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PERSPECTIVE

Creating ecologically sound buildings by integrating ecology, architecture and computational design

Wolfgang W. Weisser[1] | Michael Hensel[2] | Shany Barath[3] | Victoria Culshaw[1] | Yasha J. Grobman[3] | Thomas E. Hauck[4] | Jens Joschinski[5] | Ferdinand Ludwig[6] | Anne Mimet[1] | Katia Perini[7] | Enrica Roccotiello[8] | Michael Schloter[9] | Assaf Shwartz[3] | Defne Sunguroğlu Hensel[6] | Verena Vogler[10]

[1]Technical University of Munich, Terrestrial Ecology Research Group, Department of Life Science Systems, School of Life Sciences, Freising, Germany; [2]Department for Digital Architecture and Planning, Technical University Vienna, Vienna, Austria; [3]Faculty of Architecture and Town Planning, Technion, Israel Institute of Technology, Haifa, Israel; [4]Department for Landscape Architecture and Landscape Planning, Technical University Vienna, Vienna, Austria; [5]Studio Animal-Aided Design, Berlin, Germany; [6]Green Technologies in Landscape Architecture, School of Engineering and Design, Technical University of Munich, Munich, Germany; [7]Architecture and design Department, University of Genoa, Genoa, Italy; [8]Department of Earth, Environment and Life Sciences (DISTAV), University of Genoa, Genoa, Italy; [9]Research Unit for Comparative Microbiome Analysis, Helmholtz Munich, Oberschleissheim, Germany and [10]Research and Development Department, McNeel Europe S.L., Barcelona, Spain

Correspondence
Wolfgang W. Weisser
Email: wolfgang.weisser@tum.de

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Abstract

1. Research is revealing an increasing number of positive effects of nature for humans. At the same time, biodiversity in cities, where most humans live, is often low or in decline. Tangible solutions are needed to increase urban biodiversity.
2. Architecture is a key discipline that has considerable influence on the built-up area of cities, thereby influencing urban biodiversity. In general, architects do not design for biodiversity. Conversely, urban conservation planning generally focuses on the limited space free of buildings and does not embrace architecture as an important discipline for the creation of urban green infrastructure.
3. In this paper, we argue that the promotion of biodiversity needs to become a key driving force of architectural design. This requires a new multi-species design paradigm that considers both human and non-human needs. Such a design approach needs to maintain the standards of the architectural profession, including the aim to increase the well-being of humans in buildings. Yet, it also needs to add other stakeholders, organisms such as animals, plants and even microbiota. New buildings designed for humans and other inhabitants can then increase biodiversity in cities and also increase the benefits that humans can derive from close proximity to nature.
4. We review the challenges that this new design approach poses for both architecture and ecology and show that multi-species-design goes beyond existing approaches in architecture and ecology. The new design approach needs to

make ecological knowledge available to the architectural design process, enabling practitioners to find architectural solutions that can facilitate synergies from a multi-species perspective.

5. We propose that a first step in creating such a multi-species habitat is the design of buildings with an *ecolope*, a multi criteria-designed building envelope that takes into account the needs of diverse organisms. Because there is no framework to design such an *ecolope*, we illustrate how multi-species design needs to draw on knowledge from ecology, as well as architecture, and design computation.
6. We discuss how architectures designed via a multi-species approach can be an important step in establishing beneficial human–nature relationships in cities, and contribute to human well-being and biodiversity conservation.

KEYWORDS
architectural design, biodiversity, building envelope, cohabitation, computational design, ecological restoration, multi-species design, urban ecosystems

1 | INTRODUCTION

Urbanization is one of the major global environmental issues of the 21st century. Rapid urbanization and construction cause significant land cover change, degraded environments and novel ecosystems that have major implications for biodiversity and human well-being. It has been shown that urbanization contributes to the extinction of local species, spread of invasive species and biotic homogenization (Colleony & Shwartz, 2020; Groffman et al., 2017; McDonald et al., 2020; McKinney, 2002). In the urban environment, a reliance on 'grey' infrastructure, that is, technological solutions whose harmful effects on organisms, ecosystems and the natural environment are poorly considered, has led to a severe loss of ecosystem services (Brondizio et al., 2019). These services deliver indirect benefits for humans, such as regulation of climatic conditions and mitigation of extreme events such as heavy rainfall or heat waves (CBD, 2012), as well as direct positive effects on human health and well-being, including stress reduction and provision of a sense of place (Gilbert & Stephens, 2018; Marselle et al., 2019; Peccia & Kwan, 2016).

Increasing evidence suggests negative health effects resulting from non-existent or degraded nature in cities. Several studies reported a correlation between reduced microbial diversity, mainly during early childhood, and an increased risk for allergies such as asthma and neurodermatitis (Gilbert & Stephens, 2018; Peccia & Kwan, 2016). Furthermore, there exists evidence for a link between tlack of green space and higher human mortality (Rojas-Rueda et al., 2019). Making cities sustainable, resilient and liveable is consequently one of the greatest challenges for humans (CBD, 2012). To tackle this challenge, various plans and environmental policies have been implemented worldwide, such as the Green Deal of the European Union (European Commission, 2019). In this context, policy places special emphasis on the development of nature-based solutions, that is, cost-effective solutions inspired and supported by nature, which provide environmental, social and economic benefits and helps building resilience, as well as protecting, managing and restoring ecosystems (Eggermont et al., 2015; European Commission, 2015). In addition, urban environments will be challenged in the next decades by climate change, but at the same time experience a technological revolution, that can have both positive or negative impacts on urban biodiversity and human–nature relationships (Goddard et al., 2021). Making cities more sustainable, resilient and liveable therefore requires new planning methods that mobilizes all disciplines involved in urban development (Elmqvist et al., 2019; Kellert et al., 2008; Söderlund, 2019; Thomson & Newman, 2018; Thomson & Newman, 2020).

We start from the premise that to create sustainable, resilient and liveable cities, architecture needs to be activated for the support of biodiversity. This is because constructions cover large parts of the urban footprint and designing these is the domain of architecture. We commence by outlining the challenges that including biodiversity presents to architectural design. We then discuss the contribution that ecology needs to make to a novel architectural design approach that is not exclusively human focused. Finally, we propose the novel concept of an *ecolope*, a shared multi-species architectural space that can replace the currently prevailing building enclosure or envelope of buildings. For this, an integrative approach to the built environment is needed in which biodiversity and multi-species design become an integral part of architectural design. This requires a change in paradigm for both architecture and ecology. Architecture needs to move away from its traditional anthropocentric approach, while ecology, and especially conservation, needs to consider humans, and hence urban ecosystems, as a part of the natural world. In this context, we address some of the shortcomings of existing approaches.

2 | CHALLENGES OF MULTI-SPECIES DESIGN TO ARCHITECTURE

2.1 | Architecture as a human-centred discipline

Architecture is generally human centred (Zöllner, 2014) and there exist several reasons why a multi-species design of buildings requires a change in the self-conception of the discipline.

First, current human-centred design is deeply rooted in the dialectic between 'humans' and 'nature'. Even though humans have always inhabited cities together with 'non-human' species (Bertone et al., 2016; Wischermann et al., 2018), urban space is not understood as part of 'nature' in most contemporary human societies. Instead, modern urban planning and architecture aim to create 'civilized' spaces of human mastery over nature, to free humans from the forces and contingencies of the surrounding environment including other organisms. This endeavour was especially in Western societies accompanied by the distinction between 'nature' and 'society' (Descola & Pálsson, 1996). Bringing nature back into cities (e.g. Mata et al., 2020) and designing for multiple species therefore requires relinquishing dichotomies like humans vs. nature.

Second, one of the primary functions of most buildings in urban contexts is to provide shelter for humans. Historically, building design was informed by climate and other local conditions and resources, such as available materials. However, since the start of the broad use of air-conditioning in the 1970s, building designs have become largely uncoupled from local conditions, moving towards generic enclosures with electrical–mechanical heating, cooling and ventilation systems (e.g. Siry, 2021). By definition, contemporary building envelopes are thus conceived as a hard division between the inside and the outside (Straube & Burnett, 2005), hence separating humans from the exterior environment including nature.

Third, human comfort and the fulfilment of human needs are still at the centre of current architectural practice, even when this indirectly triggers negative feedbacks through the destruction of habitats and a lack of connection to nature. Ecological or sustainable building today is still characterized by the attempt to minimize ecological damage while meeting human needs. In contrast, recent architectural approaches such as biophilic and regenerative design (Kellert et al., 2008; Thomson & Newman, 2018) emphasize that for making cities more sustainable, architecture needs be part of a solution that goes beyond merely limiting the negative impact of building design (Colléony & Shwartz, 2019).

Thus, for multi-species design, a fundamental change is required. Architectural design of the future needs to become more biocentric, addressing the coexistence of humans with non-human stakeholders as a primary design objective. This shift can be initiated by re-considering the role of the building enclosure or envelope. The building envelope is pivotal in the discussion of multi-species design, because it establishes the interface between outside and inside, and thereby between the outside occupied by many species, and the inside of buildings that is almost exclusively occupied by humans. This enclosure offers a vital opportunity for multi-species integration. Ecological research has shown that various plants and animals try to seek shelter in and on buildings. Yet, they are mostly expelled by humans, to preserve the human sphere, as exemplified by the development of technologies designed to prevent pigeons, woodpeckers, or house martins from using or breeding on the building envelop (Duarte et al., 2011; Gagliardo et al., 2020; Harding et al., 2007; Harris et al., 2016). We propose that the building envelope can be designed in a novel way, to host local species communities, including plants, animals and other organisms such as microbiota. In recent years, a renewed interest in transitional spaces and non-energy based solutions (Hensel & Hensel, 2010a; Hensel & Hensel, 2010b; Hensel & Hensel, 2010c) that deploy natural ventilation and thermal mass and inertia (the so-called free-running buildings) has emerged (Baker & Standeven, 1996). This renewed focus on the purpose of the building envelope in the architectural discourse offers new possibilities for multi-species design.

2.2 | Integration of ecological approaches into architecture

Throughout history, the need to provide shelter is one of the core requirements of human constructions. With the appearance of different types of constructions, especially those that serve the purpose of formal representation, such as temples, treaties on architecture began to appear that described systematically the elements of a specific architecture, like Viturvius' treatise *De architectura* ('Ten books on architecture', Rowland & Howe, 2001). Gottfried Semper laid out a systematic approach to architecture that identified core elements: the hearth, the roof, the enclosure and the mound (Semper, 1851). Today, enclosure and roof together form what might be called the building envelope, the hearth can be chiefly identified in the technical apparatus for climatizing buildings, and the mound or earthwork has in some ways moved into the background as part of the preparatory work on a site. In our approach, we understand the envelope and in part earthworks as key elements of an *ecolope*.

In general, conventional architecture is anthropocentric and ecological target setting is not common. Still, there exist some conceptual approaches that integrate ecological aims to varying degrees. At the building scale, one common approach to the integration of ecological aspects is the addition of green façades or green roofs, that integrate architecture and flora for various purposes, including aesthetic, micro-climatic and ecological considerations (Pérez & Coma, 2018; Radić et al., 2019). These approaches constitute an attempt to rethink the contemporary building envelope to enable urban climate mitigation and biodiversity conservation. However, most current research focuses on ecosystem services provided to humans and remain narrow in provisions for 'non-human' species (Colléony & Shwartz, 2019; Haase et al., 2014). One example is the *Bosco Verticale* residential project in Milan, by Stefano Boeri Architects, that is well known for the use of large shrubs and trees placed on balconies as a key feature of the buildings' exterior. While this architecture, and the technological solutions concerning the irrigation system, is impressive (Well & Ludwig, 2020), and while there is a clear aim to provide humans with contact to nature, the ecological objectives are not clearly defined. For example, it is not clear for what biodiversity objectives a vertical forest is the best solution.

There are also approaches to integrating ecological objectives into architectural design that originate in ecology and conservation (Garrard et al., 2018; Mata et al., 2020; Parris et al., 2018). These also include technical guidelines for integrating nest boxes for birds or bats into the building façades, or more extended descriptions of how to design suitable measures for target species or species groups (Apfelbeck et al., 2020; Gunnell et al., 2012). Such approaches can be ecologically successful (e.g. Williams et al., 2014). However, they are rarely embedded into architectural design strategies and do not fully integrate architectural with ecological aims. As such, they are exceptions rather than examples of a systematic design approach (see, e.g. Huguet et al., 2019).

On larger spatial scales, there exist various ecological approaches to design and planning of cities or wider regions. These can be characterized as landscape architectural approaches with a main focus on open space planning. An influential example is landscape urbanism (Corner, 2006; Waldheim, 2006) that follows in the tradition of ideas such as 'design with nature' (McHarg, 1969), and clearly involves ecological goals. Here, principles from landscape ecology are integrated into the design approach, and the design is biocentric rather than anthropocentric, including the interests of diverse non-human stakeholders. Nevertheless, landscape urbanism and related approaches do not embrace the complexity of ecological relationships, and instead build upon relatively static and simplified concepts of local nature. Interaction of species with the environment, interactions among species within a local community and temporal dynamics such as succession or species turnover are not considered. Given the complexity of dynamic urban environments, such a static approach falls short in predicting ecological outcomes. As a consequence, design outcomes resulting from these approaches have a tendency to reproduce traditional images of nature, thereby masking existing uncertainties about ecological relationships within the urban environment (cf. Hamilton & Schwabe, 2016).

Finally, there are relevant approaches on a more systemic level, such as regenerative design. Similar to landscape urbanism, regenerative design is conceptually based on the book of McHarg (1969). Yet, regenerative design seeks to engender human systems that can coevolve with natural systems, that is, evolve in a way that generates mutual benefits and greater overall resilience (Mang & Reed, 2020; Middleton et al., 2020). Regenerative design (and comparable approaches such as eco-positive design [Birkeland, 2020]), does not focus on minimizing the ecological footprint of construction, but aims to improve the ecological conditions. From an ecological point of view, the time-scales considered (evolution) and the ecological objectives would need to be more clearly discussed and refined. From an architectural point of view, the design tools and frameworks that have been proposed to support regenerative design (e.g. Plaut et al., 2012) are still largely conceptual and qualitative, and do not facilitate a systematic integration of ecological objectives into design.

In contrast to ecological target-setting, target-setting for the human user is well established. For example, a wide range of requirements for a building can be summarized in a 'design brief'. This approach specifies the function of the building (e.g. residential building), gives user requirements such the lighting of the apartments or temperature control, lists architectural specifications such as the number and sizes of rooms, and determines their relationships to one another and to the outside space. In multi-species design, the design brief for a building must therefore be extended to include clearly defined objectives that address the non-human users of a building. For the design brief, the non-human user groups need to be identified, characterized and their interaction with the designed environment needs to be assessed. Importantly, there are also ecosystem disservices (e.g. Lyytimäki et al., 2008; von Döhren & Haase, 2015) that need to be avoided, including the transmission of diseases, the presence of allergenic plants, or the occurrence of wildlife that people fear, or do not want close to their home. All these considerations present a reasonable challenge for setting objectives compared to the well-established assessment of standard human requirements.

Multi-species design requires that architects embrace ecology as a fundamentally important discipline to jointly develop a systematic design approach. A core challenge for architects is shifting away from conceiving buildings as discrete objects that are decoupled from their surroundings (Hensel, 2013), and as static products that do not develop further after the building has been completed. The projection of building development beyond the end of construction is important because both the increasing need to design for adaptation of building use, and the dynamic nature of ecological communities, must be embraced. For this reason, a new emphasis must be foregrounded in architecture that focuses on merging object and surrounding, and that facilitates processes that unfold and evolve over time, resulting in a constantly changing appearance and performance of an architecture (Hensel, 2013).

2.3 | Challenges to data-driven computational design

Designing a multi-species habitat necessitates that architects include knowledge and data pertaining to a broader range of knowledge fields than usual. There are already notions of multi-disciplinary collaboration within the Architecture, Engineering and Construction (AEC) industry (e.g. Guarini et al., 2018; Tan et al., 2021), but improved methods and tools are needed to incorporate knowledge from ecology into the design process more effectively than is currently possible. One challenge is to discover how knowledge and data from different disciplines and domains can be integrated in a meaningful way, to inform the design of a multi-species space. A second challenge is to develop a data-driven design process that is coupled with simulating the dynamic development of such multi-species space, its various sub-systems and their interactions. A third challenge is to investigate how this information can be modelled to enable design decision support. Urban and landscape modelling requires both Geographical Information System (GIS) mapping and Building Information Modelling (BIM). While GIS is a spatial system that merges massive natural resource datasets for the creation and analysis of digital maps, BIM is a standard for a digital modelling and planning process in the AEC industries. BIM converts 3D geometry into an informed object by adding detailed hierarchical information in relation to construction, life cycle assessment including cost-, project- and facility management and also has applications in green building. Thus, BIM is a standard to make planning more efficient and sustainable (Catalano et al., 2021; Jalilzadehazhari et al., 2019; Shadram & Mukkavaara, 2018).

With the new potentials of web and cloud computing, and integration with real-time information via the Internet of Things, GIS has become not just a powerful mapping platform, but also a technology that represents how the planet is interconnected. Thus, GIS plays a crucial role in addressing global challenges with respect to loss of nature and biodiversity. The challenge in landscape architecture and urban planning is to combine both technologies for a data-integrated workflow that can be applied in real-world construction projects. Even though both systems are similar in concept, it is a challenge for software vendors making GIS and BIM models interoperable, because in GIS models vectors are featured as points, lines, polygons, while BIM models are non-metric (e.g. Catalano et al., 2021; Mignard & Nicolle, 2014). Catalano et al. (2021) have developed a promising framework that represents a spatial-based approach to integrate species habitats in constructed ecosystems. This framework tackles the issue of biodiversity loss and habitat fragmentation across multiple scales (landscape, urban and building), using GIS and BIM technologies. It aims at a collaboration between ecologists and designers from the early design stage of a project onwards, to integrate habitats, and to facilitate multi-species colonization and movement through built areas. A major component that is still missing, but required for multi-species design is, however, the relationship between ecology and architecture.

3 | CHALLENGES OF MULTI-SPECIES DESIGN TO ECOLOGY

Emerging design concepts such as the ones discussed above include ecological aims, but the ecological integration has so far often been limited to very general or simplified ecological objectives, such as, for example, greening a site or supporting a particular species of butterfly, rather than more complex tasks such as the restoration of particular food webs (Apfelbeck et al., 2020; Felson & Ellison, 2021). One likely reason for the lack of collaboration between designers and ecologists (Felson & Ellison, 2021) is that ecological relationships are complex and hence difficult to implement. Each individual species has its own ecological requirements, such that the processes involved in explaining the presence of species in a given area are manifold, act at different scales, and depend on the target species and the local environmental conditions (e.g. Goddard et al., 2010). This ecological complexity, that is further complicated by the stochastic nature of many of the processes involved, makes it difficult to link architectural design to an ecological outcome. Multi-species design requires the development of an approach that integrates ecological knowledge into the architectural design processes. Such an approach should

a. connect ecology to architecture in a predictive way, so that it will be possible to model, e.g., community assembly and dynamics in response to architectural design
b. provide the understanding of how a building needs to be designed in order to reach a given ecological objective.

Such an approach should encapsulate general ecological knowledge and rules, and be applicable, in theory, to any architectural project in any environmental condition, to be able to evaluate any ecological objective. In the following sections, we outline the challenges ecology has to overcome to allow for such an approach.

3.1 | Modelling at the local scale requires understanding the different urban filters

Local community assembly in an urban environment differs from community assembly in a natural environment due the strong influence of humans (Andrade et al., 2021; Aronson et al., 2016; Fournier et al., 2020; Goddard et al., 2010). Aronson et al. (2016) proposed to organize the different processes involved in species filtering and ultimately community assembly in cities into a number of hierarchical filters. To detail the challenges for multi-species design, we reorganize these filters according to their origin, that is, biophysical or anthropogenic, and to their scale of action, that is, the local (building) scale vs. larger scales (city or regional). First, species arriving in a city are either part of the regional species pool that is affected by the regional climate, biogeography and human land use, are migratory species that only spend part of their life cycle in the area, or are introduced by people into the city, intentionally or non-intentionally (Global scale human facilitation filter, Aronson et al., 2016). How many species are part of the *urban species pool*, that is, are principally able to live in a city, is still under discussion. While many species of regional species pool cannot live in contemporary cities (La Sorte et al., 2018; Piano et al., 2020), a high proportion of species from the regional species pool may live in the city provided that conditions are right ('urban adapters', McKinney, 2002; Sweet et al., 2022).

Second, from an ecological perspective, urban landscapes are characterized by high heterogeneity at a small scale, with vegetated patches such as woodlands, parks, ruderal sites, lawns, ornamental plantings and meadows embedded in an impervious matrix made of buildings, roads and parking lots, whereby many of these patches are very small (Vega & Küffer, 2021). The small and disconnected vegetated patches contain many of the resources in the urban environment, such as food, shelter or nesting sites (e.g. Goddard et al., 2010). For many species, shelter can also be provided by man-made structures, such as cavities in a building envelope (Gunnell et al., 2013). Thus, connectivity between patches is of overriding influence (Alberti, 2005; Mimet et al., 2020). Connectivity is strongly affected by *urban form*, that is, by the way in which patches that can be used by species are interspersed with buildings, roads and other human-made structures. Urban form is important at two spatial scales. At the city scale, urban morphology influences which organisms of the urban species pool can reach a given area within the city (Alberti, 2005; Mimet et al., 2020). At the local scale, local urban form determines which species can find the different resources they need to complete their life cycle (Fournier et al., 2020; Goddard et al., 2010).

Third, there is a strong *socioeconomic and cultural filter* which encompasses all human activities including management (Aronson et al., 2016), and which operates both at the city and the local scale. Different management regimes lead to the selection of species with different traits (Muratet et al., 2007; Muratet & Fontaine, 2015; Politi Bertoncini et al., 2012). At the city scale, management can support or impede connectivity and hence the likelihood that a species reaches a given area of the city. At the local scale, management includes the frequency of disturbances that can strongly impact community composition (Lososová et al., 2006; Muratet & Fontaine, 2015; Shwartz et al., 2013).

Fourth, species interactions are also important within the urban environment; yet, these interactions may be very different from the interactions outside the city (Harrison & Winfree, 2015). Understanding the consequences of multi-species design for community assembly at the local scale needs to take account of all these filters, starting from the urban species pool.

3.2 | Modelling approaches exist but need to be adapted

While many spatially explicit models have been developed that can capture the processes underlying the different filters, there is no single model that encapsulates all of them for the urban environment (for an overview of models, see e.g. D'Amen et al., 2017; Briscoe et al., 2019; Zurell et al., 2022). One major challenge are the different spatial scales involved. *Individual-based models* (IBM) such as RangeShifter (Bocedi et al., 2014) can dynamically and spatially model population dynamics in response to habitat locations and barriers. In these models, a cell is required to be at least large enough to support a few individuals. Adapting an IBM for modelling organisms living on and around a building is difficult, as for many organisms, in particular animals, home ranges are larger than the scale of a single building. A detailed understanding how architectural form affects community assembly on and around a single building is thus only possible for very small organisms such as plants, where a building can be represented by a number of cells.

In contrast to IBM, *home range formation models* explicitly model the home range of an individual depending on the suitability of a subsection (cell) with the potential home range. As the suitability of a cell may be different for different species, such models can be used to model community responses (e.g. Buchmann et al., 2013). These models can also include population dynamics or species interactions (Wang & Grimm, 2007; Zurell et al., 2015). Home range models can be formulated at a scale that is coherent with a building. The area covered by a building would then correspond to a number of home ranges for smaller species, or to a part of one home range for a larger species. Thus, home range formation models have the potential to model animal communities in an architectural context.

For plants, a simpler solution exists in the form of state-and-transition models. These models predict ecosystem dynamics in response to changes in the environment or disturbance regimes (Bestelmeyer et al., 2017; Moore & Noble, 1990; Noble & Slatyer, 1980). The notable strength of these models is that they have already been used to assess the impact of management on the temporal development of a plant community (Quétier et al., 2007; Rumpff et al., 2011). The model of Boulangeat et al. (2014), FATE-HD, proposes a functional group approach to simplify the parametrization and to increase the versatility of the state-and-transition model, allowing it to become widely applicable in modelling vegetation dynamics at the landscape scale, while accounting for environmental conditions, disturbances, species interactions and dispersal. FATE-HD could be extended to model plant dynamics at a very local scale in the urban environment.

Any of these models would need to be adapted to the appropriate spatial scales, that is, home range formation and local community assembly at the local building scale, and immigration and population viability at a larger scale.

3.3 | Specific challenges of understanding ecological processes on buildings

At the building scale, there are a number of additional challenges for understanding the ecological consequences of architectural design. This is because research on community assembly on buildings is still in its infancy, with most information currently coming from green roofs (Filazzola et al., 2019). The following non-exhaustive list points to important research gaps:

- *Soil formation and soil–plant interactions*: the physical, chemical or biological properties of soil are key for rainwater retention, carbon sequestration, and nutrient availability, and immobilization of pollutants, and strongly affect vegetation dynamics (Rodríguez-Espinosa et al., 2021). Soils in urban areas are particularly diverse and heterogeneous, and include, for example, heavily polluted industrial areas, public green spaces and different substrates use for green roofs (Burghardt et al., 2015). Common soil taxonomies (WRB, USDA) do not account for the complexity of urban soils and simply classify them as *technosols* ('soils with a strong imprint by human activities'), but this approach obfuscates their high functional variability (e.g. Charzyński et al., 2018). As many urban soils differ in key physical properties from natural soils, our knowledge of the functional role of urban soils is still low, and this is particularly true for artificially constructed technosols on green roofs (Ivashchenko et al., 2021; Ondoño et al., 2014; Panico et al., 2019). More research is needed to understand how urban soils, and artificial substrates in particular, affect plant and animal communities, and how urban soils and substrates develop in response to animal, plant and microbial activity.

- *Feedbacks between the biotic and abiotic components*: the community of organisms living on the building will affect the physical structures created by humans, as the growth of plants or the excrements of animals will potentially affect the building materials. Conversely, there are a number of specific abiotic effects on species in the urban environment, such as artificial light at night (Sanders et al., 2021) or noise pollution (Senzaki et al., 2020), in addition to effects of buildings on local air temperature, air flow, humidity and light conditions. Understanding these feedbacks is important for understanding the relationship between architectural form and ecological communities.
- *Feedbacks between humans and the ecological community*: the ecological communities that assemble as a response to multi-species design will facilitate interactions between humans and nature. The effect that the presence of other organisms on the building will have on humans will affect how the multi-species space is accepted and managed. These effects on humans include ecosystem services such as thermal comfort (due to shading or water interception of plants, e.g. Pérez & Perini, 2018), but also more direct health effects, both positive (e.g. challenging the immune system, which reduces the risk for allergies) and negative (e.g. transmission of ticks from animals to humans, or an increase in species that are deemed as pests by humans).
- *Community assembly of other organisms such as microbiota*: models of local community assembly on buildings are likely to focus on larger organisms such as plants or animals, but not on, for example, microbiota such as bacteria and fungi. Nevertheless, these organisms will invariably be part of the community that assembles locally, for example, as part of the soil, or because all higher forms of life host microbiota. The composition of the microbiota community has consequences for, for example, soil function, but also potentially human health, e.g. when the higher organisms living on a building potentially transmit disease, as in the case of bats (Li et al., 2010; Poel et al., 2006). Human acceptance or management of such risks will have consequences for the assembly of the local ecological community, for example, when bats are not accepted as parts of a local community. More research on this *socioeconomic and cultural filter* is needed to be able to realistically assess the chances and limits for multi-species design.

Modelling the ecological consequences of architectural form for local community assembly does not have to wait until these research gaps have been closed, as models could start with simplifying assumptions, for example, about the effect of soil on plant development. Nevertheless, the different feedbacks between species and the built environment, and between humans and other species, need to be addressed for a realistic understanding of local community assembly.

3.4 | Accepting the work ethics of architecture

There is another challenge to ecology, which concerns the relationship to architecture as a discipline with a long tradition, elaborated theories and very practical experience in constructing buildings. While there are abundant calls in ecology for city development and architecture to be more biodiversity-friendly (e.g. Beatley, 2011; CBD, 2012; Garrard et al., 2018; Mata et al., 2020; Parris, 2018), the challenge is to make ecological knowledge available and usable to architects, while fully respecting their professional philosophies' and design approaches. Knowledge is needed not only concerning the resource requirement of species and community assembly at the building scale, but also concerning human–nature relationships that go beyond the domain of ecology. It may be argued that for conservation purposes, it is better to preserve large natural habitats outside the city or in its outskirts, rather than creating habitats in the built-up part of the city. First, there is the possibility of creating ecological traps for some species (Battin, 2004; Demeyrier et al., 2016). Second, evidence suggests that sparing land for conserving biodiversity can better serve many species than land sharing at the regional scale (e.g. Soga et al., 2014; Sushinsky et al., 2013). However, this approach does not consider the benefit humans have from having green spaces close to their homes (Colléony & Shwartz, 2019). The challenge of a multi-species space for ecology is therefore to embrace the possibilities that architecture offers to the design of multi-species habitats, rather than to perpetuate the people–nature dichotomy from a conservation viewpoint.

4 | DESIGNING A MULTI-SPECIES SPACE: THE *ECOLOPE*

4.1 | Transforming the building envelop into an *ecolope*

Here, we propose the design of an *ecolope*, a shared multi-species architectural space which blurs the boundaries between the outside environment, the building's envelope and the interior (Figure 1). Our vision of the *ecolope* is that a building envelope should no longer be a generic separating boundary between humans within a building and the environment outside the building. An *ecolope* will be in intensive exchange with the environment outside the building and needs to be designed to allow for this exchange. The *ecolope* then has the potential to act as an enabler of human–nature interactions. This can be accomplished by designing it with the aim to support the life of other species as well as for humans. Such *ecolopes* could play a key role in overcoming the human–nature dichotomy, and could help to overcome the difficulty of providing spaces for green areas inside cities.

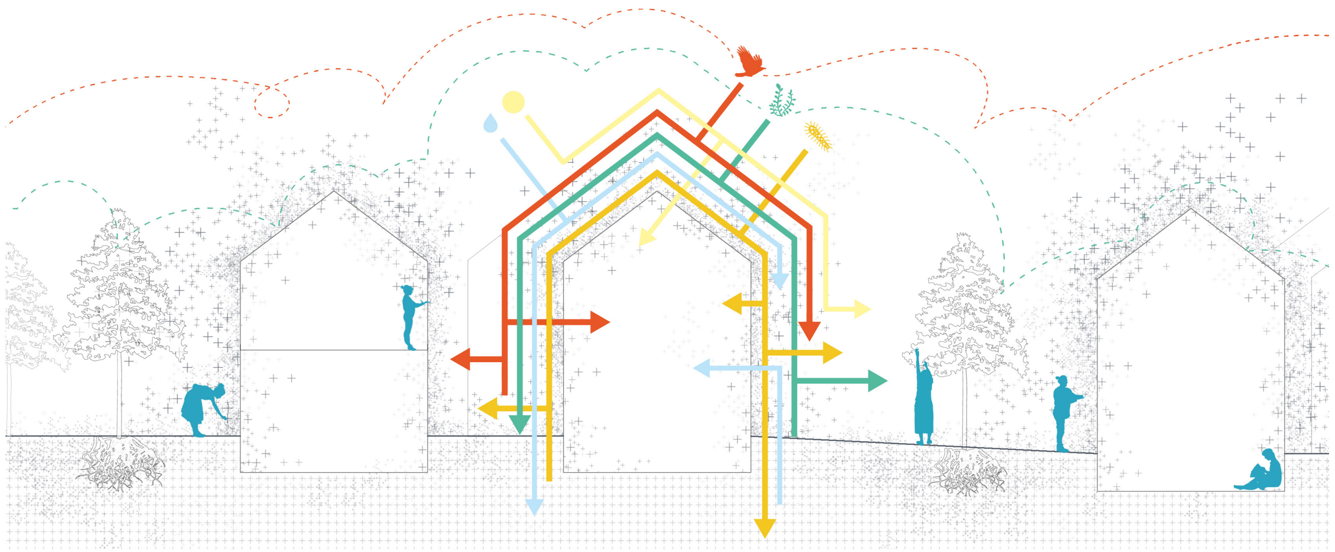

FIGURE 1 The *ecolope*, designed by transforming a conventional building envelope into a dynamic living space for animals, plants and even microbiota. It modulates environmental conditions such as sunlight and water/humidity, thereby creating and connecting habitats and improving human well-being (unscaled diagram).

We envisage the *ecolope* as a designed ecosystem whose community assembly is driven by architectural design, local and regional environments—including the regional species pool—as well as human use and management. We propose the *ecolope* to be a dynamic space shared between humans, animals, plants and also microbiota, that is constantly transformed through species interactions. Within the *ecolope*, positive feedback loops can be generated by way of, for example, decreased temperatures through evapotranspiration, which consequently affects all inhabitants. Designing an *ecolope* requires changing the paradigms of both architecture and ecology, as outlined in the previous sections.

In this section, we outline a possible design strategy for the *ecolope*, that builds on computational design and integrates both ecology and architecture.

4.2 | A design strategy for the *ecolope*

We envisage the process of designing an *ecolope* to be an iterative procedure, that takes into account architectural, environmental and biological variables. We also envisage the design process to take into account the dynamic nature of the *ecolope* ecosystem. This includes questions such as which plants and animals can immigrate and emigrate to and from the *ecolope*, and how species interactions drive the development of the species community on the *envelope*. Processes such as succession, as well as the effect of human management on the development of the community, need to be considered. Due to the complex nature of these interactions, an approach that is solely based on expert knowledge, trial and error, and intuition, will not suffice. Instead, designing an *ecolope* requires a knowledge- and evidence-based computational modelling approach that takes into account state-of-the-art approaches of the various disciplines involved in *ecolope* design. These need to be coupled in a useful way, requiring a novel design technology. We envision such technology to act as a design recommendation system, assisting architects in the design of buildings and their envelopes, aiding decision-making, and facilitating coordinated planning actions. The technology needs to make ecological knowledge available for the architectural design process. This is done with the aim of finding architectural solutions that enable synergies and limit conflicts between the inhabitants of the *ecolope*. Such a systematic approach needs to consider the interactions that occur between the abiotic environment, architecture, the different species living in an *ecolope*, some of which may be managed by humans, and between the different organisms themselves. Furthermore, local context-specific information, such as the structure of the surrounding city with its greenspaces, needs to be brought into the design process.

We envisage the following design workflow from the user perspective (Figure 2). As a user, we consider an interdisciplinary design team, consisting of, for example, architects, landscape architects and ecologists. The workflow includes several steps.

The first step is to select a site where the project takes place. This is typically done by the (public or private) client as a representative of human stakeholders who would like to develop a project. This client will have certain objectives with the project. In addition, there are legal requirements and higher-level planning objectives. It is important to note that the framework conditions for an *ecolope* do not include objective factors only, such as the local climatic conditions or the urban structure, but also normative settings and cultural urban conditions. Here, a distinction can be made between external and internal normative constraints. The external constraints are set by government rules (laws and regulations) and by administrative proceedings and plans; the internal constraints are set by the values and commitments (e.g. in the form of a corporate mission and

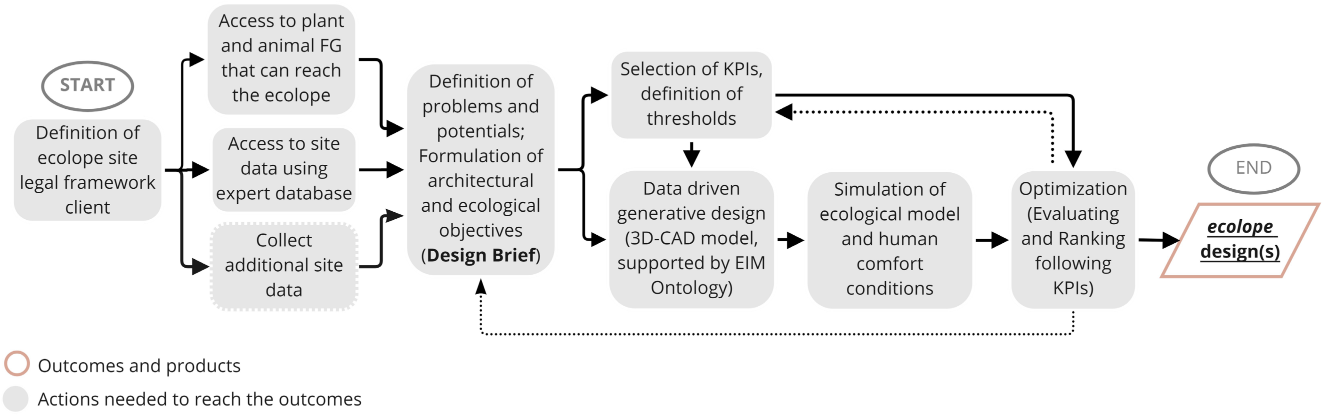

FIGURE 2 Design workflow for an *ecolope* from a user's perspective.

compliance management) of the client, which are expressed in the client requirements, and by the values of the interdisciplinary planning team. External normative constraints are thus also captured in the *ecolopes* design workflow.

In a second step, the urban and environmental conditions of the site will be analysed. These site data include data on the 3D geometry of the site, urban form, climate, topography, population but also information specific for *ecolope* design such as terrain and the occurrence of plant, animals and microbes on the site and in the surroundings. For the user, the raw data will already be processed to, for example, reduce the list of species to those that can reach the building site. Wherever necessary, additional data will be collected. Note that while Figure 2 specifically spells out ecological requirements, all analyses and data pertaining to the requirements of the human client that are normally obtained in a human-centred design approach will also be included in the design workflow for an *ecolope*.

The third step in the workflow corresponds to formulating the design brief. This design brief brings together the existing data, the client's requirements, the legal framework, higher-level planning strategies and also the design goals of the interdisciplinary design team with respect to aesthetic quality, urban context, ecology and other functional requirements. The design brief defines both the design objectives (e.g. ecological and architectural objectives) and the boundary conditions of the design (*ecolope's* design space). Thus, it is the human stakeholders that will evaluate all information and set design targets, yet based on a large array of data. The design brief is the starting point for the selection of key performance indicators (KPIs), defined for each stakeholder (humans, plant, animals and microbiota), that will guide the design of the *ecolope*. We envisage a generative design process whereby architectural forms are generated in a data-driven way. The settings for the design process concern, for example, architectural geometry, soil (compaction, depths) and water drainage. Following the requirements, a number (*n*) of variants are developed in the interplay of terrain and building structure. Generation of the variants is supported by an ontology, that encapsulates relationships between architectural form and function, and that draws on a knowledge base where these relationships are stored. The consequences of the design variants are then evaluated for the human user (e.g. with respect to human comfort), and also for plants, animals and microbes, with the help of the ecological model that also considers the interactions between the different stakeholders. The KPIs will be used to numerically grade the different variants, to assess their performance, resulting in a ranking of the design solutions.

In a final step, the user will assess the results of this computational evaluation process, that is, the ranking of the variants and their performance, to decide which initial design solution should be chosen. Thus, the user workflow mixes computer-aided design recommendation with human evaluation of the outcome. Importantly, the design process will be iterative. Based on the user assessment of the design outcome, the user can decide to modify the design objectives, the settings for the generative design, and the KPIs, to start a next design cycle. We envisage that the cycle (design loop) from formulating design objectives, specifying settings for the generative design, and formulating KPIs to assessment of the optimization outcomes, is repeated several times. The design solutions obtained in this iterative design process will become more and more efficient and precise, until the user is satisfied with the design. The first design loops will likely explore the widest possible range of suitable and performing variants. For example, the first design loop may focus on optimizing the use of terrain, by exploring simple building shapes with the aim to provide sufficient soil for the growth of plants.

4.3 | Modelling the *ecolope* ecosystem

Designing a multi-species space requires assessing the consequences of architectural design for the ecological communities living in and around the *ecolope*. As pointed out above (Section 3.2), this requires modelling the *ecolope* communities in a spatially explicit way, to be able to understand the interdependent spatial and temporal dynamics of the different organisms. The dynamics of the organisms will be affected by immigration from the regional species pool, and locally by the geometry of the building, the local abiotic conditions, the substrate used to design the *ecolope* and by *ecolope* management. For a matter of generalization and simplification, such a model could focus on plant functional group (PFG) and animal functional group (AFG) instead of species (see Section 3.2). To realistically model the biological communities and their temporal development, a coupling of different models, for example, a plant, animal and soil model, will be required. In addition, management has predictable impacts on plants and animals that should be accounted for.

Developing an *ecolope* model also requires considering different spatial scales (Figure 3). A regional model should estimate the probability of colonization for each FGs present in the species pool, according to the location of the building in the city and the FG dispersal and movement abilities. Models such as RangeShifter (Bocedi et al., 2014) could be used for this end. A local model would then apply a second filter on the species reaching the *ecolope*, based on the abiotic and biotic conditions on the *ecolope*. To capture the ecological complexity of ecosystems, the local model should consider and model the dynamics of different interacting components, including soil, plants and animals. For example, architectural considerations such as slope and aspect influence soil depth and water availability, and thereby the suitability for plants; plants, in turn, condition the soil for further succession, for example, by affecting the microbiota present in the soil, and by providing resources for animals; this, in turn, allows the immigration and survival of soil arthropods such as *Collembolans*, which further affect soil development.

A suitable plant model could be, as pointed out in Section 3.2, FATE-HD (Boulangeat et al., 2012; Boulangeat et al., 2014), which predicts vegetation dynamics based on abiotic filtering, competition for light and dispersal. Being a landscape-scale model by design, FATE-HD requires, however, further amendments to predict plant communities on the scale of an *ecolope*. The model can be adapted to model plant populations on or next to buildings by taking into account the conditions of the substrate in which plants root, as well as other abiotic conditions or human management, such as trimming the vegetation at particular intervals. Particular consideration needs to be given to the substantial heterogeneity of soils in urban environments (Eviner & Hawkes, 2008). FATE-HD could thus be extended by a soil module, which describes habitat suitability of each plant functional group in response to soil differences. Furthermore, soil may erode due to wind and water runoffs, and also develops

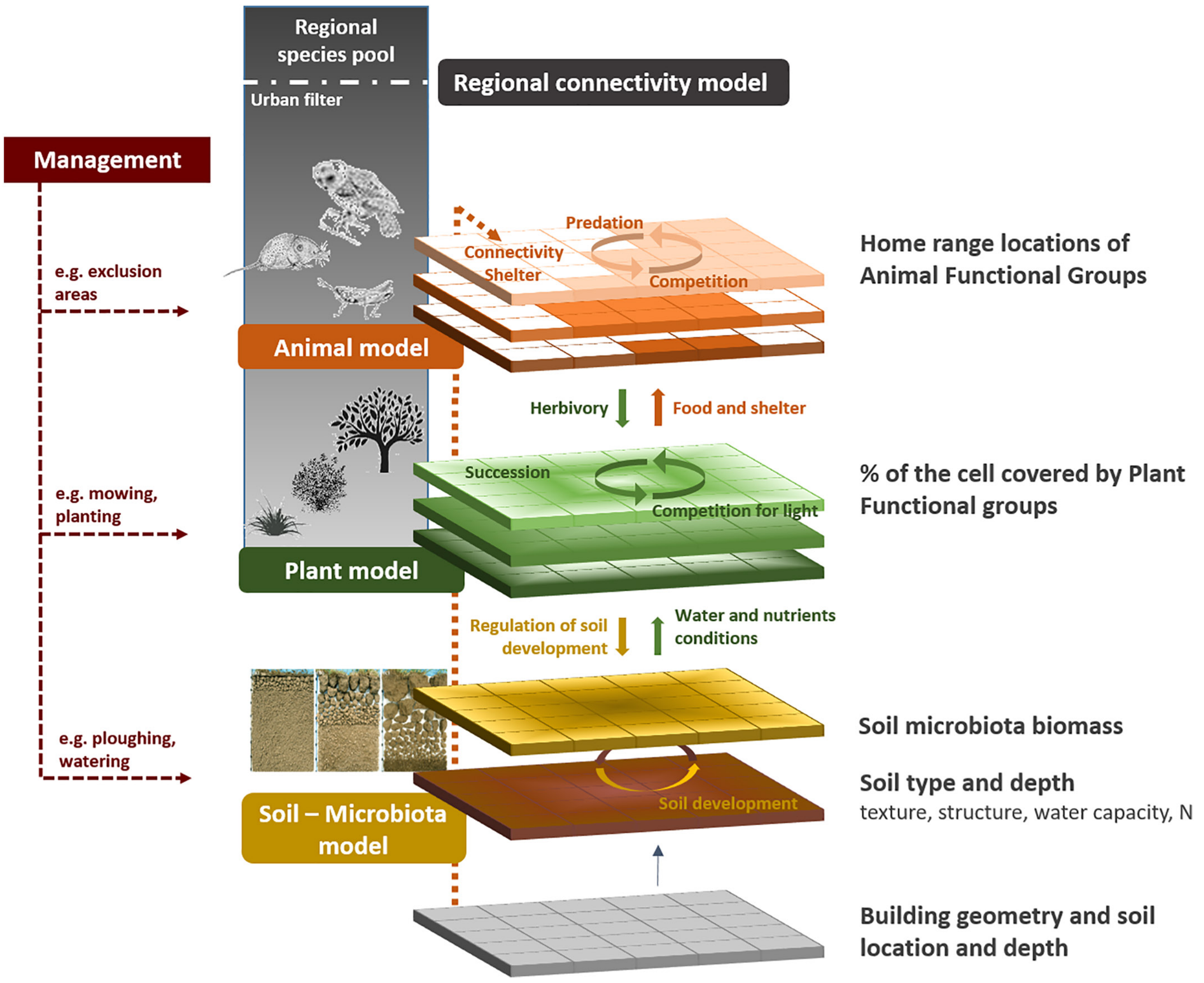

FIGURE 3 Important model elements and processes to be included into an *ecolope* ecosystem model

over time due to the activity of microbiota, plants and animals; this dynamic change in habitat suitability should also be reflected by the model (Schrader & Böning, 2006). The plant model can draw on the increasing knowledge available on plant performance and community development on green roofs (Vandegrift et al., 2019; Xiao et al., 2014), as well as on the increasing knowledge of how ecosystem functions are mediated by plant communities on buildings (e.g. Lundholm et al., 2010).

For animals, the functional groups able to live on the *ecolope* will be dependent upon the local access to a variety of resources required by each species to complete their life cycle. This, in turn, will depend on traits such as movement ability. The local model will also need to consider immigration and emigration from different green patches in the local and regional surroundings of the *ecolope*, as these patches are would likely be a source for the AFGs living on the *ecolope*. Home-range models (e.g. Buchmann et al., 2011; Buchmann et al., 2012; Buchmann et al., 2013) are well-suited to act as local model, but they need to be adapted to include, for example, reproduction and species interactions (see Section 3.2).

Modelling plant and animal communities on and around the *ecolope* will be a significant challenge. The plant and animal models need to be coupled to investigate trophic interactions. Importantly, there is flexibility in the modelling approach to increase the complexity in a number of steps. Later model versions could include the development of the microbiota community in soils (Fulthorpe et al., 2018), or consider how the *ecolope* affects human health by modifying interior conditions (Ghaffarianhoseini et al., 2018; Mitchell et al., 2007).

4.4 | From the user workflow to a computational design approach

As more and more live environmental (solar radiation, water retention, connectivity, soil depth) and ecological data (e.g. species data) are available in both GIS and BIM (Catalano et al., 2021; Jupp, 2017), the implementation of multi-species and biodiversity components into the early phases of a project can be enabled by a computational design approach. Such a computational design approach has the potential to enable a systematic multi-species design beginning with the design phase. It would also allow to effectively evaluate multiple design configurations (Figure 4).

This computational design approach needs to encode data relevant to human and non-human stakeholders, and it requires an ecological model for design decision support, algorithms for design generation and optimization, as well as KPIs that evaluate the performance of the design outcome. Since the evaluation criteria based on KPIs are explicitly formulated, greater objectivity and transparency in problem-solving can be guaranteed (Steadman, 2014). However, there are some challenges: First, the correlations between ecological and architectural design aspects need to be defined to guide multi-species design decisions. For instance, how can the geometry of an *ecolope* foster biodiversity? How can different levels of inclination affect the connectivity for certain plant or animal functional groups? Without the knowledge about how geometry and species requirements are connected, an *ecolope* cannot be designed. Second, in a data-driven computational design approach, it is not always clear what data are relevant and precise enough to significantly affect the design outcomes. Thus, the data need to be analysed, filtered and converted into relevant information for the design algorithms. Third, for the systematic integration of ecological modelling in a design context, a computational design platform is required where data, ecological and environmental modelling, architectural design, optimization as well as a reasoning and KPIs evaluation are integrated in one system/technology.

One possibility to generate the knowledge needed for starting the design process is to perform a series of computational experiments. The aim of such experiments would be to overcome the missing link between geometry and ecological dynamics, to create the knowledge necessary to inform the design process towards given ecological objectives. This knowledge will then be stored in the knowledge base, as a basis for an ontology that can leverage information from existing patterns for design recommendation. Generative algorithms for design and optimization can be driven by the information from the knowledge base, ontology, KPIs, but also by the user and the requirements of the legal framework. The computational framework needs to contain algorithms for the generation of initial design variations and further algorithms for filtering and ranking the design outputs, as well as for environmental analysis, ecological analysis and for optimization. The data conversion from CAD (geometry models) to raster data (ecological models) and vice versa can be conducted through, for example, a voxel model that divides the 3D geometry into voxel cells that can then be converted into raster data. In this approach, each voxel cell would contain the corresponding metadata from environmental (e.g. soil depth, solar radiation, water retention, connectivity) and ecological (e.g. location of different functional groups) analysis. Thus, the optimization process would include not only the optimization of the *ecolope*, but also the voxel model and the KPIs for each iteration. The optimized values (data and KPIs) can then be encoded into the respective voxel cells through the same algorithms employed in the architectural design phase.

The final outcome would be a selection of *ecolope* designs with the corresponding metadata stored in a voxel model. Additionally, the design generation and optimization environment would make it possible to suggest design solutions and analyse trade-offs between building design and ecological performance. Some of the KPIs will measure the performance of the plant and animal aspects of the *ecolope*, such as population sizes, while others will address human needs. While there are models for evaluating synergies and trade-offs among ecosystem services across domains and for Green Infrastructure (European Commission, 2012), or urban agriculture and vertical farming, these need to be critically reviewed and combined with architectural performance indicators. These KPIs will help to sort and measure possible envelope scenarios. We suggest to adopt multi-criteria decision-making strategies that are effective due to their flexibility in considering multi-disciplinary data that is qualitative as well as quantitative (Gnanasekaran & Venkatachalama, 2019; Mela et al., 2012). This

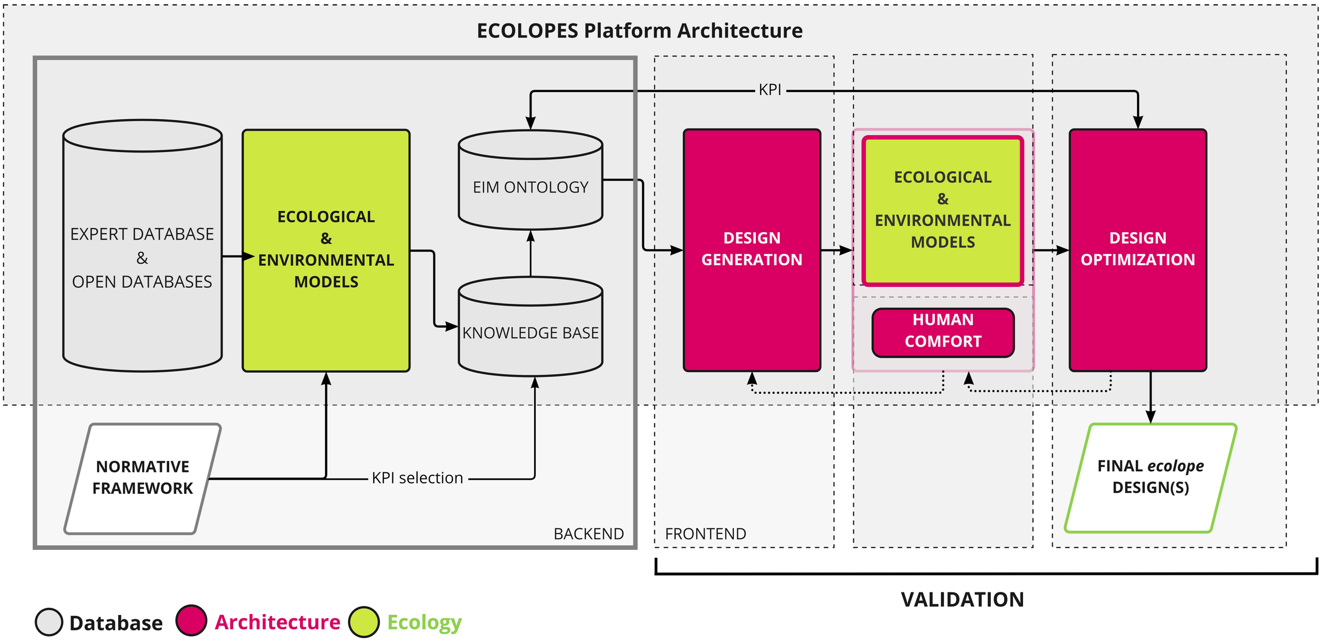

FIGURE 4 Potential computational design workflow for multi-species design. Knowledge generation (correlations between architecture and ecological aspects), ecological and environmental modelling, design and key performance indicators (KPIs) optimization have to become an intrinsic part of one computational design platform which interfaces with the user.

enables multiple stakeholders and their related KPIs to be integrated into new design decision-making processes systematically. The rating of alternative scenarios can hence be done both separately for each inhabitant, for example, from the human or the plant perspective, and also from multiple-inhabitant perspectives. In this way, trade-offs and synergies can be analysed through an iterative procedure that corresponds to the user design workflow and allows for the simultaneous development and comparison of various design solutions.

Third, such a new computational design platform would need to integrate all modules (databases, the environmental and ecological model, the knowledge base, the ontology, the design generation and optimization environment) in one system. Through a front-end design tool it allows the user to interface with the system, that is, it allows for human design.

5 | DISCUSSION

Here, we have proposed that an *ecolope*, a multi-species space that forms an integral part of a building, can be an important step in designing more sustainable cities where nature is an integral part. We have outlined that it is not enough to propose such an element of building design, but that it is necessary to provide a tangible solution for realizing an *ecolope*. In our view, this solution needs to be knowledge-based and data-driven, and based on ecological modelling and computational design in architecture. We believe that such an approach and the development of the necessary technology are feasible. Our approach differs from previous ones in that it aims at developing a systematic design strategy that clearly specifies the ecological objectives and evaluates them using ecological insights. We have deliberately avoided to present images of a potential *ecolope*, because it is the systematic design strategy and evaluation of the design outcome that sets an *ecolope* apart from other building envelopes, not its appearance. We envisage that many *ecolopes* will not look very differently from existing green buildings, at least superficially, but they will function differently and their performance, once built, can be compared to the original design aims in quantitative terms.

A successful *ecolope* can contribute to the conservation and promotion of urban biodiversity, improve the experience of nature in the city, thereby helping to overcome the dichotomy between people and nature. Building envelopes designed as *ecolopes* can therefore support the objectives of initiatives such as the EU Green deal or the EU Biodiversity Strategy 2030 (European Commission, 2020), which aim to promote the systematic integration of nature-based solutions into urban planning. The potential of an *ecolope* to improve urban conditions could also be explored in the framework of the current New European Bauhaus initiative,[1] which aims to connect the European Green Deal to the daily lives and living spaces of European citizens.

In our view, urban planning strategies can only achieve high effectiveness for people and other organisms if there are tangible solutions that integrate built space and buildings. The *ecolope* is one such solution, and can become a building block for the design of a more sustainable city. To promote the establishment of *ecolopes*, there is the need for a deeper understanding of how *ecolopes* can contribute to biodiversity at the city scale, and how *ecolopes* can be integrated with other ideas and approaches at higher planning levels and scales to achieve a high-performance urban green infrastructure that works for people and other species. The ecological potentials and objectives of an *ecolope*, as well as its benefits for humans, will depend on the environmental and urban context where it will be built. Applied to a single building in a densified urban environment, the presence of a single *ecolope* will already be able to provide benefits for humans and urban biodiversity by locally supporting some species, and by enabling human–nature interactions in an area previously deprived in such opportunities. Rightly located, even a small *ecolope* could make a difference in supporting an ecological connectivity network in a city or contribute to a well-defined urban green infrastructure scheme. Applied at the scale of districts or used as default architectural solution in city planning, the *ecolope* concept has the potential to radically change the physiognomy of the city to turn it into a shared habitat for plants, animals, microbes and humans.

Apart from these important aspects, the question is how to encourage architects and planners to embrace this concept and move from a historically anthropocentric focus on buildings and cities to a more 'green' approach that includes ecosystem design. We believe that *ecolopes* will need to be constructed and their benefits demonstrated, to be able to convince building professionals of its potential. Beyond this, it is important to establish the knowledge base that allows *ecolopes* to be designed by built environment professionals along with off-the-shelf solutions that can be drawn upon in the design strategy. Furthermore, demonstrated benefits of model *ecolopes* should be used to raise public awareness and to convince local authorities and government to act by developing policies (e.g. subsidies) that encourage architects to implement nature-based solutions such as *ecolopes*.

There is the risk that the shift from a human-centred perspective to a multi-species perspective will be considered too radical for many people, resulting in resistance. We are aware of this challenge and suggest to address this in two ways. First, it is important to inform the public and stakeholders about the idea, vision and usefulness of the *ecolope*, based on the evaluation of prototypes. Second, too explore the reaction of people to *ecolopes*, it is possible to use virtual environment experiments (cf., Shemesh et al., 2022) where people are presented with entire design solutions as well as individual features of a. The feedback obtained through these experiments can then be used to further improve the design solutions. Another risk is that the concept will be blurred such that any building solution involving the envelop, plants or animals is considered as an *ecolope*. Again, providing best practice case studies is a useful way to point to distinguishing features of an *ecolope*. Ultimately, a set of metrics needs to be developed that evaluate the performance of the *ecolope*, and that are closely linked to general KPI used in the design process.

6 | CONCLUSIONS

Bringing nature into cities is a major challenge for mankind. It is unlikely that a single strategy or a single measure can achieve this vision. Here, we have focused on the role of architecture in the creation of green infrastructure within cities, mainly focussing on the scale of individual buildings. We have outlined how an approach alongside a related method and technology can be developed that allows for the design of a multi-species living space that we refer to as the *ecolope*, which can replace conventional building envelopes. We believe that such an *ecolope* can significantly enhance biodiversity in the city and allow for better human–nature interactions. The technology we propose has the capability to constitute an important part of future city design and can thereby complement other approaches such as designation of nature conservation areas within cities. The next step will be to develop the design strategy we propose to the point where it can be applied to the real world.

AUTHOR CONTRIBUTIONS

All authors conceived the ideas and jointly designed the methodology of the *ecolope*; Wolfgang W. Weisser and Michael Hensel led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. Assaf Shwartz is an Associate Editor for *People and Nature*, but was not involved in the peer review and decision-making process.

DATA AVAILABILITY STATEMENT

No data are included in this article.

ORCID

Wolfgang W. Weisser https://orcid.org/0000-0002-2757-8959
Michael Hensel https://orcid.org/0000-0001-5899-5643
Shany Barath https://orcid.org/0000-0003-0776-7389
Victoria Culshaw https://orcid.org/0000-0002-3228-4322
Yasha J. Grobman https://orcid.org/0000-0003-4683-4601
Jens Joschinski https://orcid.org/0000-0001-7828-3336
Ferdinand Ludwig https://orcid.org/0000-0001-5877-5675
Katia Perini https://orcid.org/0000-0003-0415-8246
Enrica Roccotiello https://orcid.org/0000-0003-3701-9154
Michael Schloter https://orcid.org/0000-0003-1671-1125
Defne Sunguroğlu Hensel https://orcid.org/0000-0003-2968-6432
Verena Vogler https://orcid.org/0000-0002-6490-1380

ENDNOTE

[1] https://europa.eu/new-european-bauhaus/index_en.

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