MULTISPECIES BUILDING ENVELOPES

Adopting plant habitat suitability modelling for ecological design decision-making

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Abstract. Urbanisation catalyses habitat loss, impacting humans and biodiversity. To mitigate this, the ECOLOPES research project proposes multispecies building envelopes that enhance ecosystem services provision through cohabitation. Initial envelope designs are optimized and evaluated with a hybrid multi-criteria decision-making model informed by key performance indicators for human and non-human objectives. This paper proposes an architectural approach to derive indicator proxies for the plant stakeholders by adopting aspects of habitat suitability modelling by correlating environmental conditions with species functional traits. Using the hybrid decision-making model, we utilise these proxies to optimise multispecies objectives for a residential building envelope and evaluate the resulting alternative. This alternative is compared with one optimised using indicators inferred from general ecological correlations. Results show the effectiveness of applying the proposed habitat suitability approach in accounting for variations in plant trait values and improving multi-objective trade-offs for multispecies envelope design decision-making.

Keywords. multispecies building envelopes, hybrid multi-criteria decision-making, plant habitat suitability, key performance indicators

1. Introduction

Urbanisation catalyses habitat loss and fragmentation, negatively impacting biodiversity and human well-being (IPBES, 2019). Multispecies building envelopes alleviate this by enhancing ecosystem services provision and cohabitation opportunities between four stakeholders: humans, animals, plants, and microbiota (Weisser et al., 2022). However, computational decision-making challenges arise due to insufficient ecological knowledge for building envelope design (Grobman et al., 2023). This often leads to the use of human-centric and simplified ecological indicators to evaluate design decisions (Selvan et al., 2023). In the ECOLOPES research project, we aim to develop methodologies and computational tools for multispecies building envelope design (Weisser et al., 2022). The proposed methodology includes a hybrid multi-criteria decision-making (MCDM) model that generates and ranks optimised envelope alternatives (Selvan et al., 2023). The model is informed by a framework, termed nested hierarchies, that deconstructs stakeholder objectives to derive directional constraints and key performance indicators (KPIs) (Saroglou et al., 2024). This framework also unmasks potential multispecies trade-offs by exploring KPI relationships between the stakeholders. To effectively evaluate these trade-offs, KPIs must be explicitly computed for all the multispecies stakeholders.

In ECOLOPES, this is facilitated by several novel technologies including expert ecological modelling integrated into a computer-aided design (CAD) environment, as outlined by Vogler et al. (2023). Building upon technological concepts initiated and developed by ECOLOPES, our paper proposes a parallel approach that adopts principles of habitat suitability modelling (HSM) to derive KPI proxies specifically for the plant stakeholder. HSM, a statistical method common in ecology, computes environmental data to predict the presence or absence of a given species in a study area (Hirzel et al., 2006). We test the applicability of the proposed approach with the hybrid MCDM model by optimizing a generic residential building envelope for human and plant stakeholders. The resulting alternative was compared with one informed by KPIs derived from general ecological correlations. Finally, we discuss potential extensions of the HSM approach and outlooks for multispecies envelope design decision-making.

2. Adopting Habitat Suitability Modelling for Design Decision-making

Climatic deterioration and species extinction are catalysed by urbanization, requiring comprehensive understanding of species distribution (Mohammady et al., 2021). This can be achieved by characterising the biotic and abiotic conditions necessary for a species to persist, known as ecological niches. (Polechová & Storch, 2019). In ecology, HSMs are spatially explicit models that assess these niches by computing biotic and abiotic factors, e.g., climate, topography, and geology, with species occurrence data to predict the absence or presence of a species in a given geographical area (Hirzel et al., 2006). HSMs produce spatial-temporal maps used to visualize habitat suitability and species occurrence probability and favourability (Sillero et al., 2021).

For example, Shen et al. (2021) predicted climate change impacts on the habitat suitability of a medicinal plant, considering 19 bioclimatic variables including temperature, precipitation, and topography. Chin et al., (2022) prioritized avian diversity maintenance using avian functional traits and factors such as connectivity, patch quality, and land cover. In an architectural study by Zimbarg (2023), building envelope microclimates were utilized to map plant species based on shading, incident radiation, and humidity - implicitly using habitat suitability. As reflected, the choice of variables used to model habitat suitability depend on the research objective and target species, varying influences from the regional to local scales (Bradley et al., 2012).

2.1. PROPOSED PLANT HABITAT SUITABILITY APPROACH

Drawing insights from Zimbarg (2023), we propose a mapping approach based on HSM principles. This approach utilizes environmental simulations to predict the presence of selected plant species on an envelope geometry. We also adopt the use of species functional traits from Chin et al., (2022), which are "any traits that impact fitness indirectly via their effects on the growth, reproduction, and survival of a species" (Violle et al., 2007). Therefore, functional traits have strong associations with ecological niches and in turn, habitat suitability. The proposed approach, constructed in Grasshopper [ver. 1.0.0007], leverages open-access plugins that facilitate interdisciplinary design support, real-time simulation, and visualization of algorithmic design decisions. This approach simulates abiotic factors on a mesh geometry and correlates associated plant functional traits to generate a 3D habitat suitability map (*Fig. 1*). The map provides proxies for widely used KPIs to measure plant species diversity, e.g., species richness and abundance. This proposed approach enables these KPI proxies to be integrated into schematic design decision-making processes.

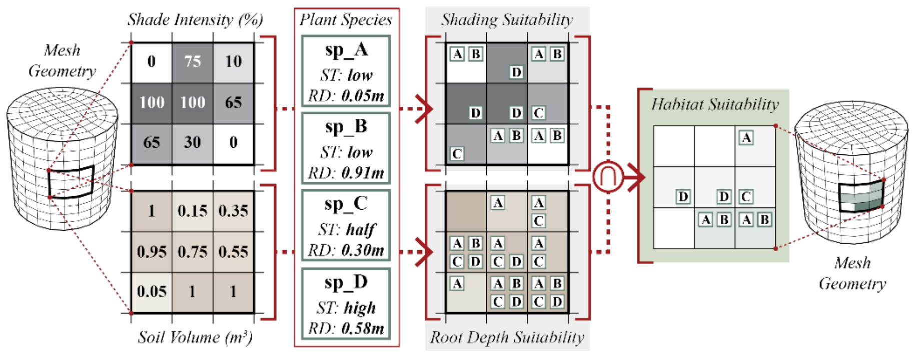

Figure 1. Approximating habitat suitability by associating abiotic factors (shade intensity and soil volume) to plant species functional traits, i.e., shade tolerance (ST) and rooting depth (RD).

In *Fig. 1*, the logic of the proposed plant HSM is illustrated using a 3x3 segment from an example envelope mesh geometry and four mock plant species *A*, *B*, *C*, and *D*. The habitat suitability of these plant species is predicted by correlating the abiotic factors, shade intensity and soil volume, to the functional traits, shade tolerance (ST) and rooting depth (RD). First, the abiotic factors are simulated using existing Grasshopper plugins and components. For example, shade can be simulated using Ladybug tools while soil volume can be distributed using native components. Then, the functional trait values for each species are obtained from ecological databases, e.g., TRY Plant Trait Database (Kattge et al., 2011). Next, these trait values are compared with the abiotic simulation results to assess suitability. For example, a cell with 75% shade might only be suitable for *sp_D* with a high shade tolerance value, while a soil volume of $0.35m^3$ is suitable for the rooting depth requirements of *sp_A* and *sp_C*.

Ultimately, the intersection of these comparisons generates a 3D plant habitat suitability map, defining the ecological niche of each species relative to the selected abiotic factors. The map also provides proxies for commonly used plant species diversity KPIs. Namely, overall and local plant species richness (*number of species*), which are approximated by counting the number of plant species present across all cells or within individual cells, respectively. In *Fig. 1*, the overall species richness is four and the local richness in the last cell is two. Likewise, plant species abundance (*number of individuals*) can also be approximated by counting the total number of cells suitable for each species. In *Fig. 1*, the abundance of *sp_A* is three while for *sp_B*, it is two.

3. Research Methodology

The proposed plant HSM approach was evaluated through a comparative experiment using the hybrid MCDM model to achieve selected multispecies objectives for a generic residential building envelope situated in Tel Aviv, Israel. The 17m-high building features five floors with a floor-to-ceiling height of 3m (*Fig. 2*). The building geometry was converted into mesh cells to facilitate the environmental simulations and application of the proposed plant HSM approach. The building was described by window and soil cell distribution variables, creating inherent conflicts suitable to generate MOO trade-offs. For example, an increase in window cells results in a decrease in available cells for soil distribution. The window cells, randomly distributed, are constrained by local architectural standards for window-to-wall ratio where the North, East and West, and South facades have maximum ratios of 12%, 8%, and 20%, respectively (*Fig 2a*). Similarly, soil cells were randomly distributed using soil-to-wall ratios across different floor groups: ground floor, 1st and 2nd floor, 3rd and 4th floor, and roof level. To generate soil volume, discrete values ranging from 0.15 to 1m were randomly assigned and extruded from the 1x1 soil cells in the z-axis (*Fig. 2b*).

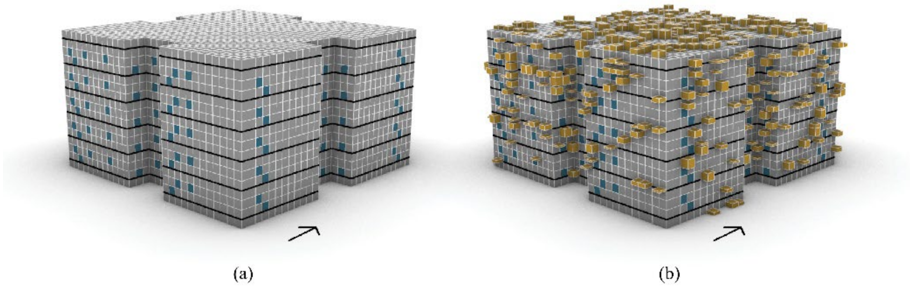

Figure 2. a) Default state of the generic residential building envelope and b) an example distribution of soil volumes from ground floor to roof level with 5%, 15%, 20%, and 25% soil-to-wall ratio.

For the multispecies objectives, the human and plant stakeholders were selected. The overarching human objectives were to improve daylighting and to reduce envelope structural loads, aligned with human-centric themes of human comfort and building performance. Simultaneously, the main plant objective aimed to enhance species diversity on the envelope, focusing on species native to the Mediterranean climate (*Table 1*). Their respective mean functional trait values, associated to the abiotic factors for shade intensity and soil volume, were obtained from the TRY Plant Trait Database (Kattge et al., 2011). Shade tolerance was valued from 0 for low tolerance to 5 for high tolerance while rooting depth was measured in meters.

Table 1. List of plant species and respective functional trait mean values from the TRY database.

No.	*Name*	*Scientific Name*	*Functional Traits (Mean Values)*	
			Shade Tolerance (0 to 5)	*Rooting Depth (m)*
1	Common Ivy	*Hedera helix* L.	4	0.1624
2	Annual Bluegrass	*Poa annua* L.	1	0.1881
3	Salad Burnet	*Sanguisorba minor* Scop.	1	0.6127
4	Common Chickweed	*Stellaria media* (L.) Vill.	2	0.3
5	Hare's-foot Clover	*Trifolium arvense* L.	0	0.05

The experiment was performed using the hybrid MCDM model developed under the ECOLOPES framework (Selvan et al., 2023). The model integrates multi-objective optimisation (MOO) using Wallacei [ver.2.65] and multi-attribute decision-making (MADM) using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) scripted in Grasshopper (Hwang & Yoon, 1981; Makki et al., 2019). First, the model optimises an initial envelope alternative using fitness objectives, defined by directional constraints and associated KPIs, outlined in a nested hierarchy for stakeholder objectives. Next, the model ranks the resulting Pareto front solutions according to KPI weights distributed based on stakeholder priorities. TOPSIS calculates scores from 0 to 1, ranking solutions from the best to worst performing based on the priorities. This sequential process of hybrid MCDM allows the generation of optimized alternatives and the identification of the most appropriate solution.

3.1. COMPARATIVE EXPERIMENT DESIGN

Two nested hierarchies were defined to derive different directional constraints and KPIs aimed at achieving the principal plant stakeholder objective "*to increase species diversity*". The first nested hierarchy (NH1), detailed in Section 3.1.1, was based on inferred correlations of plant growth and survival. The second nested hierarchy (NH2), detailed in Section 3.1.2, drew on the principles of the proposed plant HSM approach.

The model was initiated with the default configuration of the building envelope (*Fig.2a*). For MOO, the default algorithm parameters of Wallacei were used for a generation size and count of 10 each, producing 100 alternatives. Window and soil cell distribution variables, as detailed in Section 3, were used as the gene input. After the deconstruction of the primary objectives, the fitness objective for the human stakeholder was to maximize the total window-to-wall ratio and minimize total soil volume (*Fig.3&4*). The plant stakeholder fitness objectives differed in the two optimisations aligned to the nested hierarchies. For MADM, the Pareto front solutions were ranked with equal stakeholder objective priorities that distributed the KPI weights accordingly. Ultimately, the best-performing alternatives of each nested hierarchy were identified and compared based on the TOPSIS score, gene and fitness objective values, total number of suitable cells, and resulting species diversity KPI proxies.

3.1.1. Nested Hierarchy 1 (NH1): General Ecological Correlations

NH1 was based on general ecological correlations about plant growth and survival. As seen in *Fig. 3*, the first-level plant objective "*to increase plant species richness*" diverged to two lower-level objectives "*to maximise total soil volume*" and "*to maximise shade heterogeneity*". This was defined based on general ecological assumptions that higher soil depths/volumes and heterogenous shade conditions offer better opportunities for improved plant species diversity. These objectives were deconstructed into one KPI and directional constraint, each. The KPI, total soil volume, was also shared with the human objective "*to reduce envelope structural loads*" but framed in the opposite direction. This KPI was computed using the Grasshopper script constructed to distribute soil depth values. The second KPI, direct sun hours, was associated with shade heterogeneity by computing the standard deviation of the values. This KPI was computed using Ladybug [ver.1.6.0] and the Statistics component from Dodo [ver.03]. However, to streamline the species diversity comparison, the proposed plant HSM approach was performed on the best-performing optimized alternative.

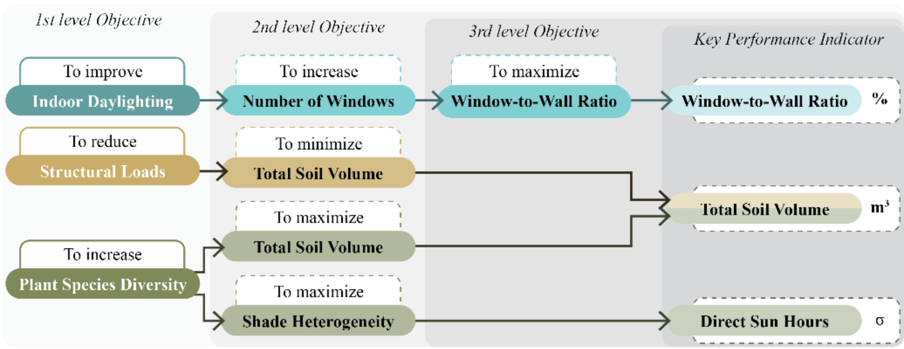

Figure 3. NH1 illustrating the human objectives (blue and brown) and the plant objective (green). The plant objective is associated with two KPIs derived from ecological correlations.

3.1.2. Nested Hierarchy 2 (NH2): Habitat Suitability Approach

NH2 was based on the proposed plant HSM-inspired approach described in Section 2.1. As shown in *Fig. 4*, the first-level plant objective remained unchanged but was deconstructed into a second-level objective "*to increase habitat suitability*". This was formulated on the prediction of habitat suitability using selected abiotic factors and correlated plant functional traits. Therefore, to achieve the objective, the number of cells with rooting depth and shade suitability must be maximized. This drives the fitness objective to accommodate the list of species across all the suitable cells. Finally, these objectives converged into the species diversity proxy, describing the richness and abundance. These proxies for the number of species and individuals on the envelope, respectively, were represented under one fitness objective to be maximised.

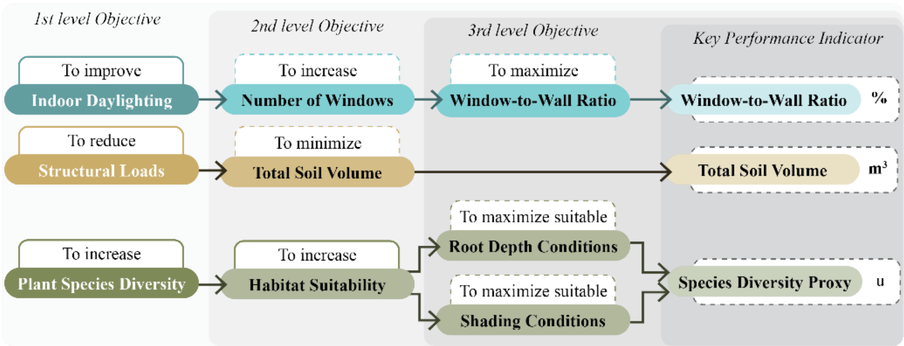

Figure 4. NH2 illustrating the human objectives (blue and brown) and a plant objective (green). The plant objective is associated with the KPI proxies computed by the proposed plant HSM approach.

4. Results and Discussion

NH1, with general ecological correlations, yielded 44 Pareto front solutions while NH2, based on the proposed plant HSM approach, had 30 solutions. As seen in *Fig. 5*, the best-performing alternative from NH1 was the third individual in the second generation: Alternative {1-2}, with a TOPSIS score of 0.5225. From NH2, it was the second individual in the second generation: Alternative {1-1} with a score of 0.6526. Referring to *Table 2*, Alternative {1-2} showcased optimal window distribution, allowing a gradual decrease in soil-to-wall ratios from the ground to roof level. A total soil volume of 818.48 m^3 was distributed across 1420 cells with habitat suitability. Across all cells, the optimized envelope supported an overall species richness of five. For each cell, the envelope had a mode and mean local richness of one and 1.14, respectively. Conversely, Alternative {1-1} had an optimal window distribution with substantially higher soil-to-wall ratios, except on the 3rd and 4th floor, which only achieved 30%. Hence, a higher total soil volume of 1260.3 m^3 was distributed across 2152 suitable cells. Similarly, across all cells, the overall species richness remained at five, with a mode local richness of one with a slightly higher mean of 1.42, per cell.

Based on the results, NH2 produced 32% fewer Pareto front solutions compared to NH1, suggesting a reduced design search space. This facilitates decision-making for selecting potential alternatives. While both alternatives achieved window distributions close to the architectural standards, Alternative {1-2} had the lowest soil volume to achieve reduced structural loads. However, Alternative {1-1} had 34% more suitable cells and 35% higher soil volume aligning with the plant objective of increasing species diversity. Moreover, while both alternatives had the same overall species richness, the mean local richness for Alternative {1-1} was 20% higher than in Alternative {1-2} due to higher species abundance (*Table 2*). Except from Common Chickweed, the abundance of Common Ivy, Annual Bluegrass, Salad Burnet, and Hare's-foot Clover in Alternative {1-1} exceeded that of Alternative {1-2} by 21%, 72%, 77%, and 68%, respectively. This suggests that the hybrid MCDM model using the proposed plant HSM achieved better trade-offs for the plant objective without compromising the human objectives by accounting for the functional trait variations in each species.

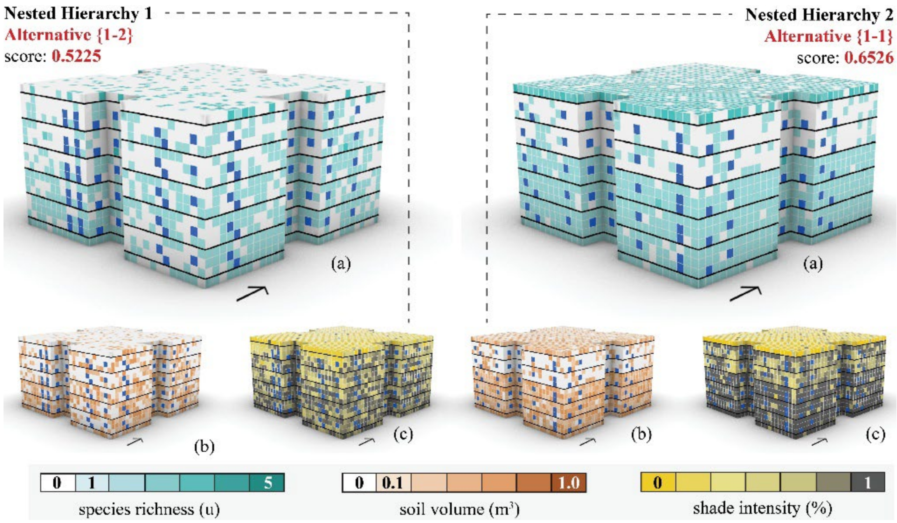

Figure 5. Best-performing alternatives from NH1 and NH2 with the a) plant suitability mapping, b) soil volume distribution, and c) shading intensity visualised.

Table 2. TOPSIS score, optimized gene and fitness objective values, overall and local plant species richness, and species abundance of the resulting best-performing alternatives.

Criteria	*Additional Notes*	*Unit*	*Experiment 1*	*Experiment 2*
			Alternative {1-2}	*Alternative {1-1}*
Performance score	-	-	**0.5225**	**0.6526**
Window-to-wall ratio	*N-S-E-W facades*	%	9, 20, 7, 6	10, 18, 7, 6
Soil-to-wall ratio	*Ground to roof level*	%	85, 70, 45, 25	95, 95, 30, 90
Total Soil Volume	-	m^3	818.48	1260.3
Number of Suitable Cells	*On envelope*	u	1420	2152
Overall Species Richness	*Across envelope*	u	5	5
Mode Local Richness	*Per envelope cell*	u	1	1
Mean Local Richness	*Per envelope cell*	u / cell	1.1358	1.1476
Total Species Abundance	*Following sequence in Table 1*	u	1008, 190, 70, 196, 216	1278, 676, 310, 198, 676

5. Conclusions

This paper proposed a mapping approach based on the principles of plant HSM to optimise and evaluate design alternatives using ecologically driven KPIs. The approach employed environmental simulation plugins to analyse abiotic conditions which were correlated with plant functional trait values extracted from an ecological database. The resulting habitat suitability map provided plant KPI proxies for species diversity to achieve a plant objective within a hybrid MCDM case study. A comparison with an alternative informed by general ecological correlations revealed that the plant HSM-informed alternative achieved higher species suitability across the envelope, without compromising the human stakeholder objectives. This highlights the advantage of the proposed plant HSM approach in facilitating improved multispecies stakeholder trade-offs through informed ecological knowledge using the hybrid MCDM model.

The adaptable "plug-and-play" format of the approach allows for the integration of additional plant or animal functional traits, given computable abiotic factors. For example, plant growth forms could be correlated with the surface normal direction of mesh faces, or animal habitat suitability correlations could be explored based on resource availability or potential living spaces on the envelope geometry. Future experiments could leverage the approach to optimize and assess objectives tailored to specific species for conservation support. Additionally, spatially informed objectives could be explored such as human-nature proximity or habitat clustering. In summary, the proposed HSM approach functions as a methodology to obtain schematic ecological results in the early design decision-making phases of multispecies building envelopes. Notably, a limitation of the proposed plant HSM is the static nature of the analysis, lacking temporal dynamics such as competition which is essential for informed design decision-making. Ongoing developments in the ECOLOPES research project bridges this gap by integrating advanced ecological modelling into CAD processes, supporting collaboration between architectural and ecological domains.

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