Recommendation. In: *Sustainability* 15 (7), S. 6014. DOI: 10.3390/su15076014.

ISO (2006a) Environmental management - Life cycle assessment - Principles and framework. ISO 14040:2006-10.

ISO (2006b) Environmental management – Life cycle assessment – Requirements and guidelines. ISO 14044:2006-10.

Jänicke, Britta; Milošević, Dragan; Manavvi, Suneja (2021): Review of User-Friendly Models to Improve the Urban Micro-Climate. In: *Atmosphere* 12 (10), S. 1291. DOI: 10.3390/atmos12101291.

Ketterer, Christine; Matzarakis, Andreas (2015): Comparison of different methods for the assessment of the urban heat island in Stuttgart, Germany. In: *International journal of biometeorology* 59 (9), S. 1299–1309. DOI: 10.1007/s00484-014-0940-3.

Ling, Tzen-Ying (2022): Rethinking greening the building façade under extreme climate: Attributes consideration for typo-morphological green envelope retrofit. In: *Cleaner and Circular Bioeconomy* 3, S. 100024. DOI: 10.1016/j.clcb.2022.100024.

Liu, Zhixin; Cheng, Ka Yuen; Sinsel, Tim; Simon, Helge; Jim, C. Y.; Morakinyo, Tobi Eniolu et al. (2023): Modeling microclimatic effects of trees and green roofs/façades in ENVI-met: Sensitivity tests and proposed model library. In: *Building and Environment* 244, S. 110759. DOI: 10.1016/j.buildenv.2023.110759.

Manso, Maria; Teotónio, Inês; Silva, Cristina Matos; Cruz, Carlos Oliveira (2021): Green roof and green wall benefits and costs: A review of the quantitative evidence. In: *Renewable and Sustainable Energy Reviews* 135, S. 110111. DOI: 10.1016/j.rser.2020.110111.

Motazedian, Asieh; Coutts, Andrew M.; Tapper, Nigel J. (2020): The microclimatic interaction of a small urban park in central Melbourne with its surrounding urban environment during heat events. In: *Urban Forestry & Urban Greening* 52, S. 126688. DOI: 10.1016/j.ufug.2020.126688.

Mughal, Muhammad Omer; Kubilay, Aytac; Fatichi, Simone; Meili, Naika; Carmeliet, Jan; Edwards, Peter; Burlando, Paolo (2021): Detailed investigation of vegetation effects on microclimate by means of computational fluid dynamics (CFD) in a tropical urban environment. In: *Urban Climate* 39, S. 100939. DOI: 10.1016/j.uclim.2021.100939.

Najjar, Mohammad K.; Figueiredo, Karoline; Evangelista, Ana Catarina Jorge; Hammad, Ahmed W. A.; Tam, Vivian W. Y.; Haddad, Assed (2022): Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design. In: *International Journal of Construction Management* 22 (4), S. 541–555. DOI: 10.1080/15623599.2019.1637098.

Oquendo-Di Cosola, V.; Olivieri, F.; Ruiz-García, L. (2022): A systematic review of the impact of green walls on urban comfort: temperature reduction and noise attenuation. In: *Renewable and Sustainable Energy Reviews* 162, S. 112463. DOI: 10.1016/j.rser.2022.112463.

Ottelé, M.; Perini, K.; Haas, E. M. (2014): Life cycle assessment (LCA) of green façades and living wall systems. In: Eco-efficient Construction and Building Materials: Elsevier, S. 457–483.

Peng, Lilliana L.H.; Jiang, Zhidian; Yang, Xiaoshan; He, Yunfei; Xu, Tianjing; Chen, Sophia Shuang (2020): Cooling effects of block-scale facade greening and their relationship with urban form. In: *Building and Environment* 169, S. 106552. DOI: 10.1016/j.buildenv.2019.106552.

Perera, T. A. N. T.; Nayanajith, T. M. D.; Jayasinghe, G. Y.; Premasiri, H. D. S. (2022): Identification of thermal hotspots through heat index determination and urban heat island mitigation using ENVImet numerical micro climate model. In: *Model. Earth Syst. Environ.* 8 (1), S. 209–226. DOI: 10.1007/s40808-021-01091-x.

Pioppi, Benedetta; Pigliautile, Ilaria; Pisello, Anna Laura (2020): Human-centric microclimate analysis of Urban Heat Island: Wearable sensing and data-driven techniques for identifying mitigation strategies in New York City. In: *Urban Climate* 34, S. 100716. DOI: 10.1016/j.uclim.2020.100716.

Rüter, Sebastian; Diederichs, Stefan (2012): Ökobilanz-Basisdaten für Bauprodukte aus Holz. Hg. v. Thünen-Institute of Wood Research Report (2012/01).

Salonen, Tarja; Hollands, Jutta; Sesto, Eldira; Korjenic, Azra (2022): Thermal Effects of Vertical Greening in Summer: An Investigation on Evapotranspiration and Shading of Façade Greening in Vienna. In: *Buildings* 12 (10), S. 1705. DOI: 10.3390/buildings12101705.

Santos, Teresa; Silva, Caio; Tenedório, José António (2019): Promoting Citizens' Quality of Life Through Green Urban Planning. In: Lemonia. Ragia, Robert Laurini und Jorge Gustavo Rocha (Hg.): Geographical Information Systems Theory, Applications and Management. Third International Conference, GISTAM 2017, Porto, Portugal, April 27{u2013}28, 2017, Revised Selected Papers, Bd. 936. First edition 2019. Cham: Springer International Publishing; Imprint: Springer (Communications in Computer and Information Science, 936), S. 153–175.

Shamsuddeen Abdullahi, Muhammad (2016): Facade Greening: A Way to Attain Sustainable Built Environment. In: *IJEMA* 4 (1), S. 12. DOI: 10.11648/j.ijema.20160401.13.

Stavrakakis, George M.; Katsaprakakis, Dimitris Al.; Damasiotis, Markos (2021): Basic Principles, Most Common Computational Tools, and Capabilities for Building Energy and Urban Microclimate Simulations. In: *Energies* 14 (20), S. 6707. DOI: 10.3390/en14206707.

Teichmann, Florian; Horvath, Andras; Luisser, Markus; Korjenic, Azra (2022): The Impact of Small-Scale Greening on the Local Microclimate—A Case Study at Two School Buildings in Vienna. In: *Sustainability* 14 (20), S. 13089. DOI: 10.3390/su142013089.

Toparlar, Y.; Blocken, B.; Maiheu, B.; van Heijst, G.J.F. (2017): A review on the CFD analysis of urban microclimate. In: *Renewable and Sustainable Energy Reviews* 80, S. 1613–1640. DOI: 10.1016/j.rser.2017.05.248.

Yang, Junyan; Hu, Xinyu; Feng, Haiyi; Marvin, Simon (2021): Verifying an ENVI-met simulation of the thermal environment of Yanzhong Square Park in Shanghai. In: *Urban Forestry & Urban Greening* 66, S. 127384. DOI: 10.1016/j.ufug.2021.127384.

Yudina, Anna (2017): Garden city. Supergreen buildings, urban skyscapes and the new planted space. London: Thames & Hudson.

Zihlmann Sánchez, Violeta (2023): Stakeholder analysis on the current situation and possible integration of Nature-based Solutions in Zurich and investigation of cooling efficiency and improvement of outdoor thermal conditions with Nature-based Solutions in Novi Sad. ZHAW Zürcher Hochschule für Angewandte Wissenschaften.