Resilient Green Building Envelopes

A computational method for holistic sustainability assessments and interdisciplinary design decision-making

Surayyn Uthaya Selvan[1] & Francesca Mosca[2], Katia Perini[3], Yasha J. Grobman[4] & Shany Barath[5]
[1, 4, 5]TECHNION – Israel Institute of Technology [2,3] University of Genoa
[1]surayyn@technion.ac.il [2]francesca.mosca@edu.unige.it [3]katia.perini@unige.it
[4,5]{yasha|barathshany}@technion.ac.il

Urbanisation catalyses environmental degradation, leading to reduced ecosystem services and compromised human well-being. To mitigate negative anthropogenic impacts, cities draw on sustainable and resilient design strategies. Among these solutions are green envelopes, which are highly beneficial in densely populated environments. However, existing sustainability methods lack a comprehensive framework to holistically evaluate the influence of green building envelopes. This paper introduces a computational method for the holistic sustainability evaluation of green envelopes, focusing on climate change and material usage impacts through strategic indicators. By employing a hybrid multi-criteria decision-making model, our method facilitates the generation and selection of optimised design alternatives aimed at enhancing environmental resilience. We examine the trade-offs between alternatives, prioritising various objectives related to architectural and sustainability performances. The results show that accounting for climate change and material use impacts enhanced trade-offs between design alternatives without compromising key architectural considerations. This research provides valuable insights for resilient envelope designs amidst rising urban environmental complexities.

Keywords: *urban environmental resilience, sustainability assessment, multi-criteria decision-making, green envelope design*

INTRODUCTION

Urbanisation threatens ecosystem service provision and compromises human health and well-being (McDonald, Marcotullio and Güneralp, 2013). Consequently, cities adopt climate-resilient strategies and leverage digital technologies to address rising anthropogenic activities (Pee and Pan, 2022). Design solutions, especially nature-based solutions (NbS), mitigate air pollution, flooding, and heat waves in dense urban areas (Abdulateef and Al-Alwan, 2022; Biswal *et al.*, 2022). Green interventions like green roofs and walls enhance the building envelope, which often contributes to enhanced thermal comfort and environmental resilience (Heaviside, Macintyre and Vardoulakis, 2017; Rossi *et al.*, 2015). In bioclimatic and green architecture, this is often implemented through vegetated surfaces (Thorpert, Englund and Sang, 2023).

While implementation of NbS is important, assessing the degree of improvement is equally as crucial. Current assessment schemes, such as life-cycle assessment (LCA), frequently fall short in addressing environmental resilience and design flexibility (Mosca, 2024). New sustainability evaluation methods considering climate change, material impact, and biodiversity loss are needed for better-informed design solutions. Additionally, a systematic decision-making process, facilitated by multi-criteria decision-making (MCDM), is necessary for effective implementation (Selvan et al., 2023).

This paper explores integrating holistic sustainability evaluation into MCDM using computational methods and tools proposed by Mosca (2024) and Selvan et al. (2023). The main aim is to assess the trade-off impacts of sustainability indicators concerning climate change and material usage on a green envelope building design. The paper begins with an overview of green envelope design objectives, followed by a description of hybrid MCDM for design decision-making. We then present a case study to test the proposed interdisciplinary approach. Finally, future outlooks for environmentally resilient building envelope solutions are discussed.

BACKGROUND

Building envelopes have traditionally mediated indoor and outdoor environments (Mirzabeigi and Razkenari, 2022). However, increasing urban complexities necessitate enhancing building envelopes by incorporating sustainability principles into the design process. This ensures that sustainability is as important as architectural considerations. The following sections discuss green envelope designs by correlating architectural and sustainability objectives. Then, we detail the computational decision-making process using a hybrid MCDM model that optimises and evaluates design alternatives with strategic sustainability indicators.

Green building envelope design

Green envelope designs vary based on intervention locations and management strategies (Perini and Roccotiello, 2018). However, two key aspects are the aperture and green ratios. Apertures influence solar radiation, daylighting, and energy consumption, leading to local regulations on window-to-wall ratios (Ayoosu *et al.*, 2021; Elghamry and Hassan, 2020). The green ratio determines vegetation distribution by considering the soil volume required for accommodating plant rooting depths (Selvan *et al.*, 2023). Vegetative layers enhance efficiency by providing insulation, reducing solar radiation, and mitigating uncomfortable wind speeds (Tan *et al.*, 2020).

While these two aspects perform in tandem, design conflicts can also arise. For example, increasing the window-to-wall ratio may result in the reduction of vegetated areas. Additionally, increased soil volume can affect the envelope's structural performance due to excessive material usage (Ogut, Tzortzi and Bertolin, 2022). To alleviate this conflict, key design factors must be explored, such as the building massing configuration, represented by the envelope shape coefficient, i.e., envelope surface area to volume ratio (Ciardiello et al., 2020).

Sustainability objectives for green envelope design

Vegetated building envelopes offer opportunities to integrate sustainability-driven objectives which are vital in design decision-making. Some examples of these objectives include climate change adaptation and mitigating negative material impacts (Mosca, 2024). Climate change adaptation can be achieved by reducing the UHI effect to regulate outdoor thermal comfort (Heaviside, Macintyre and Vardoulakis, 2017). By introducing vegetation onto surfaces, local thermal conditions can be greatly improved. This can be evaluated by measuring the Universal Thermal Climate Index (UTCI), an indicator which accounts for local microclimatic parameters and the impact on human physiological processes (Błazejczyk *et al.*, 2013). In addition to accounting for vegetation on envelopes, the envelope

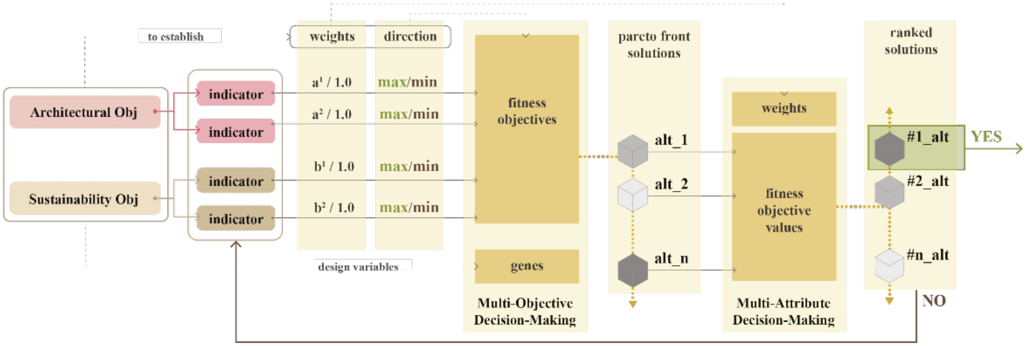


Figure 1
Schematic hybrid MCDM model process, adapted from Selvan et al. (2023)

material composition also has significant environmental impacts. Envelopes are predominantly composed of materials with high carbon footprints (Riahinezhad *et al.*, 2021); thus, it is necessary to measure the potential environmental degradation that may occur. This can be strategically implemented by measuring the indicator, global warming potential (GWP) which is associated with design and material configurations (Xu, 2022). Operationally, this indicator is quantified as the weight of carbon dioxide emissions equivalent to describe greenhouse gas effects, maintaining a standard unit of measurement ("*Carbon Dioxide Equivalent*", 2023).

Computational hybrid multi-criteria decision-making

As explicated in the previous sections, green envelope design is heavily interwoven with various building operations and sustainability objectives. This multitude of criteria requires strategic methods and tools to support interdisciplinary design decision-making. The well-researched field of MCDM offers decision-makers with algorithms and techniques to identify best-case scenarios, known as alternatives, to solve a problem. Chen and Hwang (1992) categorised two MCDM strategies based on the problem typology and criterion characteristics.

The first is multi-objective decision-making (MODM), employed to generate a range of alternatives using an initial alternative state. This strategy often utilises heuristic algorithms to improve upon a decision-making problem. Here, the criteria are represented by fitness objectives which have directional constraints. The second is multi-attribute decision-making (MADM), employed to select the most suitable alternative(s) from a pool of existing alternatives. MADM algorithms leverage mathematical equations and weighting strategies to evaluate the performances of the alternatives. Here, the criteria are represented by attributes.

A third category emerged because of the increased complexity of decision-making – hybrid MCDM. This strategy is characterised by two or more MCDM strategies in a sequential or combinatory approach. One example is the use of MODM and MADM in a sequential manner to generate and evaluate optimised design alternatives based on key performance indicators (KPIs) (Selvan et al., 2023). As reflected in Fig. 1, this strategy was translated into a computational model to provide decision-makers with flexibility in defining fitness objectives and attribute priorities to meet specific design briefs. The model leverages Grasshopper plugins and components to support parametric design processes. The model is initiated with MODM using the plugin, Wallacei (Makki, Showkatbaksh

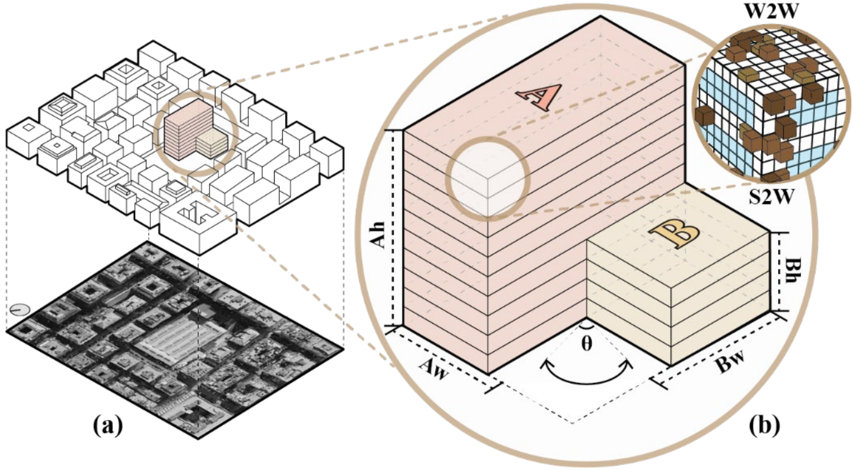


Figure 2
(a) Proposed building site in Genoa, Italy and (b) The building form and relevant design parameters

and Song, 2019), which employs the Non-dominated Sorting Genetic Algorithm II (NSGA-II) for MODM. The fitness objectives are defined by applying directional constraints to the defined KPIs. Subsequently, the MADM algorithm, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), constructed using native components, calculates the optimised fitness objective values into performance scores based on weights. These weights can be defined by establishing priorities for the associated fitness objectives. This sequential process allows decision-makers to identify best-suited alternatives for various priorities within the same pool of solutions.

RESEARCH METHODOLOGY

Drawing from green envelope design aspects and potential objectives, the main aim of this paper is to develop computational methods and tools to evaluate trade-offs between architectural and sustainability performances. We implemented a comparative experiment employing the hybrid MCDM model on a case study located in Genoa, Italy (Fig. 2a). The site, considered a compact midrise local climatic zone, is characterised by temperate microclimatic conditions. Additionally, the site is described by a conventional grid layout, limited green spaces, and dense buildings. Therefore, this results in low levels thermal comfort during the summer due to the UHI effect. Additionally, current local regulatory plans proposed the development of a new residential building on the selected site. These factors provide opportunities to explore comprehensive design solutions, as presented in the previous sections, to facilitate early-stage design decision-making aligned with site-specific criteria for urban redevelopment (Moscovitz and Barath, 2022). By exploring trade-offs between the selected architectural and sustainability indicators through the hybrid MCDM model, a more comprehensive design decision-making process integrating environmental sustainability can be implemented.

Green envelope design variables

To test the proposed computational approach, we selected a generic multistorey building typology which has multiple floors and different form configurations, as defined by Lehner and Blaschke (2019). This allows for more flexible massing configurations in the design exploration which also alters the microclimatic conditions. As illustrated in Fig. 2b, the proposed building has a design space comprised of two blocks, labelled *A* and *B*, enclosed within a 30 x 35m boundary. The height ratio of *A* and *B* is constrained to 2.5 times that of the smaller block, with the ratio being interchangeable between the two. The height (*h*) of the taller block is determined by the number of floors (*f*), ranging from 5 to 10 storeys, with a floor-to-ceiling height of 3.5m. The block widths (*w*) are defined by reparametrized thresholds based on the boundary extents. Additionally, the building orientation (θ) ranges 15-degree steps between -90 to 90 degrees, allowing rotation.

To facilitate the sustainability indicator simulation and hybrid MCDM model, the building and site geometries are converted into mesh cells (Fig. 2b). Then, the multistorey building is distributed with window and soil cells informed by design variables. Window cell distribution is constrained by window-to-wall ratios (*W2W*) between 20% to 60% per façade orientation, generated using the Honeybee plugin [ver.1.7.1]. Then, soil cells are distributed on the envelope, with locations shuffled by a random seed value and constrained by an overall soil-to-wall ratio (*S2W*) between 10% to 100%. To generate soil volumes, discrete values ranging from 0.1 to 0.8m are randomly assigned and extruded perpendicularly from each soil cell.

Architectural fitness objectives

The architectural objectives were defined based on the key design aspects and potential building operation performances of green building envelopes. The first objective was to enhance building operation efficiency by minimising the envelope shape coefficient (*sCof*), computed using the value derived from the relationship between the total envelope surface area and building volume. The second was to improve indoor daylighting conditions which was correlated to maximising the average window-to-wall ratio (*aW2W*), calculated by the mean ratio across each façade orientation. Finally, to propagate vegetative growth, the last objective was to maximise the total soil volume (*sVol*) to accommodate different plant rooting depth requirements. However, the structural performance of the envelope must also be considered, requiring the simultaneous minimisation of the *sVol*.

Sustainability fitness objectives

The sustainability objectives aimed to improve local liveability and reduce heat-related risks, aligned with the 11th Sustainability Development Goals for Sustainable Cities and Communities (United Nations, 2015). Two main targets were translated into three fitness objectives. The first target was to mitigate the UHI effect by minimising the local mean radiant temperature (MRT) and associated UTCI values of the site. These were computed using the Ladybug plugin [ver.1.7.0] for the peak summer day, August 15th between 12:00 pm to 14:00 pm, considering local microclimatic conditions and context and building geometries. The second target was to reduce material impacts by minimising the GWP of the building. Using the Cardinal LCA plugin [ver.0.0.1], GWP was calculated based on the total surface area of concrete and glass materials.

Table 1
Weight distribution for equal, architectural (ARC), and sustainability (SUS) objective priorities

Obj.	*Computed Indicator*	*Abbr.*	*Unit*	*Direction*	*Priority*		
					Equal	***ARC***	***SUS***
ARC	Shape Coefficient	sCof	n/a	MIN	0.143	0.175	0.075
	Average Window-to-Wall Ratio	aW2W	%	MAX	0.143	0.175	0.075
	Total Soil Volume	sVol	m^3	MIN	0.143	0.175	0.075
				MAX	0.143	0.175	0.075
SUS	Mean Radiant Temperature	MRT	°C	MIN	0.143	0.1	0.233
	Universal Thermal Climate Index	UTCI	°C	MIN	0.143	0.1	0.233
	Global Warming Potential	GWP	$kgCO^2e$	MIN	0.143	0.1	0.233

Criteria		*Unit*	***Benchmark* Alternative**	*Equal*	*ARC*	*SUS*
				Alt. {7-8}	**Alt. {8-2}**	**Alt. {8-5}**
TOPSIS Score		-	-	0.523	0.532	0.633
Genes	*Block Af : Bf*	u	10 : 4	6 : 2	9 : 3	2 : 5
	θ	°	0	-30	-75	30
	W2W (N,S,E,W)	%	30,30,30,30	52,55,53,55	58,55,56,59	55,30,33,41
	S2W	%	0	20	80	80
(ARC) Fitness Objectives	*sCof*	-	0.28	0.271	0.246	0.402
	aW2W	%	0.3	0.538	0.57	0.398
	sVol	m^3	0	143	717	383
(SUS) Fitness Objectives	*MRT*	°C	49	49.8	48.5	50.39
	UTCI	°C	27.9	28.14	27.8	28.3
	GWP	$kgCO^2e$	408215.7	292046.9	376092.7	185719.9

Table 2
TOPSIS scores and optimised criteria values for best suited alternatives considering equal, architectural (ARC), and sustainability (SUS) priorities

Based on the Inventory of Carbon and Energy (ICE) database, the GWP coefficients were: 0.1033 for walls and planters and 0.14369 for 5mm single-pane windows.

Computational hybrid multi-criteria decision-making

The hybrid MCDM model was used as the tool to evaluate the trade-offs between the defined architectural and sustainability objectives. As illustrated in Fig. 1, the green envelope design variables and associated objectives were used as the gene and fitness objective input to initiate the MODM. Then, the resulting Pareto front solutions were evaluated using MADM to identify the best-suited alternatives for three priority scenarios: equal, architectural and sustainability. Each alternative was compared against a benchmark design (Fig. 3) with the design variables detailed in Table 2.

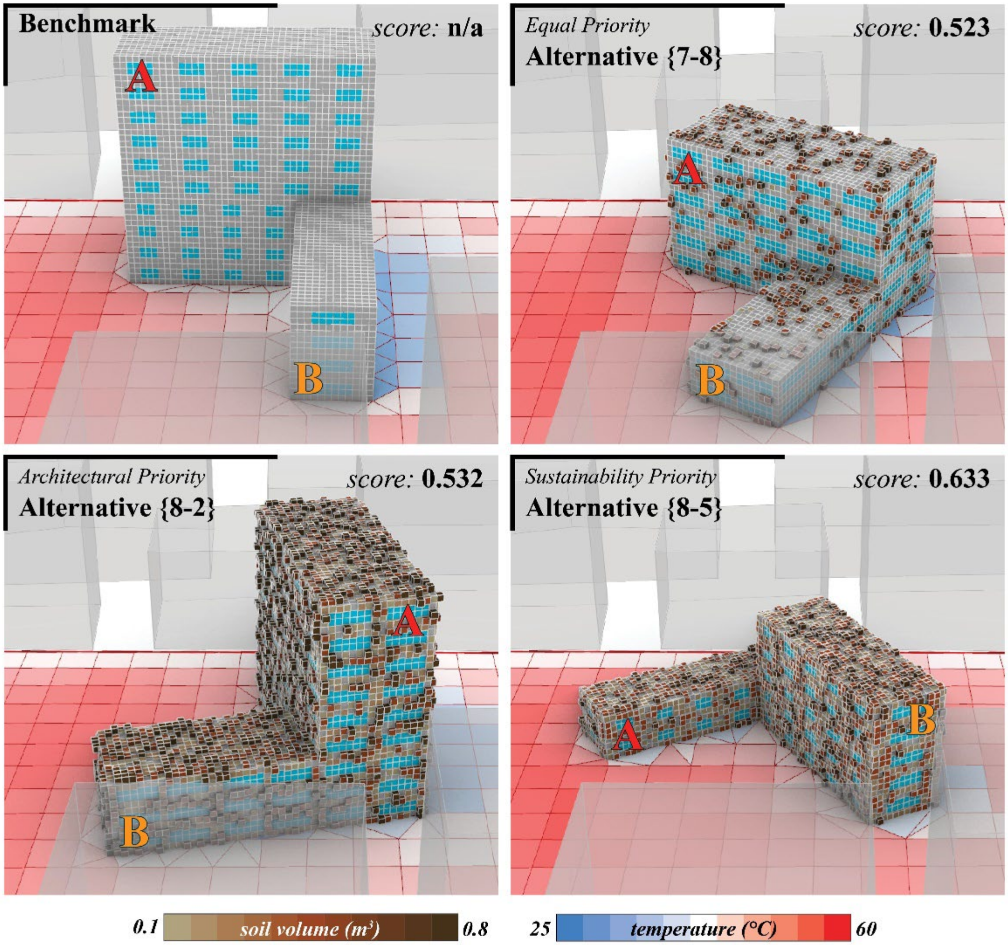
The MODM process of the model was set to run for a generation size and count of 10, resulting in 100 alternatives. For the MADM process, weights were assigned to each fitness objective based on the associated priorities (Table 1). Ultimately, the trade-offs between the resulting alternatives were quantitatively evaluated based on the resulting TOPSIS score and optimised gene and fitness objective values.

RESULTS AND DISCUSSION

Out of the 100 alternatives, only 41 Pareto front solutions were generated, in which three alternatives were identified as best suited for each objective priority (Fig. 3). The alternatives for equal, architectural, and sustainability priorities were the ninth individual in the eighth generation (Alt. {7-8}), the third individual in the ninth generation (Alt. {8-2}), and the sixth individual in the ninth generation (Alt. {8-5}). These alternatives achieved performance scores of 0.523, 0.532, and 0.633, respectively.

As detailed in Table 2, for the gene values, i.e., design variables, all three alternatives had a reduced number of floors compared to the benchmark alternative. However, Alt. {7-8} had six floors, suggesting a compromise between the architectural and sustainability priorities. Additionally, each alternative had rotations where the lesser façade surface areas were positioned toward the East-West orientation. As seen in Fig. 3, all alternatives except Alt. {8-5}, maintained the height ratio, with block A having the tallest block. Moreover, all three alternatives had improved *W2W* ratios, except Alt. {8-5}, which retained a 30% ratio on the South façade and a slightly higher ratio of 33% on the East. Notably, Alt. {8-2} and Alt. {8-5} achieved a much higher *S2W* ratio of 80% compared to Alt. {7-8}, which only had

Figure 3
Best suited alternatives based on equal, architectural, and sustainability priorities, visualising window and soil distribution and thermal conditions



20%. Regarding the architectural fitness objectives, in comparison to the benchmark alternative, Alt. {7-8} and Alt. {8-2} had a decrease in the *sCof* value by 3.2% and 12.1%, respectively, while Alt. {8-5} had an increase of nearly 43%. Additionally, Alt. {8-2} and Alt. {8-5} had significantly more soil volume distributed with value for Alt. {8-2} and Alt. {8-5} achieved a slight reduction of 1% each, while Alt. {7-8} saw a slight increase of 1.6%. Similarly, the UTCI values for Alt. {7-8} and Alt. {8-5} experienced slight increases of 0.9% and 1.4% each, while Alt. {8-2} remained mostly unchanged. Contrastingly, all three alternatives had more significant changes in the GWP values with Alt. {7-8} and Alt. {8-5} showing reductions of 28.5% and 54.5%, respectively, while Alt. {8-2} had a smaller reduction of only 7.9%.

The resulting alternatives demonstrated enhanced architectural and sustainability performances compared to the benchmark alternative. For example, Alt. {7-8} which was best suited for equal priority, illustrated satisfactory trade-offs despite a lower soil volume distribution of 143m^3. This is reflected by the optimised fitness objective values that fall within the ranges of the alternatives best suited for architectural and sustainability priorities. Additionally, Alt. {7-8} had improved *sCof* and *W2W* values and, although the MRT and UTCI values were inconsequential, there was an enhancement reflected in the GWP. The architecturally suited alternative, Alt. {8-2}, featured the highest number of floors, with improvements across the architectural objectives. Minor changes were seen in the sustainability fitness objectives, especially in the MRT and UTCI values. Finally, Alt. {8-5}, best suited for the sustainability priority, had the lowest number of floors but the highest *sCof* value, with a slight enhancement in the *W2W* ratio. As with the remaining alternatives, the MRT and UTCI values had minimal changes, but a significant improvement was achieved in the GWP compared to the other alternatives.

Overall, the results highlight the importance of refining objectives for site-specific criticalities and potentials, particularly in defining overarching sustainability objectives. The minimal deviations in the MRT and UTCI values suggest that massing configurations of the same building typology, do not drastically alter the thermal microclimatic conditions. Therefore, to observe consequential improvements, variations in building typologies must be explored in design optimisation. Additionally, façade geometries must be explored as they have significant consequence on the thermal performances of building envelopes (Hershcovich *et al.*, 2021). Distinctly, the soil volume distribution indicates that a large amount of soil does not compromise the carbon footprint or structural performance of the design as reflected in Alt. {8-5}. Nevertheless, by integrating architectural priorities such as structural loads, more balanced design solutions can be generated and identified.

CONCLUSIONS

This paper presented computational methods and tools to facilitate the integration of holistic sustainability evaluation measures in a hybrid MCDM process to streamline design decision-making. Through a contextualised green building envelope case study, we defined architectural and sustainability objectives to inform the generation and evaluation of optimised design alternatives. This was driven by strategic sustainability indicators to provide refinement in optimising and identifying suitable alternatives with balanced objective performances. The hybrid MCDM model generated and identified alternatives based on varied objective priorities. These alternatives were compared to a benchmark design whereby the trade-off between the fitness objectives was achieved. In particular, the alternative for equal priority had fitness objective values that occur between the ranges of the alternatives best suited for architectural and sustainability priorities. This comparative evaluation highlights the effectiveness of assessing optimisation trade-offs. Future research will focus on the performance of varied building typologies and configurations on the UHI effect reduction, exploring how design-led optimisation processes can support site-specific objectives. Finally, vegetative properties, such as evapotranspiration (Jones, 2013), could be modelled and simulated to enhance microclimatic conditions while considering impacts on biodiversity and ecosystem service provision (Mosca, 2024). This ecological facet will also contribute to more holistic sustainability considerations. In summary, the proposed computational methodology for design decision-making using sustainability indicators provides valuable insights to navigate urban complexities and generate resilient building envelope designs for future cities.

REFERENCES

Abdulateef, M.F. and A. S. Al-Alwan, H. (2022) 'The effectiveness of urban green infrastructure in reducing surface urban heat island', *Ain Shams Engineering Journal*, 13(1), p. 101526. Available at: https://doi.org/10.1016/j.asej.2021.06.012.

Ayoosu, M.I. *et al.* (2021) 'Daylighting Evaluation and Optimisation of Window to Wall Ratio for Lecture Theatre in the Tropical Climate', *Journal of Daylighting*, 8(1), pp. 20–35. Available at: https://doi.org/10.15627/jd.2021.2.

Biswal, B.K. *et al.* (2022) 'Nature-based Systems (NbS) for mitigation of stormwater and air pollution in urban areas: A review', *Resources, Conservation and Recycling*, 186, p. 106578. Available at: https://doi.org/10.1016/j.resconrec.2022.106578.

Błazejczyk, K. *et al.* (2013) 'An introduction to the Universal thermal climate index (UTCI)', *Geographia Polonica*, 86(1), pp. 5–10. Available at: https://doi.org/10.7163/GPol.2013.1.

Carbon Dioxide Equivalent (2023) *Eurostat Statistics Explained*. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Carbon_dioxide_equivalent (Accessed: 10 March 2024).

Chen, S. J. and Hwang, C. L. (1992) 'Introduction', in S. J. Chen and C. L. Hwang (eds) *Fuzzy Multiple Attribute Decision Making: Methods and Applications*. Berlin, Heidelberg: Springer (Lecture Notes in Economics and Mathematical Systems), pp. 1–15. Available at: https://doi.org/10.1007/978-3-642-46768-4_1.

Ciardiello, A. *et al.* (2020) 'Multi-objective approach to the optimization of shape and envelope in building energy design', *Applied Energy*, 280, p. 115984. Available at: https://doi.org/10.1016/j.apenergy.2020.115984.

Elghamry, R. and Hassan, H. (2020) 'Impact of window parameters on the building envelope on the thermal comfort, energy consumption and cost and environment', *International Journal of Ventilation*, 19(4), pp. 233–259. Available at: https://doi.org/10.1080/14733315.2019.1665784.

Heaviside, C., Macintyre, H. and Vardoulakis, S. (2017) 'The Urban Heat Island: Implications for Health in a Changing Environment', *Current Environmental Health Reports*, 4(3), pp. 296–305. Available at: https://doi.org/10.1007/s40572-017-0150-3.

Hershcovich, C. *et al.* (2021) 'Thermal performance of sculptured tiles for building envelopes', *Building and Environment*, 197, p. 107809. Available at: https://doi.org/10.1016/j.buildenv.2021.107809.

Jones, H.G. (2013) Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. 3rd edn. Cambridge University Press.

Lehner, A. and Blaschke, T. (2019) 'A Generic Classification Scheme for Urban Structure Types', *Remote Sensing*, 11(2), p. 173. Available at: https://doi.org/10.3390/rs11020173.

Makki, M., Showkatbaksh, M. and Song, Y. (2019) 'Wallacei Primer 2.0'. Available at: https://www.wallacei.com/.

McDonald, R.I., Marcotullio, P.J. and Güneralp, B. (2013) 'Urbanization and Global Trends in Biodiversity and Ecosystem Services', in T. Elmqvist et al. (eds) *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment*. Dordrecht: Springer Netherlands, pp. 31–52. Available at: https://doi.org/10.1007/978-94-007-7088-1_3.

Mirzabeigi, S. and Razkenari, M. (2022) 'Design optimization of urban typologies: A framework for evaluating building energy

performance and outdoor thermal comfort', *Sustainable Cities and Society*, 76, p. 103515. Available at: https://doi.org/10.1016/j.scs.2021.103515.
Mosca, F. (2024) 'A conceptual framework for the optimization of environmentally sustainable nature-based solutions', *Journal of Digital Landscape Architecture*, 9-2024, p. 173-181. Available at: https://doi.org/10.14627/537752017.
Moscovitz, O. and Barath, S. (2022) 'A Generative Design Approach to Urban Sustainability Rating Systems During Early-Stage Urban Development', in. *CAADRIA 2022: Post-Carbon*, Sydney, Australia, pp. 171–180. Available at: https://doi.org/10.52842/conf.caadria.2022.1.171.
Ogut, O., Tzortzi, N.J. and Bertolin, C. (2022) 'Vertical Green Structures to Establish Sustainable Built Environment: A Systematic Market Review', *Sustainability*, 14(19), p. 12349. Available at: https://doi.org/10.3390/su141912349.
Pee, L.G. and Pan, S.L. (2022) 'Climate-intelligent cities and resilient urbanisation: Challenges and opportunities for information research', *International Journal of Information Management*, 63, p. 102446. Available at: https://doi.org/10.1016/j.ijinfomgt.2021.102446.
Perini, K. and Roccotiello, E. (2018) 'Chapter 3.4 - Vertical Greening Systems for Pollutants Reduction', in G. Pérez and K. Perini (eds) *Nature Based Strategies for Urban and Building Sustainability*. Butterworth-Heinemann, pp. 131–140. Available at: https://doi.org/10.1016/B978-0-12-812150-4.00012-4.
Riahinezhad, M., Hallman, M. and Masson, J.-F. (2021) 'Critical Review of Polymeric Building Envelope Materials: Degradation, Durability and Service Life Prediction', *Buildings*, 11(7), p. 299. Available at: https://doi.org/10.3390/buildings11070299.
Rossi, F. *et al.* (2015) 'Retroreflective façades for urban heat island mitigation: Experimental investigation and energy evaluations', *Applied Energy*, 145, pp. 8–20. Available at: https://doi.org/10.1016/j.apenergy.2015.01.129.
Selvan, S.U. *et al.* (2023) 'Multi-species building envelopes: Developing a multi-criteria decision-making methodology for cohabitation', in *Proceedings of the 28th International Conference of the Association for Computer-aided Architectural Design Research in Asia*. *CAADRIA 2023*, India: The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), pp. 645–654. Available at: https://doi.org/10.52842/conf.caadria.2023.2.643.
Tan, H. *et al.* (2020) 'Building envelope integrated green plants for energy saving', *Energy Exploration & Exploitation*, 38(1), pp. 222–234. Available at: https://doi.org/10.1177/0144598719875529.
Thorpert, P., Englund, J.-E. and Sang, Å.O. (2023) 'Shades of green for living walls – experiences of color contrast and its implication for aesthetic and psychological benefits', *Nature-Based Solutions*, 3, p. 100067. Available at: https://doi.org/10.1016/j.nbsj.2023.100067.
United Nations (2015) 'Transforming our world: the 2030 Agenda for Sustainable Development'. Available at: https://wedocs.unep.org/20.500.11822/9814.
Xu, X. *et al.* (2022) 'How to minimize the embodied environmental impact of green building envelope? An automatic optimization method', *Environmental Impact Assessment Review*, 93, p. 106732. Available at: https://doi.org/10.1016/j.eiar.2021.106732.