ECOLOPES

ECOlogical building enveLOPES: a game-changing design approach for regenerative urban ecosystems

H2020-FET-OPEN-2021-2025

Action number 964414

D1.3

Report of Year 1

Dissemination level:	Public
Contractual date of delivery:	Month 12, 31. March 2022
Actual date of delivery:	31.3.2022
Work package:	WP1: Project Management and Coordination
Task:	T1.1: Overall project and financial management
Type:	Report
Approval Status:	Submitted
Version:	V3.0
Number of pages:	45
Filename:	D1.3_Ecolopes_ReportOfYear1.docx

Abstract

ECOLOPES proposes a radical change for city development: instead of minimizing the negative impact of urbanisation on nature, we aim at urbanization to be planned and designed such that nature - including humans - can co-evolve within the city. In the project, we envisage a radically new integrated ecosystem approach to architecture that focuses equally on humans, plants, animals, and associated organisms such as microbiota. To do so, ECOLOPES focusses on the envelope, the building enclosure. We will transform the envelope into an *ecolope*, a multi-species living space for four types of inhabitants, humans, plants, animals, and microbiota. To achieve this, ECOLOPES will make biological knowledge available for the architectural design process, to find architectural solutions that enable synergies and limit conflicts between the inhabitants. This report describes the progress of the project in the first year, in the period 1.April 2021-31.March 2022. Major achievements that are described in this report and in several deliverables submitted along with this report include the user workflow to design an *ecolope*, the computational workflow including technical requirements, and the development process for the ECOLOPES algorithms. The deliverables of the first year also include a preliminary dissemination and exploitation plan as well as a report of the respective activities in year 1.

Funded by the European Union

HISTORY

Version	Date	Reason	Revised by
1.0	20.1.2022	First version	Wolfgang W. Weisser
2.0	22.2.2022	Second version	Wolfgang W. Weisser, Anne Mimet, Shany Barath, Katia Perini, Surayyn Selvan, Yasha Grobman, Verena Vogler
3.0	30.3.2022	Third version	Wolfgang W. Weisser, Anne Mimet, Surayyn Selvan

AUTHOR LIST

Organization	Name	Contact Information
TUM	Wolfgang Weisser	wolfgang.weisser@tum.de
TEC	Yasha Grobman	yasha@technion.ac.il
TEC	Shany Barath	barathshany@technion.ac.il
TEC	Surayyn Uthaya Selvan	surayyn@campus.technion.ac.il
TUM	Anne Mimet	anne.mimet@tum.de
UNIGE	Katia Perini	katia.perini@unige.it
MCNEEL	Verena Vogler	verena@mcneel.com

EXECUTIVE SUMMARY

In ECOLOPES we propose a radical change for city development: instead of minimizing the negative impact of urbanisation on nature, we aim at urbanization to be planned and designed such that nature - including humans - can co-evolve within the city. We envisage a radically new integrated ecosystem approach to architecture that focuses equally on humans, plants, animals, and associated organisms such as microbiota. ECOLOPES focusses on the envelope, the building enclosure. We will transform the envelope into an *ecolope*, a multi-species living space for four types of inhabitants, humans, plants, animals, and microbiota. ECOLOPES will make biological knowledge available for the architectural design process, to find architectural solutions that enable synergies and limit conflicts between the inhabitants.

In the first year of the project, we have provided the basics for the development of the core technologies that will allow the design of *ecolopes* in a systematic way. In close collaboration between disciplines, we have developed the user workflow for the design of an *ecolope*, as well as a first version of the computational workflow. A core element of bridging between ecological dynamics and architecture is the ECOLOPES ecological model. In the first year, the conceptual framework for the modelling has been developed, consisting of local models that can simulate the dynamics of plants and animals at the spatial level of a home-range. This is supported by a soil-microbiota model. The local model will be connected to a regional model that takes into account the connectivity of the entire city. The local ecological models are already connected to architectural forms in the Mi(ni)-Mo(del)--experiment, to explore the relationship between architectural parameters and ecological function. The conceptual approach to the ECOLOPES Information Model (EIM) ontology has been developed and the databases needed for the design workflow have been identified. A first conceptual and initial technical understanding of the multi-criteria decision-making (MCDM) strategies to integrate the multi-disciplinary information of ECOLOPES was also developed, to work towards the formulation of the key performance indicators (KPIs) that will guide the design. A first approach to the use of algorithmic tools has also been developed.

A number of architectural studios have explored the requirements to architecture of designing for nature, in particular the role of terrain as enabler of human-nature interactions. To select case studies in a systematic way, an urban classification procedure has been developed, that integrates site variables such as local climate, built environment, ecological as well as socio-economic data.

The ECOLOPES consortium meets regularly as a whole in general monthly meetings as well as targeted topic in meetings and the interactions are lively and fruitful. This regular exchange has proven to be key for progress. The deliverables of the first year also include a preliminary dissemination and exploitation plan as well as a report of the respective activities in year 1. To summarise, the ECOLOPES project has made considerable progress in the first year and we are optimistic that our development of a design procedure will be successful.

Abbreviations and Acronyms

AI: Artificial Intelligence

BOT: Building Topology Ontology

ecolope: An ecological building envelope

ECOLOPES: the Ecological building envelopes project

EIM: ECOLOPES Information Model

KPI: Key Performance Indicator

LFRO: Landform Reference Ontology

MiMo: Mini Model (Experiment)

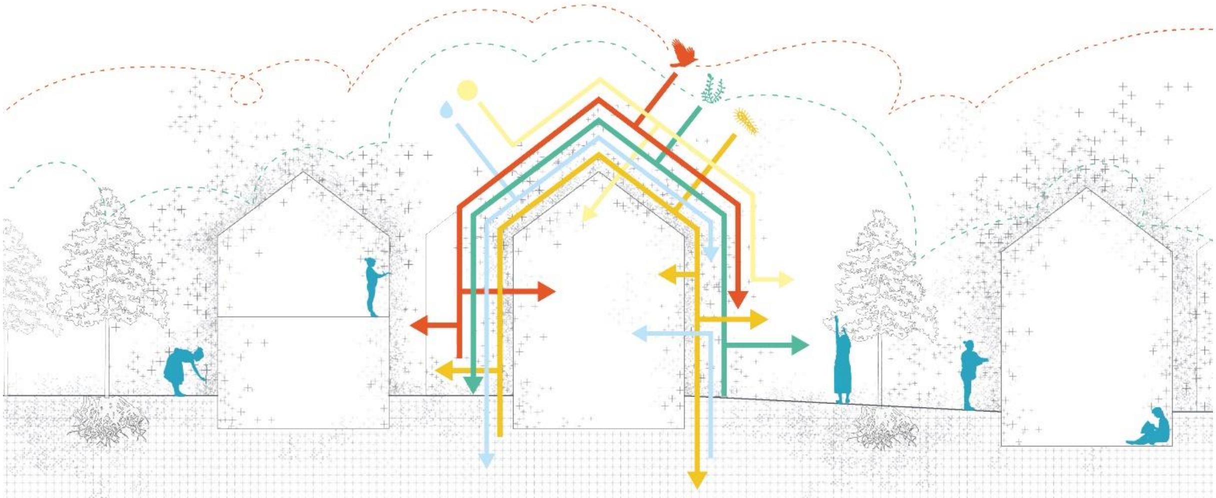
OBO: Open Biological and Biomedical Ontologies

OWL: Web Ontology Language

WP: Work Package

Table of Contents

1 INTRODUCTION



Urbanization constitutes a major environmental issue of the 21st century. Within cities, densification, the decrease of green open spaces, and a continued reliance on grey infrastructure approaches result in increasing separation of people from nature and decreased access to ecosystem services. This decreases the liveability of cities and reduces human well-being. Current approaches fall short in providing breakthrough solutions, because they perpetuate the human-nature dichotomy due to anthropocentric design.

In ECOLOPES we propose a radical change for city development: instead of minimizing the negative impact of urbanisation on nature, we aim at urbanization to be planned and designed such that nature - including humans - can co-evolve within the city. We envisage a radically new integrated ecosystem approach to architecture that focuses equally on humans, plants, animals, and associated organisms such as microbiota. Over the next few years, ECOLOPES will provide the technology that will help to achieve this vision.

In our ECOLOPES EU FET project, we focus on the envelope, the building enclosure, as it is the buffer zone between the inside and outside that has been tried so far as a single function entity - a barrier between the inside and outside. We will transform the envelope into an *ecolope*, a multi-species living space for four types of inhabitants, humans, plants, animals, and microbiota. ECOLOPES will develop the core technologies for designing *ecolopes* in a systematic way, considering the needs of both humans, as well as of plants, animals and beneficial microbes. To do so, ECOLOPES will make biological knowledge available for the architectural design process, to find architectural solutions that enable synergies and limit conflicts between the inhabitants. The *ecolopes* designed by this multi-species approach will restore the beneficial human - nature relationships in cities.

In ECOLOPES we develop a design approach that is supported by a computational framework and workflow that includes a range of expert data-bases, an information model and algorithmic processes and tools, to result in a data-driven design recommendation system. This also includes an ECOLOPES Information Model (EIM Ontology) that defines the relationships between the inhabitants, architecture and the abiotic environment. A tailor-made computational framework will make the knowledge embedded in the information model and databases available for design. This includes front-end tools for design, modelling and visualisation, and a computational simulation environment that enables iterative design development integrated with multi-criteria decision-making strategies. The ECOLOPES design approach will be validated through design cases, located in different urban environments.

2 ECOLOPES Scientific Approach

2.1 Background

Urbanisation is one of the major global environmental issues of the 21st century. Rapid urbanisation and construction cause land cover change, leading to degraded environments and novel ecosystems which have major implications for biodiversity and human well-being. Moreover, urbanisation has been shown to cause the extinction of local species, spread of invasive alien species, and biotic homogenisation (McKinney 2002, Groffman et al. 2017, Colleony and Shwartz 2020, McDonald et al. 2020). In the urban environment, a reliance on 'grey' infrastructure, i.e. 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 the regulation of climatic conditions and mitigation of extreme events such as heavy rainfall or heat waves (CBD 2012), but they also provide direct positive effects on our health and well-being, including stress reduction and providing a sense of place (Peccia and Kwan 2016, De Palma et al. 2018, Marselle et al. 2019). An increasing body of evidence outlines negative health effects resulting from non-existent or degraded nature in cities. For example, several studies reported a correlation between reduced microbial diversity, mainly during early childhood, and an increased risk for allergies such as asthma and neurodermatitis (Peccia and Kwan 2016, Gilbert and Stephens 2018). Furthermore, there is evidence for a link between a lack of green space and higher human mortality (Rojas-Rueda et al. 2019). Cities have thus been considered as an important showcase for the One Health or Global Health concept, and indicate that a healthy environment is a strong driver for human health and well-being (Bruen et al. 2014).

Making cities sustainable, resilient, and liveable is thus 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 effort, such policies place special emphasis on the development of green infrastructure, a strategically planned network of natural and semi-natural areas (Benedict and McMahon 2012, European Commission 2013). This also entails increasing the use of innovative nature-based solutions, i.e., the sustainable use of resources and natural processes for solving societal challenges and delivering a wide range of ecosystem services (Eggermont et al. 2015). In the next decades, with the advent of new robotics and autonomous systems, cities will undergo 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 biophilic thus requires new planning methods that mobilizes all disciplines involved in urban development (Kellert et al. 2008, Thomson and Newman 2018, Elmqvist et al. 2019, Söderlund 2019, Thomson and Newman 2020).

ECOLOPES starts from the premise that to create a healthy environment for humans in cities, architecture needs to be activated for the support for urban biodiversity. This is because buildings and constructions are the essence of cities, and designing these buildings is the domain of architecture. ECOLOPES proposes that a first step in creating such a multi-species habitat is the design of an *ecolope*, an ecologically designed building envelope that provides a habitat for many organisms. Because such an *ecolope* does not exist yet, ECOLOPES develops a design strategy that draws on knowledge from ecology, as well as architecture, sustainable building design, and design computation. This design strategy will make ecological knowledge available to the architectural design process, enabling practitioners to find architectural solutions that facilitate synergies from a multi-species perspective. Thus, ECOLOPES will provide technology and design methods that will help to achieve the vision of an integrated ecosystem approach to architecture.

2.2 ECOLOPES overall design approach and work packages

A systematic approach is needed to be able to consider the interactions between the abiotic environment including architecture and the different inhabitants of the *ecolope*, and between the different inhabitants themselves. A systematic approach is also needed to bring local context-specific information into the design process. ECOLOPES will tackle the challenge by simulating the *ecolope* ecosystem and its various sub-systems, in space and time. To enable a systematic approach, ECOLOPES will develop **Key Performance Indicators** (KPI's), measuring the consequences of a particular design for human well-being, and for abundance of the non-human inhabitants (see WP6, section 8). ECOLOPES considers the *ecolope* as a dynamic system that can be adapted to changing needs. Thus, modelling will also need to include the projection of *ecolope* development after initial building completion. This will include ecological succession, e.g., how soil will develop and generate positive feedback for plant development and colonization of animals. It will also include modelling the effects of human management, such as trimming of vegetation. Our approach will capture the relevant processes for *ecolope* design. This includes the development of a **data-driven design recommendation system**, which will radically advance our understanding of the feedbacks between building design, the ecology of species in cities, and consequences for human well-being. See Deliverable D4.1 Preliminary EIM Ontology for a description of the achievements of year 1, in particular the different modelling components. We will also create the **ECOLOPES Computational Modelling and Simulation Environment**, which will make knowledge available for design. Advances are described in Deliverables D3.1 Prototype technical requirements report and D5.1 Development process for the ECOLOPES algorithms.

The proposed data-driven design recommendation system will assist architects and planners in the design of *ecolopes*, aiding decision making and facilitating systemic coordinated action in the planning of multi-species environments for regenerative cities. The overall goal of ECOLOPES is thus to provide the technology that enables this iterative design process based on the simulation of the dynamic development of the *ecolope*, and of its various subsystems and their interactions.

Altogether, ECOLOPES has five specific objectives (SO), each of which is targeted in a specific Work package (WP):

►SO1: develop the ECOLOPES computational platform, as basis of the computational design process, including data warehousing capabilities and front-end tools to allow users to view and modify the design outcome (WP3).

►SO2: develop the ECOLOPES Information Model (EIM) Ontology, which defines the fundamental relationships between architecture, the abiotic environment, soil, plants, animals and microbiota. The modelling approach to the *ecolope* ecosystem is core to our project and central to the design of the *ecolope* (WP4).

►SO3: develop the computational tools for modelling and visualizing the *ecolope*, to link the EIM Ontology via a datapoint (Voxel) model to algorithmic processes and tools integrated in Rhino3D and VR (Virtual Reality) (WP5).

►SO4: set-up a computational simulation environment, to enable the iterative design process, including computational simulations, multi-criteria analysis and rating strategies, resulting in an informed decision-making process (WP6).

►SO5: demonstrate the effectiveness of the ECOLOPES design platform, by validating the ECOLOPES' overall design process through specific design cases in four cities, and by assessing synergies of, and trade-offs between, different design solutions (WP7).

In total, the work of ECOLOPES is carried out in eight work packages (Table 2.2.3).

Table 2.2.3: Work package structure

WP	Title	Leader	Email Address
WP1	Project management and coordination	TUM Wolfgang W. Weisser	wolfgang.weisser@tum.de
WP2	Dissemination and exploitation	TUM Ferdinand Ludwig	ferdinand.ludwig@tum.de
WP3	ECOLOPES Platform Architecture	MCNEEL Verena Vogler	verena@mcneel.com
WP4	Data acquisition and information modelling	TUM Michael Schloter Defne Sunguroglu-Hensel	schloter@helmholtz-muenchen.de defne.hensel@tum.de
WP5	ECOLOPES Voxel & Computational model	VIE Michael Hensel	michael.Hensel@tuwien.ac.at
WP6	Computational Simulation and Analysis	TEC Shany Barath	barathshany@technion.ac.il

WP7	Overall Validation	UNIGE Katia Perini	katia.perini@unige.it
WP8	Ethic	TUM Anne Mimet	anne.mimet@tum.de

2.2.1 Achievements of the first year

The work of the ECOLOPES project in the first year is described in this report and in the following deliverables

- D2.1 First report on dissemination and communication activities
- D2.2 First dissemination and exploitation plan
- D3.1 Prototype technical requirements report
- D4.1 Preliminary EIM Ontology
- D5.1 Development process for ECOLOPES algorithmic tools

Please also note the deliverables D1.1 Data Management Plan (submitted Month M6), D1.2 Risk and Quality Management plan (Month M9), and D2.1 Website and project logo (M9) that are already submitted.

Here, we give an overview over major achievements of the first year and point to the sections and deliverables, respectively, where these are described in more detail:

- A **management structure** has been set up along with a communication strategy. This and the regular meetings of the consortium are described in section 3 of the report.
- The ECOLOPES project has set up a preliminary **dissemination and exploitation** plan and has started to communicate regularly not only within the project, but also to people outside of the project, using a number of platforms. This is described in the deliverables D2.3 First dissemination and exploitation plan and D2.2 First report on dissemination and communication activities.
- The **design workflow** of ECOLOPES has been developed. This workflow describes the steps in the design of an *ecolope* from the *user* perspective, e.g., a team of architects and ecologists. This workflow is described in section 2.3.1 and is taken up in all deliverables.
- The **computational workflow** of ECOLOPES that supports the design workflow has been elaborated. The computational workflow is described in section 2.3.2, and more extensively in deliverable D3.1 Prototype technical requirements report, which also specifies the technical requirements for the ECOLOPES platform, the system architecture and the 1st prototype of the platform that is implemented as “sandbox”.
- The general approach and important elements of the **ecological model** have been developed. The ecological model will assess the consequences of architectural design for the dynamics of soil, plants, animals, and microbiota. First versions of the plant model, of the animal model, and of the soil-microbiota model have been developed. To reduce the complexity of the task of modelling many species a framework for using functional groups has been developed. Modelling proceeds by coupling a local and

regional model. The modelling approach is described in D4.1 Preliminary EIM Ontology.

- The conceptual approach for the **EIM Ontology** has been detailed. This is also described D4.1 Preliminary EIM Ontology.
- The principal approach to the **algorithmic design process** has been outlined, including the identification of an adequate conceptual approach and related types of data sets, as well as approaches to the generative algorithmic design process. This is described in D5.1 Development process for ECOLOPES algorithmic tools
- To investigate general relationships between architectural parameters and the ecological community that can live on an *ecolope*, a Mini-Model experiment (**MiMo experiment**) has been set up that connects architectural shapes to environmental models, e.g., a solar radiation model, that in turn will connect to the ecological model. The relationships found with this experiment can feed the EIM Ontology and the computational workflow.
- A first conceptual and initial technical understanding of the **multi-criteria decision-making (MCDM) strategies** to integrate the multi-disciplinary information of ECOLOPES was developed. This is described in section 8 of this report.

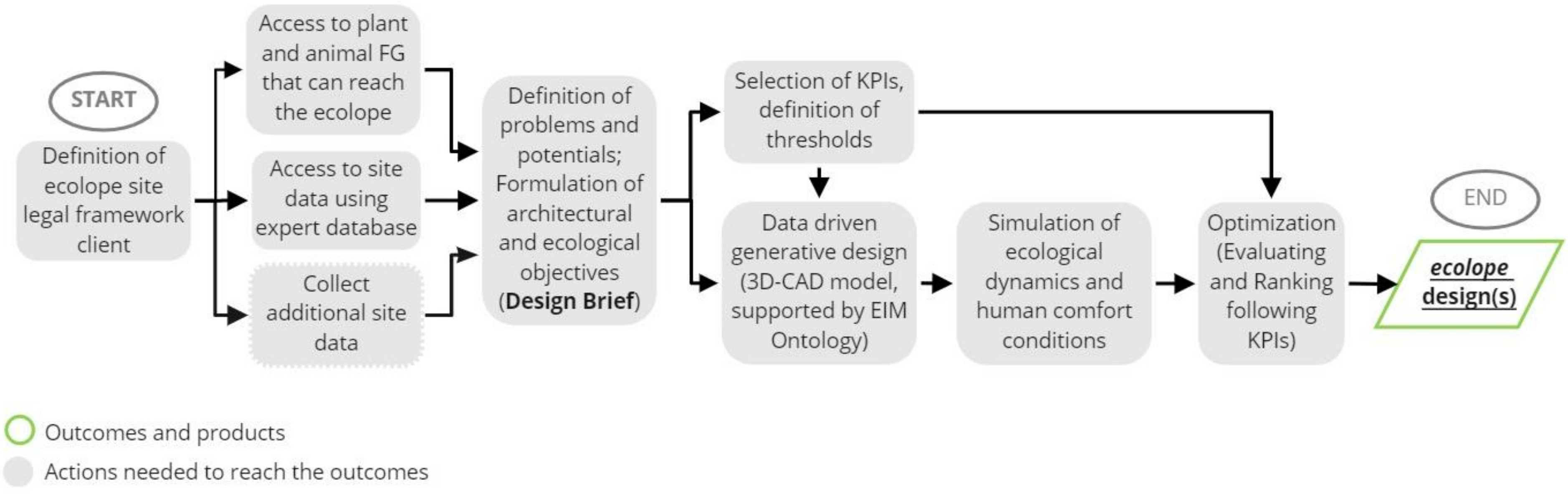


Figure 2.3.1. ECOLOPES design workflow

2.2.2 ECOLOPES design workflow and design brief

The design workflow (Fig. 2.3.1) has been drafted in order to describe the ECOLOPES approach to design from the user perspective. This user will be an interdisciplinary design team, consisting of e.g., 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 client 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 thus important to consider that the framework conditions for an *ecolope* are not just defined by objective factors, such as the local climatic conditions or the urban structure, but by normative settings (Box 2.3.1). Here, a distinction can be made between external and internal normative constraints. The external constraints are set by government rules (laws and regulations), 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 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 the second step, the environmental conditions of site will be analysed. These site data include data on the 3D-geometry of the site, urban form, climate, topography, 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 (Fig. 2.5). For the user, the raw data will already be processed to e.g., reduce the list of species to those that can reach the building site. Wherever necessary, additional data will be collected. In a later state of the ECOLOPES project, an initial analysis (zero variant) would be to analyse the ecological potential of the site based on available data to help the user defining reasonable ecological objectives, before the design process starts.

The third step of 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, 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 (*ecolopes* design space). Thus, it is the human user 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. One of the approaches used to generate architectural forms are geomorphons (see Deliverable 5.1). 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 the ontology, that encapsulates relationships between architectural form and function and draws on the knowledge base where these relationships are stored (see computational workflow, Deliverable 3.1). 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 report of the performance of the variants for the different criteria, and ranking of the design solutions.

In a final step, the user will assess the results of this computational evaluation process, i.e., 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 optimisation outcomes is repeated several times.

Importantly, 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 aim of 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, explore simple building shapes based on the concept of geomorphons (cf. D5.1 Development process for the ECOLOPES algorithms) and providing sufficient soil for the growth of plants.

BOX 2.5. Normative considerations in *ecolope* design

Here we provide a non-exhaustive list of the normative considerations that underlie the design of a building with an *ecolope*. While most of these normative considerations also apply to conventional architectural design, the design of an *ecolope* makes it necessary to explicitly specify them, as the design for organisms other than humans will be strongly influenced by target-setting for the other stakeholders plants, animals and microbiota. In contrast to standard approaches where plants and animals are regulated by e.g. nature conservation requirements whereas microbiota are regulated by hygienic requirements, these organisms are true stakeholders in the design of the *ecolope*. The key performance indicators (KPIs) related to them will therefore reflect the normative decisions of the design team and are subject to discussions. Making all normative considerations explicit in the design process is important helpful in formulating both the design brief, but also the development of KPIs.

<u>External normative constraints</u>

These are the normative constraints set by building laws and nature conservation laws, i.e. outside the project.

Building law framework conditions are specified in spatial planning laws, urban development plans, land use plans, building regulations, development plans, design statutes, or urban development contracts. These define, among other things:

- whether and what may be built on a certain area
- the type of land and building use
- building density, height, percentage of buildable area, building lines, distance zones
- legal rainwater runoff, proportion of on-site rainwater infiltration
- regulations for roof and building greening
- designation of green spaces with specific characteristics; specifications for vegetation, e.g. type and number of tree plantings
- specifications for bird-friendly glass and light use, building-related nesting aids

Nature conservation laws primarily concern the animals, plants and other environmental goods present in an area and the ecological functions of the area, e.g.

- presence and status of protected areas (e.g. protected habitat types)
- protection for particular species (e.g. according to EU Habitat directive, e.g. prohibition of killing, prohibition of destruction of habitats, etc.)
- Environmental impact assessment regulations
- Nature conservation and green space planning objectives at different planning levels (biodiversity strategies, landscape framework programmes, landscape plans, green space plans)
- municipal tree and urban forest protection regulations

<u>Internal normative constraints and design objectives</u>

These are developed in consultation between the client and the interdisciplinary design team. In addition to the architectural goals regarding the use, aesthetic quality and costs of the ecolope, these also include the ecological functions that an *ecolope* should fulfil, beyond the legal and administrative requirements. The internal normative conditions and design goals are project-specific and derived from the respective design task and the values and goals of the clients and the interdisciplinary design team. The set of KPIs, which is one of the ECOLOPES design components, provides a basic structure for setting quantifiable environmental design objectives.

2.2.3 ECOLOPES computational workflow

The computational workflow (see chapter 3 in D3.1 Prototype technical requirements report) was developed in WP3 to define the technical requirements, and to better understand the core processes that need to be supported in the ECOLOPES computational platform (SO1). The computational workflow identifies and defines the data connections and data exchange mechanisms (inputs and outputs) required for the integration of computational components developed in the other WPs. This concerns data such as raster data, tabular data, dynamic data, static/referential data, voxel models, and 3D CAD models. Finally, the computational workflow provides a roadmap for the integration of the computational framework and for the deployment of the computational components developed in WP3, WP4, WP5, and WP6.

Here we briefly introduce the five major modules of the computational workflow, each responding to specific data and functional requirements. The modules are: The open and expert databases, the ecological model, the knowledge base, the ontology, and the design generation and optimization environment (Figure 2.3.2).

Open and expert databases (white): The open databases are publicly available data sources on species, soil, abiotic concerns, built environment, available local 3D assets, and other concerns, which are pertinent to the composition of the expert databases and occasionally to the execution of the ecological models. In contrast, the expert database contains datasets that have been compiled from open sources and expert models to capture computationally-relevant concerns (e.g., species pools, KPIs, etc.), or to describe ECOLOPES-related concerns, such as human-nature interactions. The expert database is regularly queried by the ecological model.

The ecological model (green): The Ecological model is a composite spatially-explicit model that models the interdependent spatial and temporal dynamics of the soil, microbiota, plants, and animals, in response to the regional species pool, the geometry of the building, the local abiotic conditions, the substrate used to design the *ecolope*, and the management. It integrates all elemental models developed to address concerns related to ecology and their interfaces have been standardised by definition, so that they support the same data model in terms of input and output. The ecological model interfaces with other components of the ECOLOPES platform through secure HTTP requests. The ecological model, as well as the environmental models that describe e.g., radiation or soil erosion, are described in detail in deliverables D3.1 Prototype technical requirements report and D4.1 Preliminary EIM Ontology.

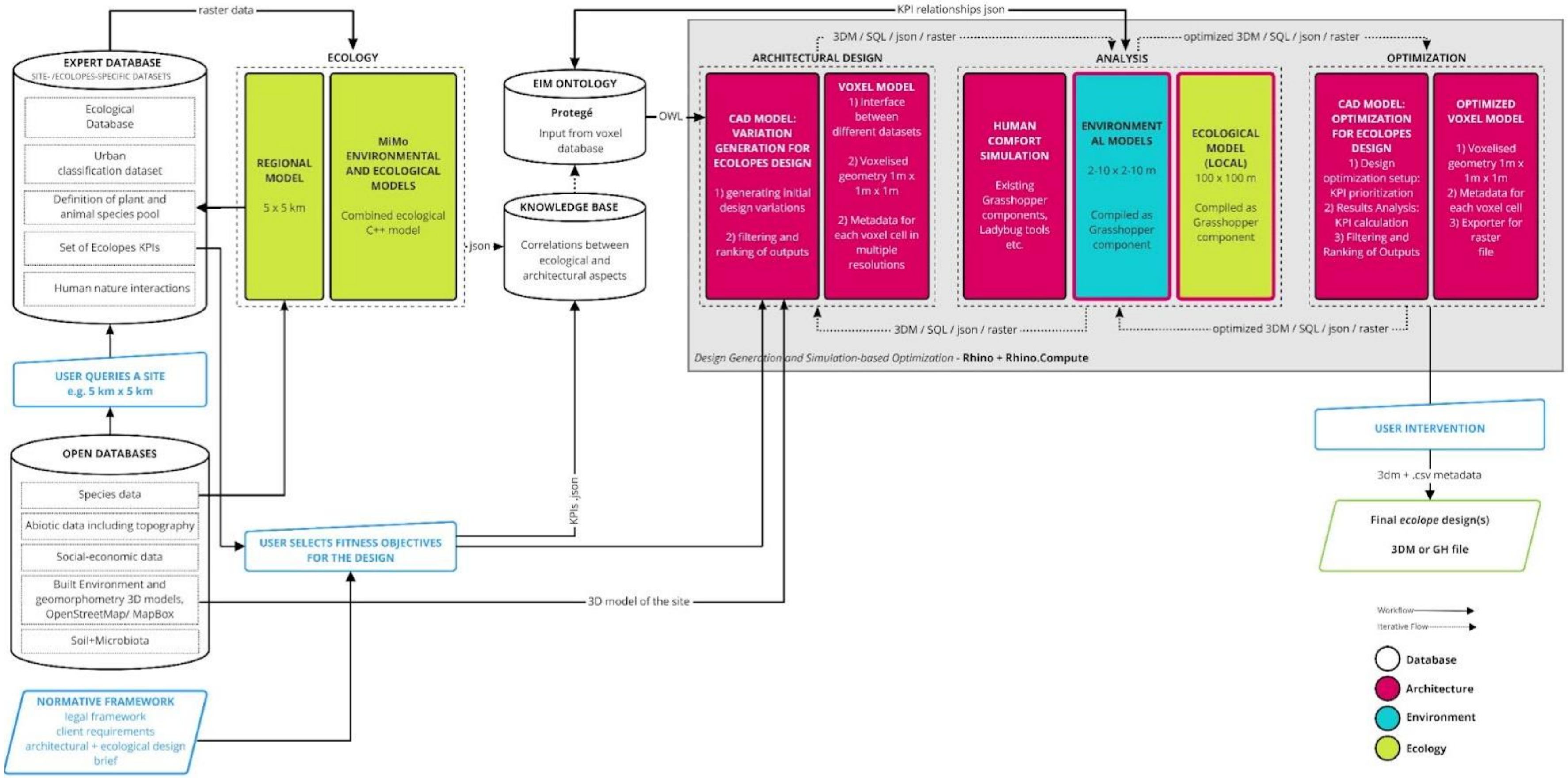


Figure 2.3.2: The computational workflow for the development of the ECOLOPES platform.

The Knowledge Base (KB) (white): The KB is a data storage system used to store structured and unstructured data resulting from the execution of the ecological model and the selected KPIs. It is designed to support the discovery and valuation of correlations between different data variables, namely between architecture-related variables and ecologically-related variables. Its role is to cumulate and statistically analyse the output of the ecological model at each execution, including the resulting environmental and ecological characteristics of the modelled *ecolope* modelled by the environmental models (e.g., radiation input, soil depth, water retention, composition and location of different plants and animal functional groups, etc.). The knowledge base can be queried to provide statistical correlations on-the-fly that befit particular criteria (e.g., location, design parameters, climate parameters, ecological conditions, etc.).

The EIM ontology (white): The EIM ontology is the reasoning framework for the ECOLOPES platform. It will leverage information from the KB and will capture existing patterns that have been proposed to define an annotation model that can be queried by other components of the computational framework. The design principles of the EIM ontology are described in the Deliverable D4.1 Preliminary EIM Ontology. The EIM Ontology will interface with expert data and the design generation and optimisation environment through an SQL database.

The design generation and optimisation environment (grey): The design generation and optimisation environment is a 3D CAD modelling environment (built on top of Rhino and Rhino.Compute, D3.1 Prototype technical requirements report). New algorithms for generative design and optimisation processes are informed by the output of the EIM ontology through a data voxel model (SQL database), the selected KPIs (user), the requirements from the legal framework, and by 'learning' through feedback. There are algorithms for the generation of initial design variations and algorithms for filtering and ranking the design outputs, as well as for environmental analysis, ecological analysis (Environmental and ecological models are compiled as analysis algorithm in CAD), and for optimization. The data conversion from CAD to raster data and vice versa is conducted through a voxel model that divides the 3D geometry into voxel cells that can then be converted into raster data (D3.1 Prototype technical requirements report). Each voxel cell contains the corresponding metadata from environmental (soil depth, solar radiation, water retention, connectivity) and ecological (location and information of FG) analysis. However, the optimization process includes not only the optimization of the envelop design but also the voxel model and the KPIs for each iteration. The optimised values (data and KPIs) will be encoded into the respective voxel cells through the same algorithms employed in the architectural design phase which will then be exported as raster information, if running through an iterative loop, or .csv in the case of a final design selection. They will also be sent to the EIM ontology. Thus, the final outcome of the computational workflow is a final selection of envelope design with the corresponding metadata stored in a voxel model.

3 WORK PACKAGE 1

3.1 Work package description, tasks and deliverables

WP no.	1	**WP title**	**Project management and coordination**			
Lead partner	TUM	**Start month**	1	**End month**	48	
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
PMs/partner	22	8	8	8	4	10

Objectives: WP1 deals with all coordination and management aspects of the project including project coordination, communication with EC and reporting, risk management and ICT management, and the elaboration and maintenance of the DMP and DEP. The Coordinator (CO), Wolfgang Weisser (TUM), will have overall responsibility for WP1, assisted by all other partners including technical management (McNeel).

Task 1.1: Overall project and financial management (M1-48, 33PMs) Lead: TUM. Participants: All. The CO will organise and control the activities of the consortium and ensure attainment of goals and delivery of project deliverables and milestones. Duties include monitoring of compliance by participants with their obligations, responsibility for timely and accurate submission of all reports, financial claims, costs statements. On completion of the project, a final report to the EC will be prepared. Task will also oversee other activities such as management of gender aspects and ethical issues arising from implementation. **Tangible outcome:** Interim and final reports (D1.3).

Task 1.2: Data Management and ethical framework (M1-48, 11PMs), Lead: TUM. Participants: All. Ensure legal and ethical standards for data handling throughout the whole project, including determining data to be shared in the open data initiative. A formal Data Management Plan (DMP) will be produced covering procedures for identification, collection, indexing, access, maintenance, transfer and potential public archiving of all data, including metadata. **Tangible outcome:** Data Management Plan and Ethical Framework (D1.1).

Task 1.3: Risk management & quality assurance (M1-48, 16 PMs) Lead: McNeel. Participants: All. Our quality assurance plan will guide and monitor scientific and technical outputs, detect risks and take corrective measures as necessary with the help of a Quality and Risk Manager (QRM). QRM will establish a platform to support knowledge sharing, transfer and storage of key documents, document lifecycle management and internal communication between consortium partners. After each major stage of the project, the QRM will conduct a risk assessment. **Tangible outcome:** Risk log and quality assurance plan (D1.2).

No.	**Description**	**Month(s)**
D1.1	Data management plan	6
D1.2	Preliminary risk and quality assurance plan	9
D1.3	Report of year 1	12
D1.4	Technical/scientific review meeting documents 1st meeting	13
D1.5	Report after 2nd year	24
D1.6	Technical/scientific review meeting documents 2nd meeting	31
D1.7	Risk and quality assurance plan	36
D1.8	Report after 3rd year	36
D1.9	Technical/scientific review meeting documents 3rd meeting	48
D1.10	Final reports	48

3.2 Work in the first year

3.2.1 General overview

Deliverables D1.1 and D1.2 have been submitted in time. D1.3 is this document and D1.4 will be submitted one month after D1.3.

3.2.2 Project organisation

The organisational structure in ECOLOPES is described in some detail in deliverable D1.2. Basically, the structure has been designed in such a way that it:

(i) provides an efficient decision-making structure;
(ii) ensures the involvement of all partners in the decision-making processes;
(iii) provides efficient management procedures that will keep the project performing on time, with high quality of results and within the budget;
(iv) ensures smooth communication with the European Commission;
(v) involves key experts from outside into the project steering procedure; and
(vi) provides a mechanism for the prevention and resolution of disputes.

Figure 3.2.2 describes the project management structure. All responsibilities and competencies are divided among: The Coordinator (CO), the Exploitation and Dissemination Manager (EDM), the Quality and Risk Manager (QRM), and the Work Package Leaders (WP Leaders). Furthermore, three groups are formed that include members of the Consortium or external partners that have specific responsibilities: The General Assembly (GA), the ECOLOPES Project Management Board (PMB), and the End User Advisory Board (EUAB). A more detailed description of the role of each of the groups, and the names of the people leading the WPs is given in deliverable D1.2.

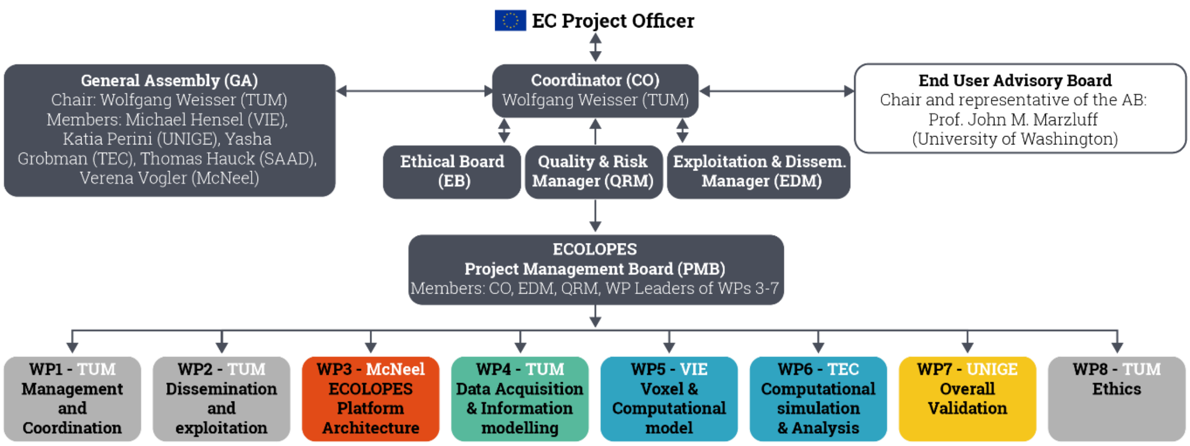


Figure 3.2.2: The project management structure of ECOLOPES.

3.2.3 Advisory board

ECOLOPES recruited a number of external experts to obtain regular feedback on the work (Table 3.2.3). Prof. J. M. Marzluff currently acts as head of the advisory board (AB). There are some changes in AB membership compared to the proposal. Prof. Erika von Mutius had to decline becoming a member because of additional workload in the home institution. She was replaced by Dr. Marie Standl who is an epidemiologist/statistical modeller of health effects. Mr Corrado Ragucci also had to decline membership due to early retirement. He was replaced by Ms. Chiara Wolter who represents practical expertise in efficient energy design as well as local government strategies for sustainable buildings. Additionally, we asked Dr. Isabelle Boulangeat to join the AB due to her expertise in plant functional group modelling, to support the development of the ecological model. We also asked Dr. Cédric Pruski to join, with his expertise in ontology development. The members of the AB thus have complementary expertise in both theoretical and practical aspects of sustainable design related to human-nature interactions.

The AB members took part in the online Kick-Off-meeting and in the first General Assembly Hybrid Meeting in Barcelona in December 2021 (see below).

Table 3.2.3: Advisory Board members.

Member	Company/ University	Field of Expertise	Short description
Prof. John M. Marzluff	School of Environmental and Forest Sciences University of Washington Seattle	James W. Ridgeway Professor of Wildlife Science, Ecology, human ecology	Prof. Marzluff studies the relationship between humans and birds to discover how best to conserve wildlife in our modern, human dominated world. Partnering with colleagues in urban planning, medicine, and natural resource agencies he strives to make our research relevant to policy makers, managers, and citizens.
William Myers	Guest Curator: Science Gallery Rotterdam | MIT Museum	Architecture, Ecology, Dissemination, Biodesign	William Myers is a curator, author, and teacher based in Amsterdam. His book *Biodesign* (2018) identifies the emerging practice of integrating biological processes into design and architecture.
Stefania Manca	Municipality of Genoa; Urban Agenda & Green Transition Office	Urban planning, Smart cities	Stefania Manca is the Resilience Manager of the Municipality of Genoa and head of the Urban Agenda & Green Transition Office; Technical Coordinator Partnership on Adaptation to Climate Change; project leader of the Action Plan of Genoa considering the current global changes. She currently works in the Innovation, Quality and Economic Development Department of Genoa Municipality.

Dr. Timothy Beatley	Department of Urban and Environmental Planning School of Architecture University of Virginia	Urban planning	Timothy Beatley's work focuses on the subject of sustainable communities, and creative strategies by which cities and towns can fundamentally reduce their ecological footprints, while at the same time becoming more livable and equitable places.
Sophie Deramond, Angela Lee	Cartier Dalix	Architecture	The famous French practice ChartierDalix architecture is well-known for extensive greening of their buildings and for integrating biodiversity into their design.
Chiara Wolter	Project Manager - Energy and Renewables, Architect Ambiente Italia Srl Energy Department	Energy, Architecture	Architect, with main experience in energy saving in residential buildings as well as in commercial and industrial plants, set-up of development scenarios for the impact of energy efficiency measures at urban and territorial level, as well as monitoring systems.
Dr. Marie Standl	Head of Research Group 'Allergic Disease Epidemiology', Helmholtz Centre Munich	Epidemiology	Dr. Marie Standl background is in statistics with focus on statistical modelling of high dimensional data. The current research focus includes the potential role played by gene-diet interactions and health, primarily chronic diseases during childhood, and the interplay of lifestyle, environment (e.g., greenspace and air pollution), genetic and metabolic factors.
Dr. Isabelle Boulangeat	PhD, Chargée de recherches LESSEM (Laboratoire Ecosystèmes et Sociétés en Montagne) INRAE LyonGrenoble	Ecology, Plant modelling	Her research aims to understand the dynamics of socio-ecosystems, from a theoretical viewpoint to conservation issues in alpine ecosystems. She seaks to improve biodiversity models of species distributions and community dynamics in mountain ecosystems, without neglecting the interactions with the society. She is the creator of the FateHD model, used for modelling plant dynamics in this project.
Dr. Cédric Pruski	Senior Researcher ITIS Department Luxembourg Institute of Science and Technology (LIST)	Ontologies	Cédric Pruski's research interests are Artificial Intelligence and knowledge representation and reasoning. He successfully coordinated national and international research projects that have generated many publications in major conferences and peer-reviewed journals of the field Artificial Intelligence and knowledge representation.

3.2.4 Microsoft Teams platform

Internal communication and document sharing is carried out using the platform Microsoft Teams (Fig. 3.2.4). The consortium uses Teams for calls, chats, and scheduling meetings (calendar function). Meeting protocols, notes and internal progress reports are also shared through Teams. The platform links to MIRO boards that are used to develop workflows.

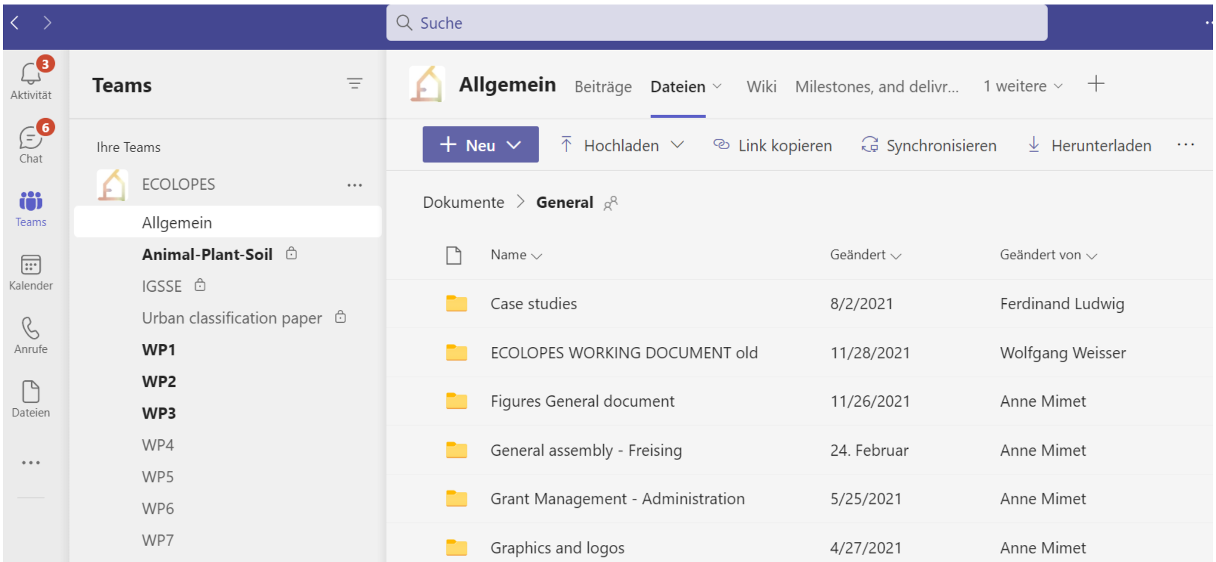


Figure 3.2.4: Screenshot of the TEAMS management platform

3.2.5 Meeting structure

In addition to the Project Management Board meetings (every three months, see Deliverable D1.2) and the annual General Meeting (see below), the consortium has established a number of other regular meetings. These include a monthly meeting for all members of the consortium, as well as topical meetings, either WP-related or on cross-cutting issues.

3.2.6 Monthly consortium meetings

The consortium meets every month, on the first Tuesday of the months from 15.00-18.00, via Teams, to report on the progress done within each WP in the past month and to bring forward and discuss important questions for the consortium. These meetings are important for overall communication, exchange of ideas and for making progress in topics of general relevance. For example, the user workflow was discussed in several monthly consortium meetings while being prepared in individual meetings of a subset of people.

3.2.7 Regular topical meetings

In order to facilitate communication within Work packages and with respect to cross-cutting topics, one fixed time-slots per week has been reserved on Mondays 9-11. These time-slots are used for regular meetings of the work packages, and they can also be booked for cross-cutting topics, such as the User Workflow development.

Individual WP meetings occur at the frequency fixed by each WP leader according to the WP needs. WP1 (Project management and coordination) meets monthly. WP2 (Dissemination and exploitation) meets weekly. WP3 (Platform Architecture) meets every two weeks and requires the participation of WP4, WP5, WP6, and WP7. WP4 (Data acquisition and information modelling) meets as a large group every month. The modelling team of WP4 meets every two weeks. WP5 (ECOLOPES Voxel Model & Computational model) and WP6 (Computational Simulation and Analysis) meet weekly. WPs meetings are open to all members of the consortium, but certain WPs/members can be more specifically asked to join to contribute on given topics.

3.2.8 General Assembly

The General Assembly takes place once every year. It aims to present the current state of the project, identify emergent problematics and solutions, and get feedbacks and recommendations from the advisory board. So far, two general assemblies have been held, one online (Kickoff meeting) and one in hybrid format.

The last General assembly took place between the 30th of November and the 1st of December 2021 in Barcelona and was organized by the McNeel team. It took place as a mixed in presence and online meeting, with 19 persons attending in presence (17 ECOLOPES members, 2 members of the advisory board) and 16 persons attending online (8 ECOLOPES members, 8 members of the advisory board) (Figure 3.2.8). The Barcelona General Assembly focused on streamlining the design and computational workflows, and aimed to strengthen the communication between architects and ecologists, to better understand the challenges raised by the ECOLOPES approach in both disciplines. This aim was addressed by playing a “design game” during which teams composed on architects and ecologists were asked to create the design brief of an *ecolope* and come to design solutions (see description in D2.2 First Report on Dissemination and Communication Activities).

Among other aspects, the advisory board gave very valuable feedback on the challenges of the project that will need to be overcome. These aspects mainly regard the development of the computational workflow. Here, the multidisciplinary aspect of the project is a strength and a weakness, as it requires extensive communication effort to understand each other. The overall platform will be complex, and the time needed for its development should not be underestimated. Finally, the development of the ECOLOPES computational workflow should both rely on data that can be trusted, but also on the ECOLOPES members and user expertise.

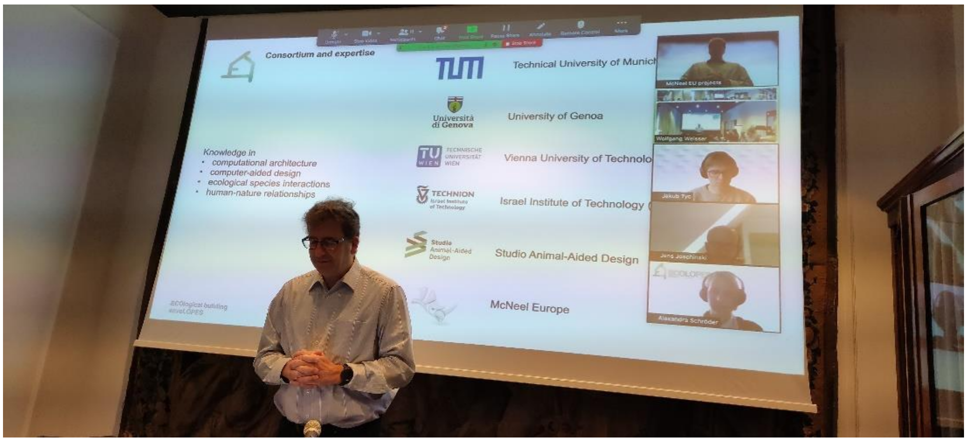


Figure 3.2.8: Photo of Prof. Dr. Wolfgang Weisser during the introductive presentation of the ECOLOPES project in the General Assembly in Barcelona. Some of the ECOLOPES and advisory board members joining online are visible on the screen.

The next General Assembly will take place from 9.-11.5.2022 in Munich, Germany (Table 3.2.8). This meeting will be in presence, but remote participation will also be possible.

Table 3.2.8: General information about the ECOLOPES meetings that took place during the first year of the project.

Meeting	Participants	Host	Venue	Date	Project Month
Kick-off meeting	Consortium and Advisory Board members	TUM	Online meeting hosted on the Zoom platform.	12.– 13.04.2021	M1
General Assembly 2021	Consortium and Advisory Board members	MCNEEL	Hybrid meeting held in Barcelona.	30.11.– 02.12.2021	M8/ M9
General Assembly 2022	Consortium	TUM	Hybrid meeting held in Munich	9.5. – 11.5.2022	M14

4 WORK PACKAGE 2

4.1 Work package description, tasks and deliverables

WP no.	2	**WP title**	**Dissemination and exploitation**			
Lead partner	TUM	**Start month**	1	**End month**	48	
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
PMs/partner	12	10	10	10	6	3

Objectives: WP2 addresses the engagement activities towards our Stakeholder Networks (SNs), incl. actors in the AEC sector and the policy/regulatory framework. It includes disseminating and communicating the project results - especially the EIM Ontology and simulation platform, and outcomes of the validation activities - through different communication channels incl. peer-reviewed publications, articles in technical journals, conference presentations, social media post success stories, organization of workshops and seminars, content production downloadable from our project website, as described in our preliminary DEP.

Task 2.1: Establishment and dialogue with Stakeholders (M1-48, 13PM) Lead: TUM, Participants: All
Identify and engage the relevant stakeholders for the AEC sector (e.g. professional organisations) and key supporting actors (e.g. local administrations and environmental bodies), as per our preliminary DEP. Define a strategy for identifying and engaging each stakeholder type, including the most adequate dissemination channels and key messages to reach them. **Tangible outcome:** Key stakeholder Network directory and engagement strategy.

Task 2.2: Dissemination implementation and evaluation (M1-48, 18PMs), Lead: TUM, Participants: All
This task will implement, regularly monitor and evaluate the impact of dissemination activities (Tables 1,2). Dissemination efforts will be adjusted where needed. The **written** (e.g. media partners, newsletters, academic and technical journals), **online** (social media, e-news and project website) **onsite** (e.g. conferences and workshops) dissemination channels will be mapped, to define their best use within ECOLOPES project. Contents and outputs of WPs 3-7 will be disseminated using relevant formats. **Tangible outcome:** DEP and Report on dissemination and communication activities

Task 2.3: Exploitation plan (M1-48, 20PM), Lead: TUM, Participants: All
Ensure full exploitation of the project results from both the economic and scientific perspective, with special reference to ECOLOPES' key outputs, i.e. EIM Ontology and simulation environment. All potential exploitable assets and IP arising from the project will be identified and categorized according to their potential impact at commercial/academic research levels, including a detailed roadmap for addressing potential IP issues (e.g. property and IPR distribution among partners). **Tangible outcome:** Dissemination and Exploitation Plan (feeds into D2.1).

No.	**Description**	**Month(s)**
D2.1	Website and project logo	2
D2.2	First report on dissemination and communication activities	12
D2.3	First dissemination and exploitation plan (DEP)	12
D2.4	Second dissemination and exploitation plan (DEP)	30
D2.5	Second report on dissemination and communication activities	30
D2.6	Final Dissemination/ exploitation plan (DEP)	48
D2.7	Final report on dissemination and communication activities	48

4.2 Work in the first year

Deliverable D2.3 First dissemination and exploitation plan describes the dissemination and exploitation strategy of the consortium. All activities of WP2 in year 1 are described in deliverable D2.2 First report on dissemination and communication activities which is submitted along with this document.

5 Work Package 3

5.1 Work package description, tasks and deliverables

<table>
<tr><td>WP no.</td><td colspan="2">3</td><td colspan="2">WP title</td><td colspan="4">ECOLOPES Platform Architecture</td></tr>
<tr><td>Lead partner</td><td colspan="4">McNeel</td><td>Start month</td><td>1</td><td>End month</td><td>38</td></tr>
<tr><td>Partner no.</td><td>1</td><td>2</td><td>3</td><td>4</td><td colspan="2">5</td><td colspan="2">6</td></tr>
<tr><td>Short name</td><td>TUM</td><td>UNIGE</td><td>VIE</td><td>TEC</td><td colspan="2">SAAD</td><td colspan="2">McNeel</td></tr>
<tr><td>PMs/partner</td><td>1</td><td>2</td><td>3</td><td>3</td><td colspan="2">0</td><td colspan="2">27</td></tr>
</table>

Objectives: WP3 creates the ECOLOPES computational platform including data warehousing capabilities, as a basis for integrating the components from WP4-5, thus enabling modelling in WP6-7. WP3 develops and connects two front-end tools to a) visualize simulated output of the ontology, b) apply it to a building.

Task 3.1: ECOLOPES system architecture (M1-12, 7 PMs) Lead: McNeel. Participants: TUM
Definition of technical requirements of the ECOLOPES platform. Design of a detailed system architecture for integrating backend services (data stream analytics, semantic integration, AI and reasoning, etc.) and frontend tools with standard open interfaces. The architecture design will outline the security framework to be implemented in T3.2. **Tangible outcome:** ECOLOPES system architecture.
Task 3.2: ECOLOPES data warehousing (M5-29, 5 PMs), Lead: McNeel. Participants: TUM, TEC
Development of the cloud infrastructure for storing information, especially in relation to WP4, including the ECOLOPES database that includes all data, including spatio-temporal, voxel and 3D models.
Tangible outcome: ECOLOPES data warehousing infrastructure.
Task 3.3: Backend development and integration (M5 -38, 5 PMs), Lead: McNeel, Part.: TUM, VIE, TEC
Development of backend services for data management, processing, analytics and visualisation. Definition of communication protocols based on identified and documented endpoints amongst modules, components, backend services of the platform. Continuous integration and improvement of the platform according to T3.1.
Tangible outcome: ECOLOPES backend services and integrated platform.
Task 3.4: Frontend development (M9-38, 10 PMs) Lead: McNeel. Part.: SAAD, UNIGE, VIE, TEC
Development of two frontend tools based on the Rhino3D platform to visualize the simulated output of the ontology, and to apply it to a building, through 3D modelling and VR.
Tangible outcome: ECOLOPES frontend tools.

No.	Description	Month(s)
D3.1	Prototype technical requirements report	12
D3.2	Draft ECOLOPES platform architecture	19
D3.3	Interim ECOLOPES platform architecture	29
D3.4	Prototypes and applications, frontend tools	38

5.2 Work in the first year

The achievements of WP3 in year 1 are described in deliverable D3.1 Prototype technical requirements report that is submitted along with this document. The report includes the definition of the technical requirements for the ECOLOPES design platform, the preliminary computational framework for the development of the ECOLOPES platform (computational workflow),the MiMo experiment, the system architecture of the ECOLOPES platform, as well as the implementation of the designed architecture as a fully operating cloud-based digital infrastructure (ECOLOPES sandbox).

6 WORK PACKAGE 4

6.1 Work package description, tasks and deliverables

WP no.	4	**WP title**	**Data acquisition and information modelling**			
Lead partner	TUM		**Start month**	1	**End month**	36
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
PMs/partner	53	25	3	30	14	3

Objectives: WP4 will develop the EIM Ontology (D4.1) that integrates architecture with abiotic environment, soil/substrate, and requirements, impacts and dynamics of humans, plants, animals and microbiota. Tasks 4.1 to 4.6 will model relationships of each component of the *ecolope* ecosystem with the other components, building on existing data bases and experiments to feed the ECOLOPES database.

Task 4.1: Abiotic environment and architecture (M1-15, 14 PMs), Lead: TECH. Participants: UNIGE
International and national georeferenced datasets (climatic conditions, urban form, etc.), local building features, normative constraints and design aims and uses (e.g., residential) will be created to support the baseline site and environmental conditions, 3D building geometry and envelope design boundary limits. Data on abiotic conditions will be included, that represent cross cutting boundary conditions for all inhabitants (T4.3 to T. 4.6).
Tangible outcome: Dataset for database, role of abiotic parameters and architecture for D4.1.

Task 4.2: Soil (1-22, 14 PMs), Lead: SAAD. Participants: TUM.
Substrate solutions for ECOLOPES from soils in the areas of the design cases as well as artificial substrates will be obtained from databases, expert knowledge and local sampling, and evaluated. Variables important for plant growth, carbon sequestration and filtering of pollutants will be collected including abiotic measures like texture, pH, volume, water storage capacity, organic carbon and nutrient content, pollution levels (mainly heavy metals). Positive feedback loops for the development of niches for biota living in soil will be evaluated.
Tangible outcome: Dataset for substrate/soil and its role in D4.1.

Task 4.3: Plant and Vegetation (M1-33, 20 PMs), Lead: UNIGE. Participants: SAAD, TUM.
Georeferenced datasets and artificial plant combinations from the building industry and horticultural practice will be used to obtain data on plant occurrences for design cases. Plant traits, related to resource and abiotic requirements (e.g., N-fixation), life-cycle strategies, and human acceptance (e.g., appearance) will be integrated at the plant functional group (PFG) level. PFG dynamics will be spatially and temporally modelled as a function of soil, architecture, abiotic conditions, animals, and human management (e.g., mowing, weeding) using an adapted version of the FATE-HD model.
Tangible outcome: Dataset for plants and their role in D4.1.

Task 4.4: Animals (M1-33, 20 PMs), Lead: TUM. Participants: SAAD
Data on animal presence in and around design cases will be collected from databases (eBird, Ornitho, GBIF, governmental). We focus on birds, mammals, reptiles, amphibian and insects. Lifecycle traits related to habitat, food preferences, and life-history strategies (e.g., dispersal, fecundity, survival probability) will be collected and integrated at the functional group level. RangeShifter model will be used to model the probability of occupancy of the *ecolope* for each functional group based on local soil, plant and architectural variables and regional conditions.
Tangible outcome: Dataset for animals and their role in D4.1.

Task 4.5: Microbiota (M1-33, 20 PMs), Lead: TUM. Participants: SAAD
Data on microbiota composition in soil, plants and animals will be acquired from molecular databases like EMBL or NCBI and own assessments at the design cases using high throughput molecular methods. Functional microbial groups will be described including catalysts for nutrient/carbon cycling and plant growth promotion to establish the relationships with soil, plants and animals. Feedback loops at the soil-

root and leaf-air interface (rhizo-/phytobiomes) will be considered. We will focus on the role of soil, plants and animals as vectors for human microbiota and health status. Relationships will be analyzed using generalized linear regression models.
Tangible outcome: Dataset for microbiota and their role in D4.1.
Task 4.6: Humans (M1-33, 20 PMs), Lead: TECH. Participants: UNIGE, SAAD, TUM.
Data on 1) human comfort conditions, 2) physiological, psychological and social benefits of nature to humans and 3) management and anthropogenic use of the *ecolope* will be compiled from the literature and from experimental work on human responses to vegetation and animals in a virtual environment. Data will be used to quantitatively identify the different forms of functional relationships (with a dose-response modelling approach) between various components of nature, and various health and well-being and comfort outcomes (including ecosystem services). **Tangible outcome:** Dataset for humans and their role in D4.1.
Task 4.7: ECOLOPES EIM Ontology (M1-36, 20 PMs), Lead: TUM. Participants: TEC, VIE, McNeel.
The EIM Ontology will be the key element of the data-driven recommendation system. It is tailored to configure the ECOLOPES Knowledge Base. Results of Tasks 4.1-4.6 will be integrated. The EIM Ontology will index and fuse data to form the basis of WP5-WP7, as it will be queried to retrieve data references for the composition of the voxel models. **Tangible outcome:** EIM Ontology to feed development of WP5-7 (D4.1).

No.	Description	Month
D4.1	Preliminary EIM Ontology	12
D4.2	Interim EIM Ontology	30
D4.3	Final EIM Ontology in Protégé	36

6.2 Work in the first year

WP4 develops the EIM Ontology that integrates architecture with abiotic environment, soil/substrate, and requirements, impacts and dynamics of humans, plants, animals and microbiota. Thus, WP4 is responsible for facilitating the relationship between architectural design and ecology, thereby providing different components to the design workflow. The results will be important for instructing the data driven design by the EIM ontology, and for simulating ecological dynamics during the design process. In addition, they will also play a vital role in earlier steps such as definition of problems and ecological potentials (design brief). In year 1, several approaches were used to achieve the integration between architectural design and ecology. WP4 thus paves the way for a successful implementation of the iterative design procedure based on the overall design workflow of ECOLOPES. In the first year, WP4 has surveyed and chosen data to be used for making environmental and architectural data available for the design process (task 4.1). The first year has also been used to conceptually develop and partly implement important parts of the ecological model. This model assesses the consequences of architectural design for the dynamics of plants and animals, as well as soil microbiota (through soil development) (tasks 4.2-4.5). In addition, the physiological, psychological and social benefits of nature to humans, i.e., human-nature interactions, as well as human comfort conditions (task 4.6), have been reviewed. Finally, WP4 has drafted the conceptual approach to design the EIM Ontology. This is detailed in Deliverable D4.1 Preliminary EIM Ontology that is submitted along with this document.

7 WORK PACKAGE 5

7.1 Work package description, tasks and deliverables

WP no.	5	**WP title**	**ECOLOPES Voxel Model & Computational model**			
Lead partner	VIE		**Start month**	3	**End month**	38
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
PMs/partner	2	9	39	5	2	2
Objectives: WP5 has three key objectives: 1) development of a Voxel model that integrates, spatializes and visualises ecological and architectural data, and links the EIM Ontology from WP4 with the computational model; 2.) development and integration of algorithmic processes and tools in Rhino3D and VR; 3) validation of algorithmic processes and tools that deliver the basis for the work in WP6 and WP7.						
Task 5.1: ECOLOPES Voxel Model (M3-30, 20 PMs), Lead: VIE. Participants: TUM, McNeel. Development of a voxel model as a link between EIM Ontology (WP4) and computational model. The voxel model will contain different types of data. The geometric data in the voxel model provides the link to the computational model in Rhino3D. **Tangible outcome:** ECOLOPES Voxel model (D5.1). **Task 5.2: ECOLOPES Computational Model (M3-36, 20 PMs**), Lead: VIE. Participants: McNeel. Development and integration of algorithmic processes and tools for the design of ECOLOPES in Rhino3D leading to the ECOLOPES Computational Model. This will be related to work on the design cases for Munich, Vienna, Genoa and Haifa. **Tangible outcome:** Algorithmic processes and tools. **Task 5.3: ECOLOPES Computational Model Validation (M13-38, 19 PMs**), Lead: VIE. Participants: All. Validation of algorithmic processes and tools in terms of the integrated ecological and architectural design output. **Tangible outcome:** Validated algorithmic toolset (feeds into D5.2).						

No.	**Description**	**Month(s)**
D5.1	Development process for Ecolopes algorithmic tools	12
D5.2	ECOLOPES Voxel Model	30
D5.3	ECOLOPES Voxel Model report	30
D5.4	Preliminary ECOLOPES computational model	30
D5.5	ECOLOPES Computational model in Rhino 3D	38

7.2 Work in the first year

The achievements of WP5 in year 1 with specific focus on the description of the algorithmic modelling approach are described in deliverable D5.1 Development process for the ECOLOPES algorithms that is submitted along with this document. This includes elaboration of the conceptual and methodological approach to the algorithmic design process up to the detailed design stage, which will constitute a subsequent extension of the algorithmic process. Furthermore, this includes detailed elaboration of the specific types of datasets (terrain, maps, networks, volumes) that form part of the algorithmic process, as well as aspects concerning the links of the algorithmic process to the voxel model and the EIM ontology.

8 WORK PACKAGE 6

8.1 Work package description, tasks and deliverables

WP no.	6	WP title	Computational Simulation and Analysis			
Lead partner	TEC	Start month	7	End month	42	
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
PMs/partner	2	4	3	42	2	2

Objectives: Development of the data-integrated computational model (WP5) into computational simulation environment by: 1) computational simulations, multi-criteria analysis and rating strategies that enable decision-making processes for the selection of ECOLOPE design cases; 2) validating the computational workflow to ensure integration and interoperability through design cases in preparation of design validation (WP7).

Task 6.1: Generating design iterations (M7-22, 15 PMs), Lead: TEC. Participants: McNeel, All.
Generating the design iterations of the building envelope based on the EIM recommendations. Tools developed in WP5 to generate design alternatives will be employed based on both trade-offs and synergies among the different inhabitants' perspectives and material organisation of the building envelope, suggested by the EIM recommendations. **Tangible outcome:** Design iterations (feed into D6.1).

Task 6.2: Developing multi-criteria evaluation (M7-42, 15 PMs), Lead: TEC. Participants: McNeel, All.
KPI's will be defined for inhabitant and architectural requirements, based on the recommendations of the EIM (WP4). The measuring and rating of envelope design cases will be developed by defining interrelationships and hierarchies between KPI's. Importance factor will be calculated and assigned to KPI's based on EIM recommendations. Selected cases per inhabitants (based on top scores) will be submitted for validation through expert knowledge. **Tangible outcome:** ECOLOPES KPI's list (D6.1).

Task 6.3: Multi-criteria simulation for validation (M20-42, 25 PMs), Lead: TEC. Part.: McNeel, All.
Iterative multi criteria simulation, results analysis and optimisation of design cases. Validation of the computational workflow through the generation of design cases on the scale of the envelope and the envelope building block. Tools will enable recursive modelling of dynamic inhabitant relations. Simulation and evaluation techniques will be based on interoperability with the EIM Ontology. For the prototype the objective is to design building blocks extracted from the design cases for validation (WP7).
Tangible outcome: ECOLOPES design cases per site of building blocks & envelopes (D6.2).

No.	Description	Month(s)
D6.1	Draft KPI descriptions	30
D6.2	KPI's report - performance results	42
D6.3	ECOLOPES design cases per site	42

8.2 Work in the first year

The primary focus of Work Package 6 (WP6) in the first year was to develop and establish a conceptual and initial technical understanding of multi-criteria decision-making (MCDM) strategies to integrate multi-disciplinary information that is both quantitative and qualitative. This was conducted through a systematic literature review in which potential strategies were extracted to develop a proposed workflow for WP6. A hybrid workshop was also conducted during the general meeting held in Barcelona to initiate an understanding of key performance indicators (KPIs). In addition, an architectural design studio was conducted with 3rd year students in the architecture programme to explore potential *ecolope* strategies for a residential building set in Tel Aviv. Finally, future developments in relation computational aspects of the optimization phase as well as KPI selection have been planned.

8.2.1 Multi-criteria Decision-Making Literature Review

A critical systematic literature review was conducted to understand applications of multi-criteria decision-making in building envelope design as well as ecological planning and design. This literature review provided the basis to structuring MCDM to develop a workflow within WP6.

Terminologies and definitions were extracted to present a common ground of understanding in the general field of MCDM (Hwang et al. 1979). They are as follows:

Alternatives: Options or solutions for MCDM problems

Attributes: Characteristics, qualities, or performance parameters of the alternatives

Objectives: Direction of the attributes to improve upon the MCDM problem (to minimize / to maximize)

Goals: Target level to achieve expressed in terms of a specific state in space and time

Criteria: Attributes and/or Objectives of a MCDM problem

MCDM can be categorized into two strategies which are determined based on the problem definition as well as the alternative (Penades-Pla et al. 2016; Chen & Hwang 1992). The first strategy is Multi-Attribute Decision-Making (MADM) which is an a priori process as the decision-maker intervenes in the initial stages of the strategy by assigning weights to the attributes of alternatives (Fig. 8.2.2a). These weights define the hierarchy of the attributes and influence the results of the strategy which generates a ranked list of alternatives.

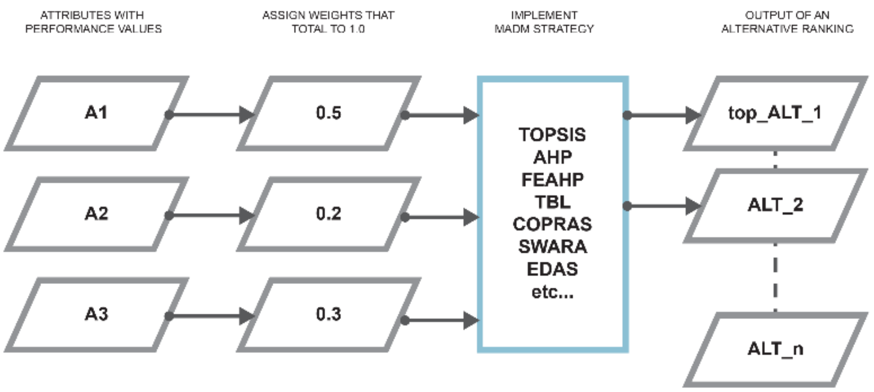


Figure 8.2.2a: Conceptual flowchart describing the process for MADM strategy

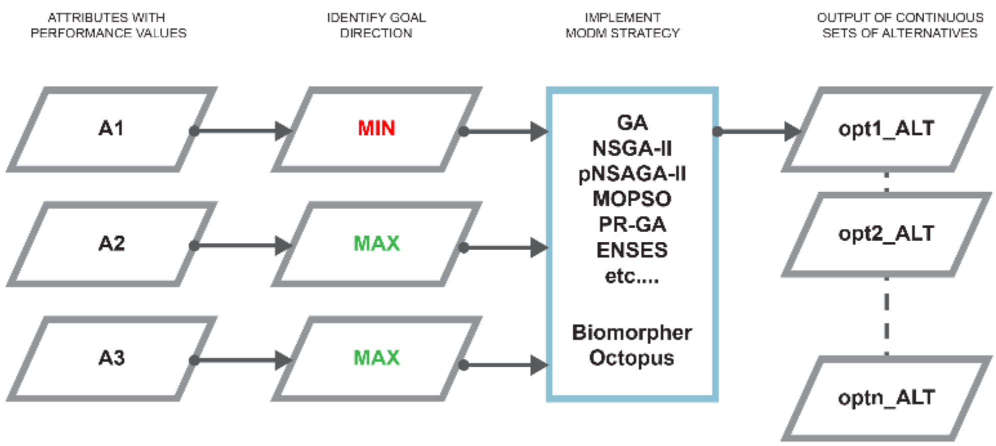


Figure 8.2.2b: Conceptual flowchart describing the process for MODM strategy

The second strategy is Multi-Objective Decision-Making (MODM) which is an a posteriori process as the decision maker engages at the end of the strategy by selecting an alternative to move forward with from a list of equally good alternatives (refer to Fig 8.2.2b). These objectives are usually conflicting in nature and are determined by cost/benefit or minimizing/maximizing to generate these range of solutions which is also known as the Pareto front.

Under the umbrella of MODM there are Multi-Objective Evolutionary Optimization (MOO) algorithms that enable the simultaneous evaluation of conflicting design objectives such as minimizing solar radiation while maximizing indoor daylighting (Hamdy et al. 2016). In the Rhinoceros 3D / Grasshopper 3D software, there are existing plugins in the form of evolutionary solvers that enable these multi-objective optimization algorithms such as Biomorpher, Octopus, and Wallacei.

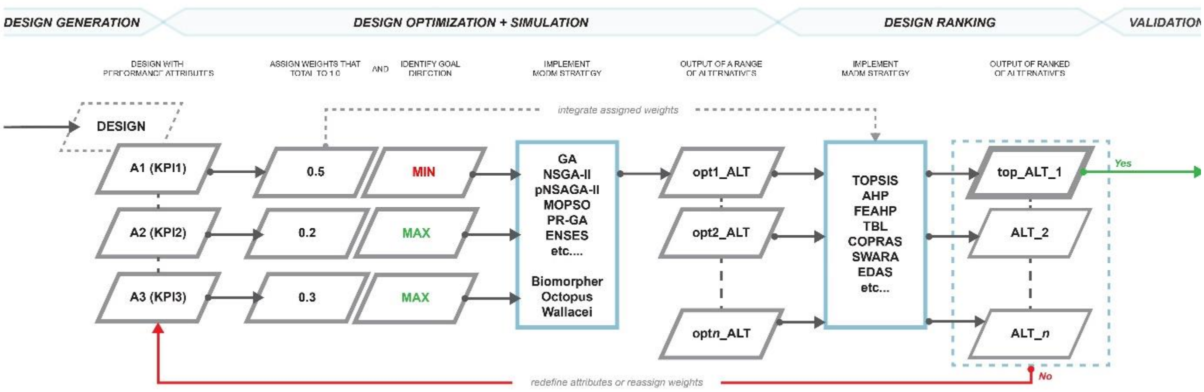


Figure 8.2.2c: Conceptual computational flowchart describing the integrated MCDM strategy where the attributes (A) are KPIs and the alternatives (ALT) are optimized designs

With the current state of the literature review, an initial understanding of the roles of the two MCDM strategies within the WP6 workflow can be established. The initial design(s) generated from the generative design phase in WP5 will be optimized using a MOO algorithm in the Rhinoceros3D/Grasshopper3D environment and these optimized solutions will then be ranked using a selected MADM strategy. The criteria of these design solutions could potentially be weighted through expert contributions, literature reviews, or specific design objectives to enable prioritization of the criteria and ranking of the design solutions. The combination of the two MCDM strategies will formulate an integrated MCDM workflow where the attributes represent selected KPIs for the evaluation of the *ecolope* (Fig. 8.2.2c). Technical parameters were also identified to provide an overview of the potential computational setup and processing for the integrated MCDM-based optimization.

One of the main contributions of this literature review is also to provide an overview of various MADM and MOO strategies implemented in architectural and ecological scenarios to identify the most common strategies as well as the most appropriate ones to be used for the WP6 workflow experimentation. Key parameters were also extracted from this review to develop an initial understanding of potential architectural and ecological evaluation criteria. These criteria will form the basis of the development, description, and categorization of the *ecolopes* KPIs.

Figure 8.2.3a: Discussion of the results of the KPI workshop held in Barcelona for the general meeting

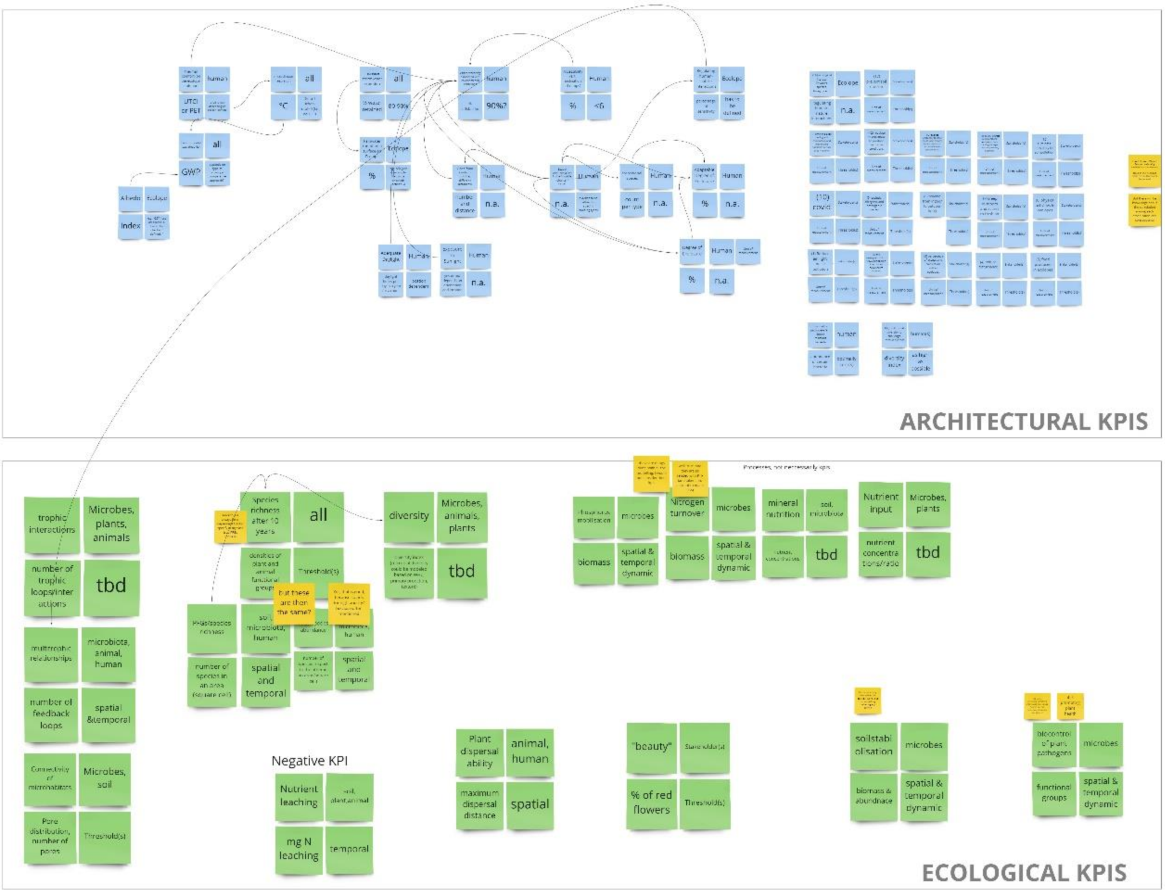


Figure 8.2.3b: Screenshot of the MIRO board to showcase the workspace of the remote participants the remote participants of the workshop.

8.2.2 KPI Workshop – Barcelona General Meeting

During the General Assembly conducted in Barcelona, a KPI workshop was organized by WP6. The workshop was conducted in a hybrid format where remote participants had a Miro board to interact with. The aim of the workshop was to establish an initial understanding of KPIs in relation to architectural and ecological objectives through an analog brainstorming session. Participants were required to use their expert knowledge to identify and generate a list of architectural (building performance) and ecological (stakeholder) KPIs as well as the respective measurements and thresholds (Figs 8.2.3a, 8.2.3b).

Once the KPIs were generated, participants then engaged in a discussion to identify KPIs in order of importance (High – Medium – Low Priority) while identifying potential relationships between the KPIs. The outcome of this workshop resulted in a potential list of KPIs that could be considered to evaluate the *ecolope* as well as their priorities (tables 8.2.3a, 8.2.3b).

Table 8.2.3a: Example of some of the architectural KPIs generated during the workshop

No.	Key Performance Indicator (KPI)	Stakholder(s)						Unit(s)	Threshold(s) Goal	Priority
		So	Mi	Pl	An	Hu	Bu			
1	Water retention					/	/	L/area or L/time	improved runoff	High
2	Urban Heat Island			/	/	/		°C	2°C +- env.	High
3	Species Settlement (Texture)			/	/			Ra	-	High
4	Microclimate	/	/	/	/	/	/	°C	ΔTime=0	High
5	Views					/		0-1	Binary	High
6	Degree of Privacy					/		% and Angle	Maximum	Medium
7	Daylight Factor			/		/		%	1.5 - 2.3	Medium
8	Indoor Air Quality		/	/	/	/		%	-	Medium
9	Carbon Sequestration			/	/	/		Plant Mass	-	Medium
10	Use of existing building materials		/	/	/	/		%	10%	Low

Table 8.2.3b: Example of some of the ecological KPIs generated during the workshop

No.	Key Performance Indicator (KPI)	Stakholder(s)						Unit(s)	Threshold(s) Goal	Priority
		So	Mi	Pl	An	Hu	Bu			
1	Plant Biodiversity Richness			/				Shannon Index	-	High
2	Species Diversity	/		/	/			count	-	High
3	Relative Abundance			/	/			count	0 - inf.	High
4	Recruitment Rate			/				% / time	0-1 / time	High
5	Allergy prevention			/		/		% / time	-	High
6	Microhabitat Connectivity	/	/					count	-	High
7	Homerange Stability				/			years / time	80 - 100	High
8	Realized food webs (Theoretical)				/			nodes per rs	60 - 80 %	High
9	Nature relatedness					/		scale	5 - 7	Medium
10	Positive-Negative Species Relations					/		PANAS	pos = 4-5	Medium

8.2.3 **ECOLOPES Design Studio**

In addition to the dissemination of the *ecolopes* concept into an architectural design studio, as described in D2.2, Section 13.3, the framework of the studio was also structured to begin conceptual and technical experimentation on multi-criteria decision-making workflows in an architectural scale of a residential building. Students were instructed to develop a parametric façade system for multi-species habitation considering the architectural requirements of a residential building as well as the needs of the human and non-human stakeholders. The students began by first identifying the façade system, grid size, and the façade elements for their proposed design. As part of the multi-criteria geometry development, students identified physical and biological necessities of local plant and animal species (stakeholders) and proceeded to establish a network of interrelationships to be integrated into the *ecolope*. Students were encouraged to use computational simulation tools in the Grasshopper environment to perform basic environmental simulations (e.g: Solar Radiation) to generate mapping strategies for the *ecolope* façade panels. Informed by their site analyses and environmental simulation results, the students were then instructed to formulate a parametric workflow to inform the geometry of the *ecolope* façade panels as well as the mapping of the panels on the building façade. Students also consulted with Prof. Assaf Shwartz who advised from an ecological perspective. Several ECOLOPES members attended the mid-term and final presentations of the students to provide input towards the design development of their proposed projects.

Future Developments

The next step for Work Package 6 is to detail the optimization process computationally to understand the input/output of the integrated MCDM workflow. This will be developed in parallel with the generative design phase and therefore will involve focused meetings with WP5 to develop compatible computational strategies. Aside from that, a synthesis of the literature review will be conducted to extract core MOO and MADM strategies to be experimented with within the Rhinoceros 3D/Grasshopper 3D environment. A strategy will also be developed from the parameters extracted from the literature review to generate and categorize *ecolope* specific KPIs, which will also be in collaboration with WP5. Computationally, strategies to potentially overcome the shortcomings of MOO and MADM strategies will also be discussed, specifically in relation to the limitations of the number of KPIs that can be computed before the algorithm loses accuracy.

9 WORK PACKAGE 7

9.1 Work package description, tasks and deliverables

WP no.	7	WP title	Overall Validation			
Lead partner	UNIGE	Start month	26	End month	48	
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
PMs/partner	9	18	3	7	3	3

Objectives: WP7 will demonstrate the effectiveness of ECOLOPES multispecies design and of the ECOLOPES design platform developed across WP3-WP6. The design process will be validated through specific design cases for selected sites to determine whether adequate outcomes for inhabitants are obtained and if the ECOLOPES design platform is adequately integrated. WP7 will provide feedback for optimization.

Task 7.1: Human comfort and wellbeing (M28-45, 14 PMs), Lead: UNIGE. Participants: TEC, McNeel
Validation for humans: **a**) virtual 3D experiment to assess people's response to different building envelopes. Assessment of well-being, health responses, people's perceptions of these envelops to validate theoretical functional relationships (WP4) and compare design outcome benefits to health and well-being. **b**) assessment of thermal comfort of ECOLOPES area (outdoor + indoor) via 3D simulation/modelling of designs for all sites to validate/compare outcomes. **Tangible outcome:** Reports on people's perception and comfort (in D.7.1).

Task 7.2: Building blocks exposure & analysis (M28-45, 13 PMs), Lead: TUM. Part.: UNIGE, SAAD, TEC
Building blocks (BB, 5-9 blocks of $1m^2$) (WP6) will be produced and placed in all sites along with a reference block (i.e. a common envelope, as plaster façade or brick wall). To allow comparison BB will be exposed for 12 months and analysed in terms of occurring plants, microbes, and insects and in terms of water management, maintenance and use. **Tangible outcome**: Report on BB analysis (in D7.1).

Task 7.3: Identification of the best design outcomes (M28-48, 16 PMs), Lead: UNIGE, Participants: All.
The multifunctionality of the *ecolope* will be tested with empirical approaches, experiments and simulations. Design outcomes (WP6) will be evaluated considering all inhabitants in relation to ecosystem services provided and estimated maintenance needs, by way of Cost-Benefit approaches and in relation to the built context. Design outcomes will be analysed via ECOLOPES multicriteria approach. KPI (WP6) will be weighted and modified based on expert assessment.
Tangible outcome: Report on best design outcomes (D7.2).

No.	Description	Month(s)
D.7.1	Report on the methodology for ECOLOPES multifunctionality evaluation	30
D7.2	Report on evaluation of inhabitants' responses	45
D7.3	Report on the best design outcome for each site	48

9.2 Work in the first year

Work Package 7 will officially start in month 26. The main activities which will be implemented in the first active year of WP7 were presented and discussed during the General Meetings and the Project Management Board Meetings. In addition, WP7 leader and participants are already actively collaborating with WP3-WP4-WP5-WP6 leaders and participants in order to set the ground for the development of each WP7 specific task, for example by defining the methodology for the design cases selection and by drafting the computational and design workflow.

10 Work Package 8

10.1 Work package description, tasks and deliverables

WP no.	8	**WP title**	**Ethics requirements**			
Lead partner	TUM	**Start month**	1	**End month**	48	
Partner no.	1	2	3	4	5	6
Short name	TUM	UNIGE	VIE	TEC	SAAD	McNeel
Objectives: WP8 addresses the ethical issues that were addressed during review of the grant proposal						
Task 8.1 Addresses ethics requirement 4: Treatment of animals in building blocks **(M1-28) Lead: TUM, Participants: All** The consortium must clarify the plans how the protection of the animals in the installed blocks will be ensured and describe the plans how the animals will be treated after project termination. This report must be submitted as a deliverable D8.1 **Task 8.2: Harm to environment due to *ecolope* design** **(M1-28) Lead: TUM, Participants: All** Further information about the possible harm to the environment caused by the research, and the measures that will be taken to mitigate the risks at least about the prevention and control of overpopulation of animals (including insects) and spread of zoonotic and vector-borne diseases, uncontrolled plant growth and inappropriate microbiota development and the measures that will be taken to mitigate the risks must be submitted as a deliverable D8.2.						

No.	**Description**	**Month(s)**
D8.1	Report on protection of animals in building blocks	28
D8.2	Report on avoiding harm to environment due to *ecolope* design	28

10.2 Work in the first year

The consortium is still in the process of developing the design of the building blocks which is needed to assess what animals will be potentially colonize the building blocks when exposed. The soil model and the plant and animal models will be used in the second year to assess potential risks to humans and livestock of microbes and pests settling or brought close to buildings by the *ecolope*.

11 References

Benedict, M. A., and E. T. McMahon. 2012. Green infrastructure: linking landscapes and communities. Island Press.

Brondizio, E., J. Settele, S. Díaz, and H. Ngo. 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES Secretariat.

Bruen, C., R. Brugha, A. Kageni, and F. Wafula. 2014. A concept in flux: questioning accountability in the context of global health cooperation. Globalization and Health 10:1-15.

CBD. 2012. Cities and Biodiversity Outlook. . Secretariat of the Convention on Biological Diversity, Montreal.

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

Colleony, A., and A. Shwartz. 2020. When the winners are the losers: Invasive alien bird species outcompete the native winners in the biotic homogenization process. Biological Conservation 241:108314.

De Palma, A., K. Sanchez-Ortiz, P. A. Martin, A. Chadwick, G. Gilbert, A. E. Bates, L. Börger, S. Contu, S. L. Hill, and A. Purvis. 2018. Challenges with inferring how land-use affects terrestrial biodiversity: Study design, time, space and synthesis. Pages 163-199. Advances in Ecological Research. Elsevier.

Eggermont, H., E. Balian, J. Azevedo, V. Beumer, T. Brodin, J. Claudet, B. Fady, M. Grube, H. Keune, P. Lamarque, K. Reuter, M. Smith, C. van Ham, W. W. Weisser, and X. Le Roux. 2015. Nature-based Solutions: New Influence for Environmental Management and Research in Europe. GAIA Ecological Perspectives 24:243-248.

Elmqvist, T., E. Andersson, N. Frantzeskaki, T. McPhearson, P. Olsson, O. Gaffney, K. Takeuchi, and C. Folke. 2019. Sustainability and resilience for transformation in the urban century. Nature Sustainability 2:267-273.

European Commission. 2013. Green Infrastructure (GI) — Enhancing Europe's Natural Capital. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Commission of the European Union, Brussels, Belgium.

European Commission. 2019. The European Green Deal (COM no. 640, 2019). Commission of the European Union, Brussels, Belgium.

Gilbert, J. A., and B. Stephens. 2018. Microbiology of the built environment. Nature Reviews Microbiology 16:661-670.

Goddard, M. A., Z. G. Davies, S. Guenat, M. J. Ferguson, J. C. Fisher, A. Akanni, T. Ahjokoski, P. M. L. Anderson, F. Angeoletto, C. Antoniou, A. J. Bates, A. Barkwith, A. Berland, C. J. Bouch, C.

C. Rega-Brodsky, L. B. Byrne, D. Cameron, R. Canavan, T. Chapman, S. Connop, S. Crossland, M. C. Dade, D. A. Dawson, C. Dobbs, C. T. Downs, E. C. Ellis, F. J. Escobedo, P. Gobster, N. M. Gulsrud, B. Guneralp, A. K. Hahs, J. D. Hale, C. Hassall, M. Hedblom, D. F. Hochuli, T. Inkinen, I.-C. Ioja, D. Kendal, T. Knowland, I. Kowarik, S. J. Langdale, S. B. Lerman, I. MacGregor-Fors, P. Manning, P. Massini, S. McLean, D. D. Mkwambisi, A. Ossola, G. P. Luque, L. Pérez-Urrestarazu, K. Perini, G. Perry, T. J. Pett, K. E. Plummer, R. A. Radji, U. Roll, S. G. Potts, H. Rumble, J. P. Sadler, S. de Saille, S. Sautter, C. E. Scott, A. Shwartz, T. Smith, R. P. H. Snep, C. D. Soulsbury, M. C. Stanley, T. Van de Voorde, S. J. Venn, P. H. Warren, C.-L. Washbourne, M. Whitling, N. S. G. Williams, J. Yang, K. Yeshitela, K. P. Yocom, and M. Dallimer. 2021. A global horizon scan of the future impacts of robotics and autonomous systems on urban ecosystems. Nature Ecology & Evolution 5:219-230.

Groffman, P. M., M. Avolio, J. Cavender-Bares, N. D. Bettez, J. M. Grove, S. J. Hall, S. E. Hobbie, K. L. Larson, S. B. Lerman, D. H. Locke, J. B. Heffernan, J. L. Morse, C. Neill, K. C. Nelson, J. O'Neil-Dunne, D. E. Pataki, C. Polsky, R. R. Chowdhury, and T. L. E. Trammell. 2017. Ecological homogenization of residential macrosystems. Nature Ecology and Evolution. Nature Publishing Group.

Hamdy, M., Nguyen, A. T. and Hensen, J.L.M. (2016) 'A performance comparison of multi-objective optimization algorithms for solving nearly-zero-energy-building design problems', *Energy and Buildings*, 121, pp. 57–71. doi:10.1016/j.enbuild.2016.03.035.

Hwang, C. L. (1979) *Multiple Objective Decision Making — Methods and Applications A State-of-the-Art Survey*. 1st ed. 1979. Berlin, Heidelberg: Springer Berlin Heidelberg (Lecture Notes in Economics and Mathematical Systems, 164). doi:10.1007/978-3-642-45511-7.

Kellert, S. R., J. Heerwagen, and M. Mador, editors. 2008. Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life. John Wiley & sons, Hoboken, New Jersey, USA.

Marselle, M. R., J. Stadler, H. Korn, K. N. Irvine, and A. Bonn. 2019. Biodiversity and health in the face of climate change. Springer.

McDonald, R. I., A. V. Mansur, F. Ascensão, M. l. Colbert, K. Crossman, T. Elmqvist, A. Gonzalez, B. Güneralp, D. Haase, M. Hamann, O. Hillel, K. Huang, B. Kahnt, D. Maddox, A. Pacheco, H. M. Pereira, K. C. Seto, R. Simkin, B. Walsh, A. S. Werner, and C. Ziter. 2020. Research gaps in knowledge of the impact of urban growth on biodiversity. Nature Sustainability 3:16-24.

McKinney, M. L. 2002. Urbanization, biodiversity, and conservation. Bioscience 52:883-890.

Peccia, J., and S. E. Kwan. 2016. Buildings, beneficial microbes, and health. Trends in Microbiology 24:595-597.

Penadés Plà, V, Garcia-Segura, T., Marti, J. & Yepes, V. (2016) 'A Review of Multi-Criteria Decision-Making Methods Applied to the Sustainable Bridge Design', *Sustainability*, 8, p. 1295. doi:10.3390/su8121295.

Rojas-Rueda, D., M. J. Nieuwenhuijsen, M. Gascon, D. Perez-Leon, and P. Mudu. 2019. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. The Lancet Planetary Health 3:e469-e477.

Söderlund, J. 2019. The emergence of Biophilic design. Page 296. Springer Nature, Switzerland.

Thomson, G., and P. Newman. 2018. Urban fabrics and urban metabolism–from sustainable to regenerative cities. Resources, Conservation and Recycling 132:218-229.

Thomson, G., and P. Newman. 2020. Cities and the Anthropocene: Urban governance for the new era of regenerative cities. Urban Studies 57:1502-1519.