Multi-species Building Envelopes: Developing a multi-criteria design decision-making methodology for cohabitation

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MULTI-SPECIES BUILDING ENVELOPES

Developing a Multi-criteria Design Decision-making Methodology for Cohabitation

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Abstract. Anthropic activities negatively impact natural and artificial ecosystems, necessitating interdisciplinary mitigation strategies such as multi-species building envelope designs. This paper introduces a computational multi-criteria decision-making (MCDM) methodology to support these envelope designs. We also propose a nested set strategy for key performance indicators (KPI) to strategically measure architectural and ecological performances. We integrate the strategy into a proposed hybrid MCDM methodology using computational design tools. The methodology was tested using a generic volume case study described by an architectural and ecological objective with varied priorities. Initial results highlight the computational interoperability of hybrid MCDM, informed by nested KPI set priorities, as support for multi-species building envelope designs.

Keywords. multi-species envelope design, key performance indicators, multi-objective optimisation, multi-attribute decision-making

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1. Introduction

Urbanization negatively impacts the biotic environment resulting in a loss of ecosystem function and biodiversity (European Environment Agency, 2020). The loss of species such as mason bees and house sparrows in high-density areas affects the stability of ecological communities which results in reduced biotic complexity (Alberti & Marzluff, 2004). In built-up areas of cities, where most of the biodiversity loss occurs, strategies to improve local biodiversity must be integrated into urban planning and design solutions (Weisser et al., 2022). Current architectural solutions, while beneficial, rarely support biodiversity and ecosystem functions and are primarily driven by human-centric objectives (Fineschi & Loreto, 2020). Although human-centricity is a key aspect in creating holistic and inclusive design solutions, the existence of other living organisms must also be acknowledged. Thus, to create truly equitable environments, designers must expand beyond human-centred paradigms and be ecologically inclusive.

While there has been research on improving biodiversity in the built environment (Mata et al., 2020), there is limited knowledge of ecological influence at the building scale. Multi-species design aims to address this notion by introducing added ecological value into architectural solutions (Weisser et al., 2022). A starting point for multi-species design intervention is the building envelope. This is because building envelopes play a significant role in mediating indoor and outdoor environments, enhancing building performance, and potentially supporting the colonization of living organisms (Mahrous et al., 2022; Mirzabeigi & Razkenari, 2022). Multi-species building envelope design equally accounts for human requirements and the requirements of other living organisms (Canepa et al., 2022; Perini et al., 2021; Weisser et al., 2022). This necessitates introducing ecological knowledge into architectural design which poses a challenge because of the varied technical requirements and decision-making support between the two disciplines (Weisser et al., 2022). In addition, accounting for multi-species requirements warrants simultaneous consideration of, potentially, conflicting design criteria. Therefore, a systematic and objective approach to decision-making is necessary.

This paper addresses these challenges as part of an ongoing research project by proposing a computational multi-criteria decision-making (MCDM) methodology to support multi-species building envelope designs. First, we present a strategy to measure architectural and ecological performances using nested sets of key performance indicators (KPIs). Then, we propose a hybrid MCDM methodology integrated with the KPI strategy and implemented in a computational environment. The methodology was tested using a generic building envelope and the initial results are discussed. Finally, we elaborate on future steps to support more informed design decision-making for multi-species building envelopes.

2. Measuring architectural and ecological performances

Architectural performances are often evaluated using energy consumption, human comfort (i.e., visual, and thermal), and cost parameters (Grobman, 2011). Currently, these performances are inherently biased towards building and human-centred evaluations. Even in instances where biotic components are introduced into design, performances are also measured with anthropocentric parameters such as the reduction of air temperature due to the transpiration of trees (Sudimac et al., 2019). Therefore, to support multi-species designs, defining true ecological objectives is imperative. This allows for more strategic evaluations of architectural and ecological performances that are inclusive of other living organisms such as plants and animals.

However, the multitude of potential ecological objectives linked to the dynamic complexity of ecological communities poses a challenge in design decision-making. Consequently, most ecological indicators only partially account for this complexity, which results in simplifications. In ecology, a widely used objective is to increase Species Diversity, whereby Species Richness can serve as an indicator. The underlying assumption is that an increased number of species is correlated to an increase in ecosystem productivity, resilience, and stability (Weisser et al., 2017). However, an indicator such as Species Richness would be difficult to measure in architectural design as it requires a prediction of how form affects the number of species, which is currently not possible. This is because knowledge of the correlations between architecture and indicators linked to ecological objectives is severely limited.

One potential approach to bridge this gap between ecological objectives and measurable indicators for design is by establishing nested sets. Nested sets establish links between subsets in a hierarchical structure, like Matryoshka dolls. Fig. 1 shows an example of a nested set for increasing Thermal Comfort and Species Diversity. Nested sets can be integrated into design decision-making by linking objectives through KPIs that are quantified by goals. Objectives are defined as directional attributes defined to improve upon a decision-making problem, while goals are target levels expressed in a specific state in space and time (Masud, 1978). In essence, objectives frame the KPI directions (e.g., to maximize or to minimize) while goals numerically represent the KPI values. For example, an objective "to maximize thermal comfort" can be quantified with the KPI "indoor temperature", which has a goal between 23.0 to 26.7°C (ASHRAE, 2016).

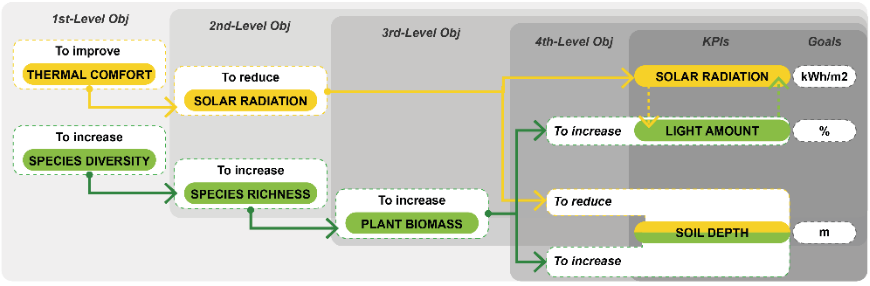


Figure 1. Nested sets example to establish links between a first-level architectural and ecological objective (Obj) by chaining lower-level objectives described by key performance indicators (KPIs).

As reflected in Fig. 1, nested sets establish correlations between higher-level objectives through a hierarchical deconstruction of lower-level objectives. For example, a lower-level objective for Species Diversity would be Plant Species Richness because it can be used as a measure of Species Diversity. A further lower-level objective, such as Plant Above-Ground Biomass, can be identified as it has been shown to be positively correlated with Plant Species Richness (Sonkoly et al., 2019). Plant Biomass is also positively influenced by abiotic properties such as light, water and nutrient availability which can serve as KPIs. A final simplification would then be to subsume the soil-related abiotic indicators into a single parameter "Soil Depth", which captures the resource availability of plants. This allows for correlations to be established between the abiotic indicators (i.e., light and soil) and Species Diversity, as seen in Fig. 1. The abiotic indicators also have a direct influence on architectural performances such as thermal performance and energy efficiency (Susorova, 2015). However, there are no known direct relationships between Thermal Comfort and Species Diversity as architectural or ecological objectives. Through nested sets, synergies and trade-offs between higher-level objectives can be evaluated through common KPIs, such as the abiotic indicators in Fig. 1. While direct objective relationships are essential in generating holistic design solutions, lower-level objectives and their correlated KPIs can be replaced by higher-level objectives when more knowledge becomes available.

3. Proposed Hybrid Multi-Criteria Decision-making (MCDM) Methodology

In an ongoing research project, a design recommendation system for multi-species building envelopes is currently being developed (Weisser et al., 2022). The following section discusses the hybrid MCDM methodology proposed to support the system. This section presents an overview of MCDM, and two corresponding strategies utilized in a hybrid sequence. Then, the methodology is described using existing computational tools and illustrated using an example for a generic building envelope. Finally, this section presents and discusses initial results for varied objective priorities.

3.1. MULTI-CRITERIA DECISION-MAKING OVERVIEW

MCDM provides decision-making techniques to generate or identify best-case alternatives for problems with multi-variate and conflicting criteria. These techniques can be categorized into two strategies (Chen & Hwang, 1992). The first is Multi-Objective Decision-Making (MODM) which generates alternatives through directional constraints. Under MODM, there is Multi-Objective Optimization (MOO) which often employs heuristic algorithms to produce a range of well-performing alternatives. The second strategy is MADM which identifies the best-performing alternative(s) from a list using weighting strategies. MOO is commonly used in architectural design to generate design alternatives using multiple optimization objectives (Moscovitz & Barath, 2022). MADM is commonly employed in ecological decision-making to identify the best alternatives based on numerous attributes (Keshtkar et al., 2016). Therefore, for multi-species design, we propose a hybrid MCDM methodology to accommodate primary decision-making procedures in both disciplines.

This hybrid methodology employs a sequence of MOO to generate optimized multi-species building envelopes and MADM to evaluate the performances using ranking strategies. While this sequence of MCDM has been frequently explored in urban design (McGlashan et al., 2021), there are limited applications in architectural research (Selvan et al., 2023). Fig.2 illustrates the proposed methodology and integrates the nested hierarchical KPI strategy to inform the design decision-making. The KPIs drive the MOO using directional constraints established by objectives. Then, the optimized alternatives are ranked based on goals using weights defined by identifying objective or KPI priorities. This hybrid methodology results in a list of optimized design alternatives ranked from the best-performing solution.

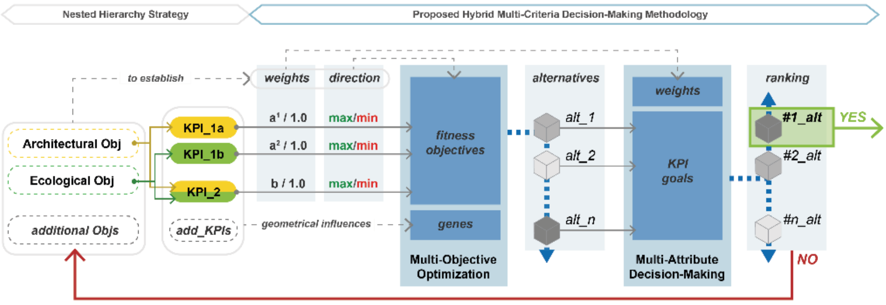


Figure 2. Schematic diagram for the hybrid multi-criteria decision-making methodology to support multi-species building envelope design.

3.2. PARAMETRIC APPLICATION OF PROPOSED METHODOLOGY

In an urban optimization study conducted by McGlashan et al. (2021), the authors developed a parametric workflow for urban design generation and evaluation using the Rhinoceros and Grasshopper software (Robert McNeel & Associates, 2022). This highlights the potential to utilize a parametric computer-aided design environment for the proposed hybrid MCDM methodology. In addition to compatibility opportunities, the Grasshopper suite contains numerous plugins to assist designers in iterative parametric design workflows. Some of these plugins can support the computation for the proposed hybrid MCDM methodology. For example, there are multi-objective evolutionary solvers such as Octopus and Wallacei used for MOO (Makki et al., 2019; Vierlinger, 2013). Aside from that, native Grasshopper components can also facilitate the construction of frequently employed MADM techniques such as the Analytical Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Negendahl, 2016). The availability of tools reinforces the use of Rhinoceros and Grasshopper as a medium for multi-species building envelope design decision-making support.

To construct the hybrid MCDM methodology, multi-objective evolutionary solvers must first be used. These solvers require fitness objectives and genes to be defined as inputs for MOO. Referring to Figure 2, fitness objectives are represented by the nested hierarchical KPIs while the optimization directions are determined by the objectives. Genes are geometrical parameters that have a direct influence on the KPIs and corresponding objectives. During MOO, genes are manipulated to generate a range of optimized design alternatives. Then, these optimized alternatives are ranked using MADM techniques. These techniques require KPI goals as input and weights determined by the objectives or KPI priority (see Fig. 2). The weights are applied to the KPI goals per optimized design alternative to rank the list of solutions.

The hybrid methodology was tested using the Wallacei plugin [ver. 2.65], for MOO, and the MADM technique, TOPSIS, constructed in Grasshopper. A building volume with parametric extrusions on a plot in Tel Aviv was used as a generic case study (see Fig. 3). The architectural objective was "To improve Thermal Comfort in the Summer" while the ecological objective was "To improve Plant Growth". Informed by the nested hierarchy strategy, both objectives were measured using the KPI, Solar Radiation, computed with the Ladybug plugin [ver. 1.5.0] (Sadeghipour Roudsari et al., 2013). However, the objectives had conflicting optimization directions. The architectural objective is achieved by "Minimizing Solar Radiation" while the ecological objective is achieved by "Maximizing Solar Radiation". To account for geometry-specific parameters in design decision-making, an objective was also introduced "To increase Panel Variation" using Standard Deviation as a KPI. The design objective is achieved by "Maximizing Standard Deviation". Parameters for distribution density along the z-axis, panel location, and extrusion distance for panel corners were used as gene inputs. MOO was performed using the default parameters in Wallacei with a generation size of 10 and count of 100. The resulting Pareto solutions were tested for two scenarios with varied KPI weights whereby the architectural objective was prioritized followed by the ecological objective (see Table 1). Then, TOPSIS was used to measure the Euclidean distance of the KPI goals from the ideal best and ideal worst values. Finally, a standardized performance score was calculated to determine the alternative ranking.

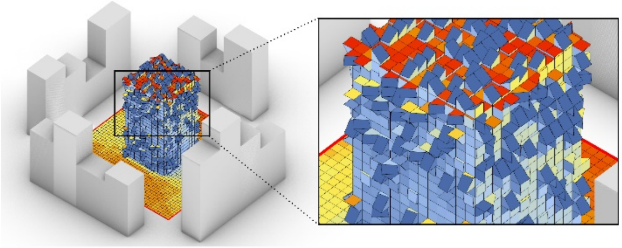


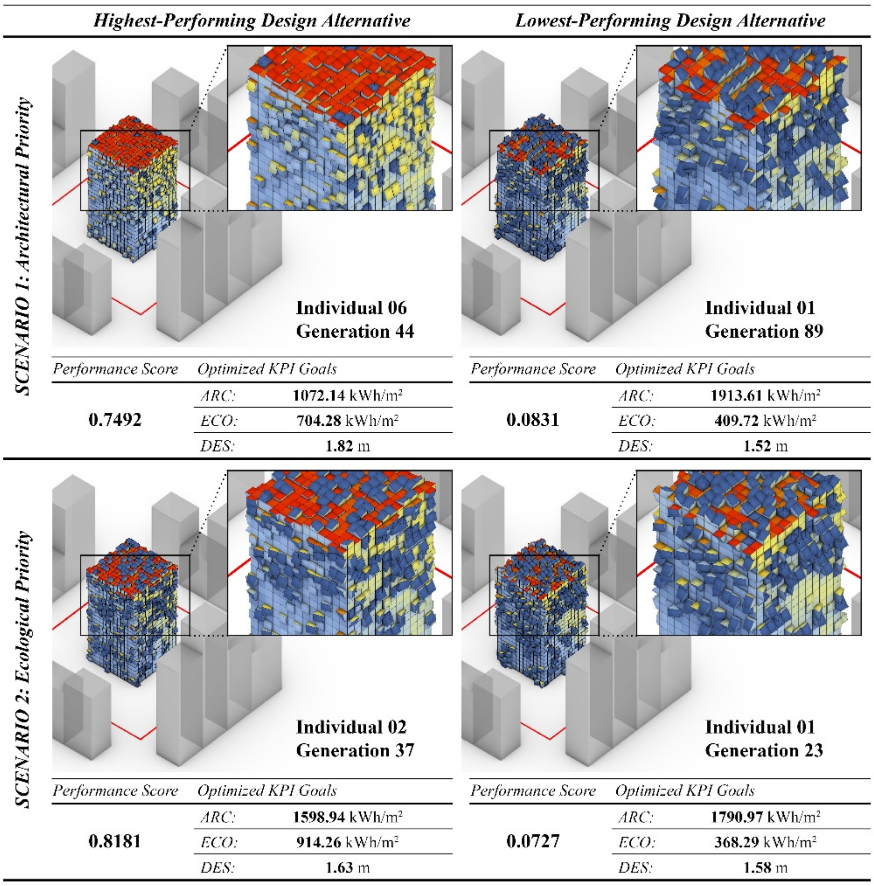
Figure 3. Solar Radiation analysis of the generic building with parametric envelope extrusions.

Table 1. Definition of architectural (ARC), ecological (ECO), and design (DES) Objectives, correlated KPIs, and the respective weights per scenario.

Objective		*Direction*	*KPI*	*Weights*	
				Scenario 1	*Scenario 2*
ARC	To improve Thermal Comfort	MIN	Solar Radiation	**0.5**	0.25
ECO	To improve Plant Growth	MAX	Solar Radiation	0.25	**0.5**
DES	To increase Envelope Variation	MAX	Standard Deviation	0.25	0.25

3.3. INITIAL RESULTS AND DISCUSSION

The MOO phase of the hybrid MCDM methodology generated 113 Pareto front solutions, characterized by fitness objectives that cannot be further optimized without compromising another. The solutions and corresponding optimized KPI goals (i.e., Fitness Values in Wallacei) were the alternatives used as input for TOPSIS. Performance scores for each alternative were calculated using the weights established in Table 1. Using TOPSIS, the 113 alternatives were ranked to identify the highest and lowest-performing design alternatives based on the different scenarios. As seen in Fig. 4, there are significant differences between the highest and lowest performance scores for both scenarios. For example, alternative 01-89 in scenario 1 has a solar radiation value that is 43.9% more than alternative 06-44. As such, alternative 01-89 performs 88.9% lesser than the best alternative under scenario 1. Therefore, given the priority to minimize solar radiation, alternative 06-44 is the highest-performing solution.



Scenario 1, Highest-Performing (Individual 06, Generation 44)

Performance Score	*Optimized KPI Goals*	
0.7492	*ARC:*	**1072.14** kWh/m^2
	ECO:	**704.28** kWh/m^2
	DES:	**1.82** m

Scenario 1, Lowest-Performing (Individual 01, Generation 89)

Performance Score	*Optimized KPI Goals*	
0.0831	*ARC:*	**1913.61** kWh/m^2
	ECO:	**409.72** kWh/m^2
	DES:	**1.52** m

Scenario 2, Highest-Performing (Individual 02, Generation 37)

Performance Score	*Optimized KPI Goals*	
0.8181	*ARC:*	**1598.94** kWh/m^2
	ECO:	**914.26** kWh/m^2
	DES:	**1.63** m

Scenario 2, Lowest-Performing (Individual 01, Generation 23)

Performance Score	*Optimized KPI Goals*	
0.0727	*ARC:*	**1790.97** kWh/m^2
	ECO:	**368.29** kWh/m^2
	DES:	**1.58** m

Figure 4. Comparison between the highest and lowest performing optimized design alternatives based on the two scenarios. The building mass is visualized using solar radiation values from the lowest (blue) to the highest (red) values.

Through Wallacei Analytics, optimization trends can be visualized and evaluated. For example, Fig. 5 shows that the lowest-performing alternatives were generated as the first individuals in generations 23 and 89. Additionally, as reflected in the standard deviation value chart, convergence was achieved by the architectural objective much earlier compared to the ecological and design objectives. Furthermore, the highest-performing solutions were generated between the convergence points for each fitness objective. These analyses will also enable trade-offs to be evaluated for design decision support when architectural and ecological knowledge is correlated and made available.

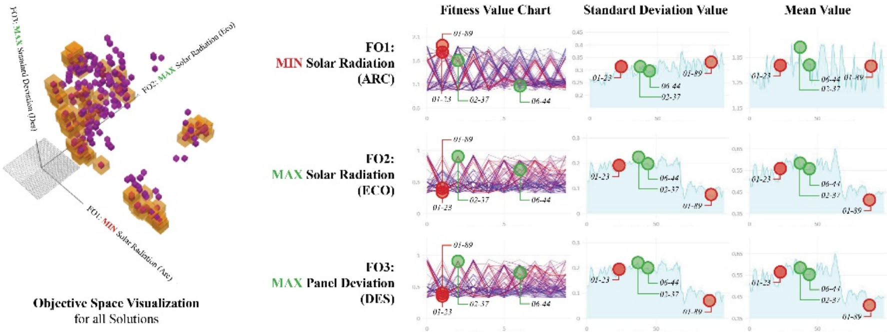


Figure 5. Optimisation analytics for the highest (green) and lowest (red) performing solutions.

4. Conclusions and Future Developments

Expanding beyond human-centred design paradigms, this paper presented key aspects to support decision-making for multi-species building envelope designs. A nested set KPI strategy was proposed to address the complexity of defining true ecological objectives in architectural design. The derivative logic enables multi-level objectives to measure multiple architectural and ecological performances using common KPIs. This strategy was integrated into a proposed hybrid MCDM methodology that employs a sequence of MOO and MADM to generate and rank optimized design alternatives. The methodology was constructed using parametric design tools available in the Grasshopper environment. The proposed methodology was tested using the Wallacei plugin and TOPSIS constructed with native Grasshopper components. Initial results showcase the potential of employing hybrid MCDM in a parametric environment to conduct architectural and ecological performance evaluations on ranked envelope design alternatives. Future developments include the implementation of the proposed methodology on a case study to utilize site-specific data. Currently, the ecological KPIs are not completely representative of ecological functionality or biodiversity because of the dynamic interrelations between living organisms in an ecosystem. To integrate more advanced ecological parameters such as connectivity or spatiotemporal ecosystem dynamics, ecological modelling is required. In the larger scope of the ongoing research project, future steps will include the integration of ecological modelling into a 3-dimensional computational environment. This will also facilitate knowledge generation for meaningful architectural and ecological correlations to enhance current building envelope performances toward multi-species cohabitation.

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