ECOLOPES

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

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ECOLOPES Voxel Model

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Abstract

The report outlines the development of the ECOLOPES Voxel Model for the ontology-aided generative computational design process for the design of ecological building envelopes. The objectives are: (1) to describe the role of the voxel model in the ontology-aided generative computational design process; (2) to provide a conceptual and technological characterization of the voxel model; (3) to describe the interactions of the voxel model with the components of the ontology-aided generative computational design process (EIM Ontologies and Computational Model / algorithms); (4) to describe the interactions of the voxel model with other components of the ECOLOPES computational design framework (Databases, Ecological Model, Knowledge Generation Framework); (5) to outline the voxel data that is delivered together with the CAD geometry and ontological output) to the subsequent optimization process; and (6) to outline open questions and future research.

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EXECUTIVE SUMMARY

This report outlines the development of the ECOLOPES Voxel Model as a component of the ontology-aided generative computational design process for the design of ecological building envelopes. This report is closely related to the simultaneously submitted reports on *D4.2 Interim EIM Ontology*, *D5.2 ECOLPES Voxel Demo*, and *D5.4 ECOLOPES Computational Model*. Together these deliveries describe the ontology-aided generative computational design process.

In the context of this research project, which requires correlating and spatializing multi-domain data, focus is placed on the use of voxels as *spatial-knowledge representation schemata* (Srihari 1981) for use in planning and design. According to Kaufman, "each voxel is a unit of volume and has a numeric value (or values) associated with it that represents some measurable properties or independent variables of a real object or phenomenon" (Kaufman 1993). This understanding implies that voxel models can be utilized as spatial data structures that encode different representations of domain-specific knowledge.

Project specific data for the generative design process is contained in the ECOLOPES Voxel Model and in the CAD model. The ECOLOPES Voxel Model consists of a SQL database. Only data that can be expressed spatially is contained within the voxel model. The data contained in the voxel model is derived from (1) open and expert databases, (2) the ecological model (See report D4.1 *Preliminary EIM Ontology*), (3) the knowledge generation framework (See report D3.2 *Draft ECOLOPES platform architecture*), (4) the EIM Ontologies (see report *D4.2 Interim EIM Ontologies*), and (5) computational simulations, generated in preparation of or as part of the generative phase of the process.

Section 1 describes the role of the ECOLOPES Voxel Model in the ECOLOPES Computational Framework. Furthermore, we elaborate the conceptual and technical characteristics of the ECOLOPES Voxel Model. Voxel models emerged in the field of computer science in the 1960s and were named "*spatial knowledge representation schemata'' according to* Srihari (1981). Single voxel unit can be seen as an 3D equivalent of a 2D pixel in an image. Although, voxel models can contain multiple numeric values assigned to a single voxel unit and are able to represent objects in multiple scales "ranging from organs interior to the human body to rock microstructures" (Srihari 1981, 399). From a technical perspective, the presented approach to voxel modeling utilizes the RDB environment (PostgreSQL) to enable adequate integration with external components and to implement basic computational procedures, such as reprojection and scaling within the RDB framework. A multi-scalar approach is introduced by the inclusion of voxel model levels, allowing the voxel data to be stored once and transparently queried in different coordinate systems and spatial resolution.

Section 2 describes the interactions of the ECOLOPES Voxel Model with the Designer and other components in the ECOLOPES Computational Framework. This includes (1) interactions with the components of the ontology-aided generative computational design process, namely the EIM Ontologies and the CAD environment / algorithmic design processes, and (2) interactions with other components of the ECOLOPES computational design framework (Databases, Ecological Model, Knowledge Generation Framework).

Section 3 elaborates the ECOLOPES Voxel Model data transferred to the optimization process (WP6). At that stage, the ontology-aided design process is completed, and the results are

expressed as static CAD geometry. This geometric representation is converted into a voxel-based representation and data describing environmental conditions is generated and exported as a single SQLite database file.

Section 4 addresses validation, TRL, FAIR principles, and open questions and future research.

Section 5 provides the publication plan for the ECOLOPES Voxel Model.

ABBREVIATIONS AND ACRONYMS

ASP	Answer Set Programming
CAD	Computer Aided Design
DEM	Digital Elevation Model
DSM	Digital Surface Model
EA	Evolutionary Algorithm
EIM	ECOLOPES Information Model
EM	ECOLOPES Ecological Model
GA	Genetic algorithm
GCD	Generative Computational Design
GH	Grasshopper
JSON	JavaScript Object Notation
KGF	Knowledge Generation Framework
KPI	Key Performance Indicator
OWL	Web Ontology Language
RDB	Relational Database
RDF	Resource Description Framework
SQL	Structured Query Language
WP	Work-package
PFGs	Plant Functional Groups
AFGs	Animal Functional Groups

TABLE OF CONTENTS

1 INTRODUCTION

The ECOLOPES computational framework, its technical components, and data flow between the latter (computational workflow) was elaborated in WP3 and the updated version presented in D3.3. (M29) (Fig. 1).

The ECOLOPES Computational Framework facilitates informed multi species design for ecological building envelopes, that we term *ecolopes* (Fig. 1) (D3.3, Weisser et al. 2022). It includes technical components such as the Ecological Model, the Knowledge Base, the design generation environment, which we term "*ontology-aided generative computational design process*", the Optimization Environment (D6.1), and components for validation. The Ecological Model, developed in WP4 (D4.1, D1.5), simulates plant, animal and soil dynamics. The Ecological Model was integrated in a 3D CAD system (Rhino/ Grasshopper) (D3.3 Chapter 3), which facilitated the generation of relational data (architecture, environmental, and ecology) for building envelopes in a resolution of 1 cubic metre. In the next step, this data was stored in the Knowledge Base (D3.3. Chapter 4). The KB was then analysed using a ML model which extracts rules for decision making for WP5 (D3.3, Chapter 4). The design generation environment (ontology-aided generative computational design process), which is developed in WP5 (*D5.2 ECOLOPES Voxel Mode*l and *D5.3 ECOLOPES Computational Model*) facilitates design generation and the generation of design search space populated with alternative solutions that can be analysed, evaluated, and ranked. The optimization environment, which is developed in WP6 aims to facilitate optimization based on the search space produced by the ontology-aided generative computational design process (WP5) and selection of the final *ecolope* design solution based on KPIs (D6.1). The ECOLOPES Computational Model provides input for optimization, the output of which provides the basis for the overall validation (WP7) of the ECOLOPES Computational Framework.

During development it became clear that the Ecological Model output is far too complex for integration into the design generation algorithms, and that the development of a comprehensive EIM ontology takes time. It was therefore decided to pursue parallel workflows: One workflow focuses on the development of the ontology-aided generative computational design process and the EIM Ontologies (TU Vienna), while the second workflow uses the Knowledge Generation Framework (KGF, D3.3) to provide correlational (ecology-architecture) information for design decision support (MCNEEL, TUM, SAAD). The KB is the joint interface of the two workflows.

In this report we describe the development of the ECOLOPES Voxel Model for the ontology-aided generative computational design process for designing ecological building envelopes. The ontology-aided generative computational design process is a key element of the Ecolopes computational framework. As described in the *D3.3* the computational workflow consists of different technical components: Open and expert databases (WP3-WP7), Environmental models (WP3), Ecological model (WP4), Knowledge base (KB) (WP3), Voxel model for interoperability (WP3), Ecological analysis in CAD (WP3-WP4), Ontologies (WP4), design generation environment and algorithms (WP5), Design optimization environment (WP6), and Validation (WP7).

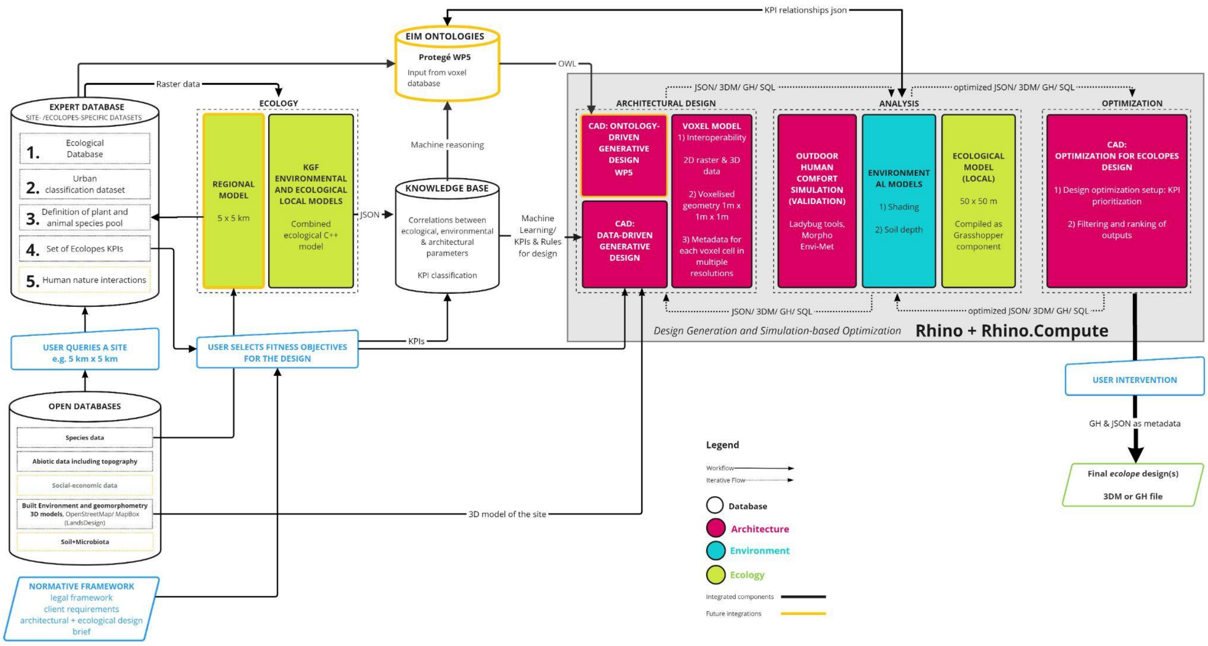


Fig. 1: Ecolopes computational framework showing integrated (black frame) and non-integrated technical components (yellow frame) (D3.3).

The ontology-aided generative computational design workflow comprises three key components: (1) the EIM Ontologies that guide the design process in its different stage and can be queried by the designer, (2) a voxel model that integrates relevant datasets for the design process, and (3) the CAD environment in which a number of algorithmic processes are implemented that are linked with and guided by the EIM Ontologies. In the generative computational design process data is collected from different sources, including databases, the ecological model, KGF, simulations, etc. This data is utilized in the ontology-aided data-driven algorithm design process with the purpose to generate design variations for a context-specific ecological building envelope.

The ECOLOPES Voxel Model offers a key utility for the different stages of the generative computational design process, which includes the translational process and (2) the generative process. The translational process serves to lay out the project-specific problem space for design. In this process requirements of the design brief for a given project and site and additional requirements are analyzed, correlated, spatialized, and prepared for design generation. This process is ontology-aided and involves the preparation of the datasets referred to as *maps* and *networks* (*D5.1 Development Process for ECOLOPES Algorithms*). The generative process serves to extend the solution space for design, which entails generation of a range of design outputs that can be evaluated and ranked. This iterative process is ontology-aided and culminates in the generation of (1) spatial organization expressed as the dataset *volumes*, and (2) site and building geometry expressed as the dataset *landform* (*D5.1 Development Process for ECOLOPES Algorithms*). Each design outcome will consist of (1) a CAD model, (2) corresponding datasets contained in the voxel model, and (3) ontological output.

In the interdisciplinary ECOLOPES research project researchers have different disciplinary expertise and approaches, as well as varied computational proficiency. For this reason, a self-explanatory and technology agnostic solution was chosen. Relational Databases (RDBs, such as SQL databases) are widely implemented and most contemporary programming languages contain well developed bindings for RDBs. User interaction will be realized through the ECOLOPES front-end tools (WP3) based on Rhino/Grasshopper, a 3D CAD software widely used in the context of architectural design.

1.1 The Role of the ECOLOPES Voxel Model in the Ecolopes Computational Framework

In the context of the Ecolopes research project it is necessary to correlate and spatialize data pertaining to different disciplines, including ecological, environmental, and architectural data, as well as data pertaining to landscape architecture.

In this project we pursue an understanding of voxels as *spatial-knowledge representation schemata* (Srihari 1981) for use in planning and design. The use of voxel models commenced in the 1960s. However, their convergence with the field of CAD only commenced in the late 1980s (Granholm et al. 1987; Jense et al. 1989). Early experiments involving voxel models were constrained by the computational performance of hardware available at the time. Constant improvement of computer hardware led to numerous developments of voxel-based methods in the field of computer graphics. These developments are present in the work of Arie Kaufman (Kaufman et al. 1987; Kaufman et al. 1988; Kaufman et al. 1993). Research conducted at that time focused on efficient processing and visualization of voxel models derived from MRI-based 3D scans. Kaufman stated that a "voxel is a unit of volume and has a numeric value (or values) associated with it that represents some measurable properties or independent variables of a real object or phenomenon." (Kaufman et al 1993, 52). This definition underlines the analytical property of the voxel models, where the values encoded in the voxel model are representative of real-world properties of the studied object.

Srihari discussed voxel models as *spatial-knowledge representation schemata* (Srihari 1981). His research primarily addressed the disciplines of computational forensics, machine learning (ML) and pattern recognition. Srihari stated that "developing systems for processing and displaying these [3D] images has revealed the need for developing new data structures, and more generally, for developing spatial-knowledge representation schemata" (Srihari 1981, 399). In so doing, Shrihari shifted the focus of the research on voxel models from visualization and processing of 3D image data towards the applications of voxel models as spatial structures able to represent knowledge pertaining to real-world objects. Jense observed that: "it is useful to note (...) the duality that exists between the interpretation of voxel models as sets of cuboid volume cells, or as sets of 3D points, each representing a discretized point sample, taken from some continuous space" (Jense 1989, 529). Currently, the dominant understanding of a voxel model is a collection of 3D boxes, stacked in the digital space of a computer game. Due to this dominant understanding, the potential of voxel models understood as s*patial-knowledge representation schemata* is currently receiving much less attention. We shed light on this discourse in a recently published scoping review of voxel model applications in the field of architectural design and urban planning (see Appendix B).

The voxel model receives data from different sources including relevant databases, the ecological model, the knowledge generation framework, and, if required, from various simulations executed in Geographic Information Systems (GIS) software. Relevant data can be indicated and / or called via the EIM Ontologies. Data contained in the voxel model can then be utilized in the data-driven generative computational design process through which design outputs are created that consist of (1) geometry contained within the CAD model, (2) design specific data contained in the voxel model, and (3) ontological output. The resulting data package can then be used within the optimization process to derive design outputs with optimized architectural and ecological performances. In the following subsections we deliver a conceptual and technical characterization of the Ecolopes Voxel Model.

1.2 Conceptual characterization of the ECOLOPES Voxel Model

Conventionally, 3D CAD models in the field architecture contain geometry that describes architectural objects created by architects. In recent years, a growing interest in the application of diverse environmental simulation methods in architectural design can be observed. Different aspects of solar performance have been integrated into architectural planning activities, with the earliest attempts dating back to 1963 (Brown 1990). Currently, tools such as Ladybug Tools (Sadeghipour Roudsari et al. 2013) and Climate Studio (ClimateStudio 2023), have become an integral part of parametric design processes. Currently those approaches exist within their own technological and conceptual boundaries, with considerably less effort invested into conceptualizing and implementing overarching data-integration strategies. Tools promoting more holistic simulation and analysis approaches, such as Ladybug Tools in GH, including for instance Dragonfly (Dragonfly-Grasshopper 2019/2022), as well as Envi-met (High-Resolution 3D Modeling of Urban Microclimate with ENVI-Met Software 2023) are emerging within the research-oriented, architectural design community. Yet, more holistic approaches that address diverse disciplinary approaches for simulation and analysis of the built environment are rarely found. Such integrative approaches are necessary to address the contemporary challenges related to climate change and sustainable development goals.

The approach presented in this report builds on the *Composite Voxel Model* (CVM) methodology that addresses data-integrated, performance-oriented computational design processes to advance the understanding of socio-ecological systems (Tyc et al, 2022). Initially the CVM spatial data integration approach was tested by the utilization of self-acquired, high-resolution, point cloud data (Tyc et al 2021). Application of the Composite Voxel Model methodology was further extended to support data-driven design activities. This approach was validated in a case study (Tyc et al 2022).

The approach introduced in the ECOLOPES Voxel Model differs from our previous experiments, since it is conceptualized as an element of a larger data integration activity. The data integration approach currently implemented in Tasks T5.1, T5.2 and T4.7 supports the ontology-aided generative computational design process for designing ecological building envelopes. A conceptual overview of this data integration approach is shown in Figure 2. In this process, multiple components are introduced and dedicated interfaces are developed to support the designers' decision-making processes. The ECOLOPES Voxel Model stores multi-scalar data that describes geometry and chosen environmental conditions. The EIM Ontology implemented in the GraphDB environment integrates external datasets, such as species occurrence data with spatial data contained in the RDB-based voxel model. The GCD process is initiated by user interaction translated into the Dataset Networks and the computational components are providing feedback based on the GraphDB reasoning capacities. Moreover, in the presented voxel modeling approach, openly available datasets are used to generate the initial datasets contained in the voxel model. To enable integration of the diverse disciplinary datasets the concept of multi-scalar data has been conceptually introduced by the inclusion of *levels* within the voxel model structure. This concept was previously described in the *D5.1 Development Process for ECOLOPES Algorithm* in section 6.2. Each level is introduced into the ECOLOPES Voxel Model to facilitate interaction with an external computational procedure. Other commonly used terms, such as *extent* or *resolution* appeared unsuitable, since multiple computational procedures might require different data inputs, while utilizing the same geometric *resolution* and *extent*. The detailed technical description of this feature is presented in section 1.3.2.

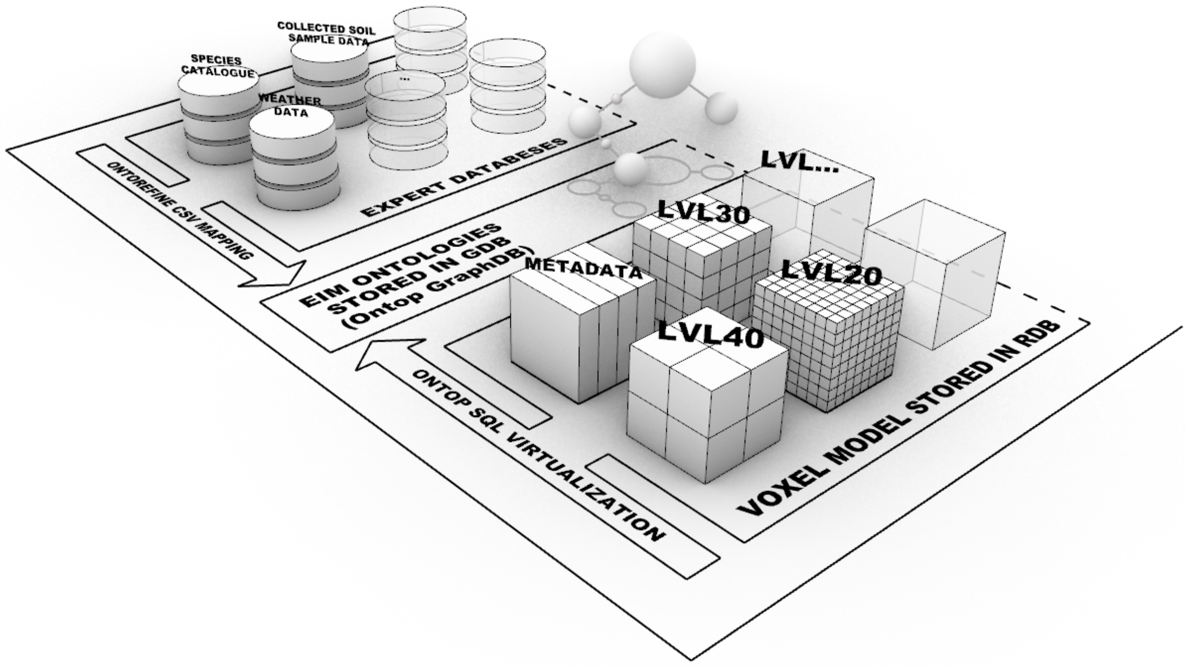


Fig. 2: This updated version of Figure 20 from Deliverable D5.1 illustrates the conceptual approach for systematic data integration and structuring. This approach is being implemented to support the ontology-aided design process. The GraphDB component stores the EIM Ontologies and establishes interfaces with external datasets and the Ecolopes Voxel Model by utilizing Ontop GraphDB virtualization and mapping techniques.

1.3 Technical characterization of the ECOLOPES Voxel Model

The ECOLOPES Voxel Model uses a range of technologies to link the voxel data encoded in a RDB-based voxel model with the Rhinoceros / Grasshopper interface. Figure 3 shows how the chosen software technologies are used in the ECOLOPES Voxel Model implementation. This implementation builds on the technologies readily available within the McNeel Rhinoceros software ecosystem. Rhinoceros and Grasshopper are one of the most widely used tools in architectural design. Originally, McNeel introduced GHPython components into the Grasshopper environment, based on the IronPython (*IronPython*, 2017). To overcome some of the limitations posed by the IronPython, we used the Grasshopper Hops components, which adds external functions to Grasshopper through Rhino.Compute. Hops integrates a modern Python interpreter (CPython 3.9) with the Rhinoceros/ Grasshopper environment through a REST API based interface. ECOLOPES Voxel Model Grasshopper definitions are written as Hops components to establish an interface with the RDB. SQLAlchemy Python library (SQLAlchemy, 2018/2023) is used to provide an SQL-dialect agnostic solution for integrating RDBs with the digital design process implemented in the Rhinoceros software. For the RDB-based ECLOPES Voxel Model, different types of RDBs, including SQLite, MariaDB and PostgreSQL, have been prototyped and tested. Python technology was chosen, among others, due to its wide compatibility. Python version 3.9 is compatible with McNeel libraries. The Python Hops application has been packaged into a single executable file for internal distribution. The presented application has been successfully tested on both Windows and MacOS platforms, including the ARM based M1 architecture. Data contained in the voxel model has been created with a range of open-source geospatial analysis tools, such as QGIS (Open-Source Geospatial Foundation Project 2020), Whitebox Tools (Lindsay 2016) and SAGA GIS (Conrad et al. 2015).

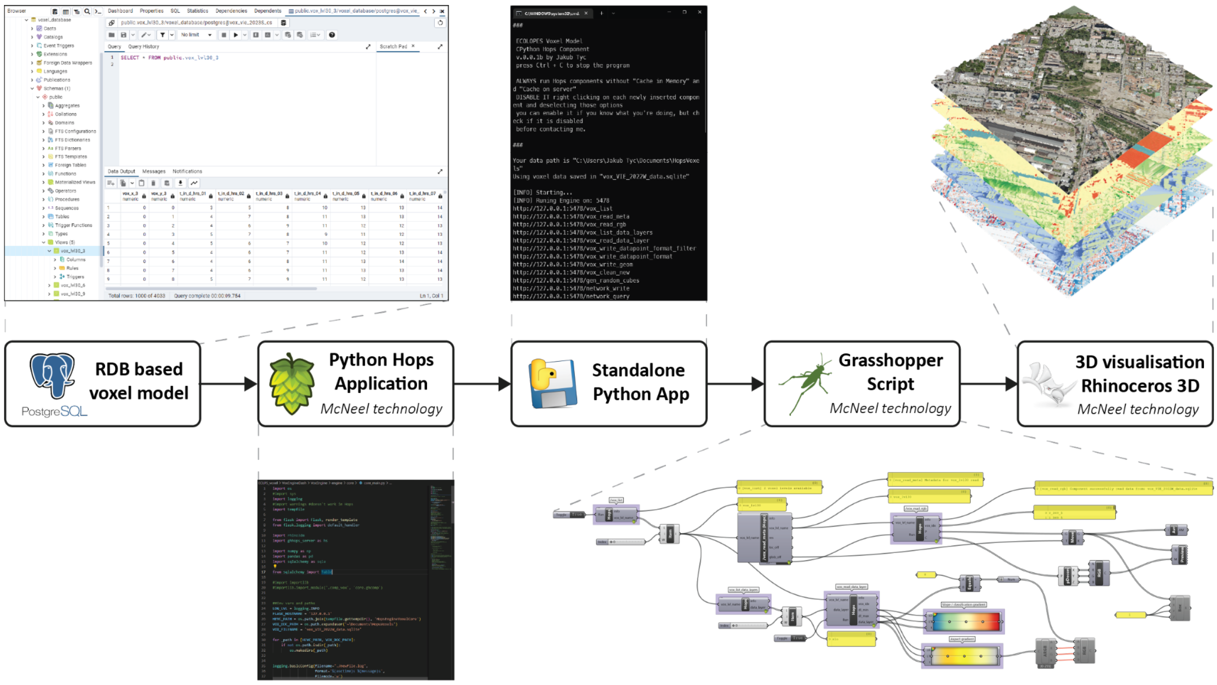
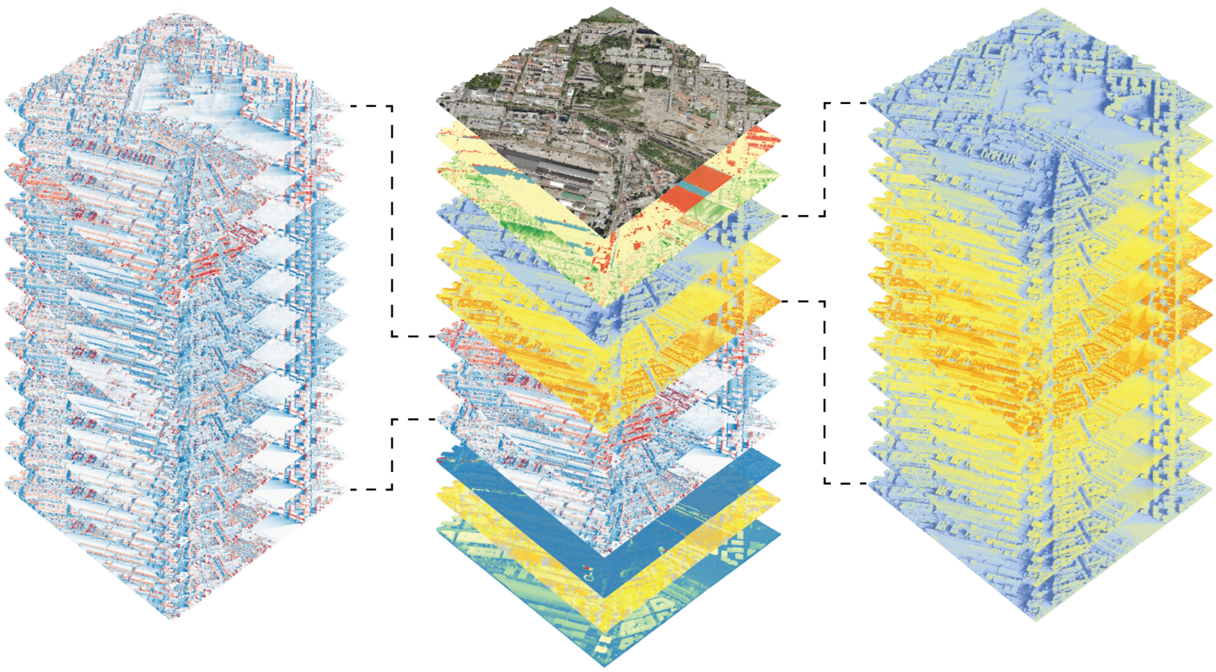


Fig. 3: Technologies utilized to implement the ECOLOPES Voxel Model were linked in a sequence. RDB-based voxel data can be queried through the McNeel Python Hops application packaged into a single executable file. This Python application exposes voxel data in the McNeel Rhinoceros/ Grasshopper environment for user interaction.

1.3.1 **Datasets encoded in the ECOLOPES Voxel Model**

Datasets currently contained in the ECOLOPES Voxel Model are based on the open-access data provided by the Vienna municipality. This exemplary data was chosen to be representative for the Vienna Case Study experiment, prepared for the validation of the selected ECOLOPES components (see *D5.4 ECOLOPES Computational Model*). The Vienna Case Study is a design experiment that builds on the large-scale city planning project "Nordbahnhof Freie Mitte" (Vlay et al. 2015). This urban project repurposes a large area that was until recently used as a railyard for a large area of mixed-use housing. The unique quality of this project is related to its aim of supporting local ecosystems that exist on the site of the current railyards and to promote innovative design approaches that support biodiversity.

For the case study geometric data pertaining to the site was constructed from the DEM and DSM data products available as a part of the Open Government Data (OGD) initiative, introduced by the Vienna municipality. This data represents real-world site conditions at a point in time when the datasets were physically acquired (ca. 2015; the location of the current Nordbahnhof Freie Mitte project is undergoing intense development). For the Vienna Case Study, a dataset that represents site conditions aligned with the status of the current stage of city development was required. This was accomplished by conventional geospatial processing techniques, such as Digital Surface Model (DSM) ground point filtering. Additional refinements were required, such as manual deletion of points that describe buildings that were demolished in preparation of this urban development project. In this preliminary phase, base data was stored in georaster files and conventional geospatial data processing methods were applied. Base layers such as DEM, DSM, and multi-purpose map containing land-use classification (MZK - Mehrzweckkarte) were manually processed in QGIS (QuantumGIS version 3.22.4 Białowieża) to reflect current conditions found on site. The results of this data preparation were exported into the RDB-based voxel-model environment. Resulting dataset represents a 3D environment in a resolution constrained by the resolution of the base data layers (DEM and DSM). Information content of the geometric data was extended through the application of a range of geospatial analysis techniques, published in the open-source domain. Selection of datasets describing environmental conditions that could be found on the site and in its immediate surrounding was chosen. Figure 4 shows the datasets that are currently encoded in the ECOLOPES Voxel Model.



Wind exposure

(exposure towards wind flux)
from prevailing wind direction
for each month in the year

Datasets currently contained in the ECOLOPES Voxel Model

Topographic Wetness Index (TWI), classification, slope and aspect

Sunlight exposure

(sunlight hours)
for each month in the year

Fig. 4: Datasets contained in the ECOLOPES Voxel Model include geometric and classification data. This includes environmental performance data such as, for instance, topographic wetness index, as well as time series data describing insolation time and wind exposure.

The selected datasets are representative of different aspects of environmental performance and are often utilized in urban planning activities (Wilson & Gallant, 2000; Conrad et al., 2015). The datasets include solar and wind exposure, as well as topographic water-related conditions. For solar exposure the average insolation time for each month in a year was computed. This parameter, often described as sunlight hours, is commonly used to evaluate sunlight availability in urban contexts. Topographic wetness conditions were evaluated using the Topographic Wetness Index (TWI). This metric is one of the simplest methods to quantify soil moisture variation based on surface geometry. For each grid point on the surface, the TWI calculation entails the local upslope area and the local slope of the surface. The local upslope area is the area from which water flows into each point in the grid, while slope is a measure of surface inclination at each point in the grid. Furthermore, the surface exposure to wind was calculated based on the dominant wind direction for each month in the year. The dominant wind directions were identified using the Grasshopper Ladybug plugin (Sadeghipour Roudsari et al., 2013) and the EnergyPlus weather file representative for this location. The Ladybug Grasshopper plugin natively supports EnergyPlus weather files and generates a graphical representation of the seasonal wind conditions in the form of Wind Rose. This technique is widely used in parametric design approaches in architectural design. Wind Rose diagrams show the directional distribution of wind for a chosen amount of time, based on the standardized wind data contained in the EnergyPlus weather file. Raw data describing directional distribution of wind can be extracted in the Grasshopper interface to identify dominant wind directions for each season in the year.

1.3.2. **Multi-scalar 3D point data expressed as levels in the ECOLOPES Voxel Model**

The role of levels within the structure of the voxel model is described conceptually in section 1.2. Each level facilitates a specific functionality in the GCD process. On the technological level, data expressed as levels in the voxel model is materialized in the PostgreSQL environment either as SQL tables or as SQL table views. This enables multiple external components to interact with the RDB-based voxel model by querying the voxel data from the chosen level. The requirement of the GCD processes to operate in different scales, necessitates changes of extent and resolution to be handled within the RDB environment. The architecture of the SQL database was planned considering performance and efficiency, and repeated storage of the same data was avoided. Data can be visualized and queried from the McNeel Grasshopper interface by using dedicated Grasshopper components, developed to accommodate required functionalities. An example application of the developed components was evaluated through the definition of Grasshopper component sequences. Each sequence is constructed to facilitate a specific functionality, and the intended functionality is tested by the designer. Furthermore, the designer can filter the data contained in the voxel model by executing a predefined SQL query and interactively evaluate the outcomes of the query. Lastly, multi-scalar voxel model data can be transformed into a graph-representation that can be queried through the GraphDB endpoint. In result, simple SPARQL-based reasoning queries can be executed directly on the data contained in the ECOLOPES Voxel Model. Figure 5 shows the different levels in the ECOLOPES Voxel Model that facilitate interactions between different processes implemented within the GCD process. A detailed description of the Grasshopper components developed to enable interaction with the ECOLOPES Voxel Model is provided in section 2.1.1. A tabular overview of the implemented Grasshopper components is included in Appendix A in this report.

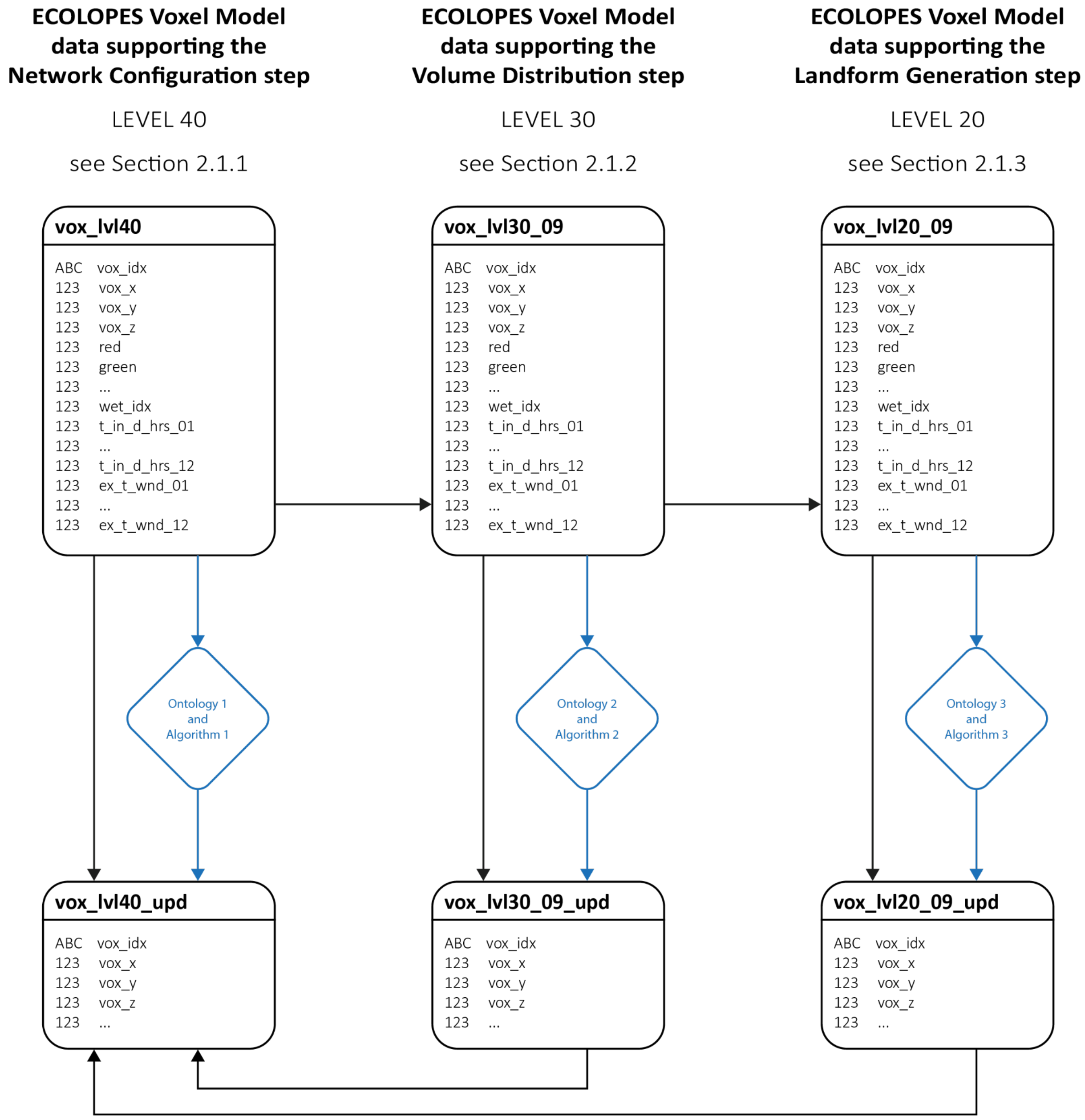


Fig. 5: Overview of the selected levels contained in the ECOLOPES Voxel Model and their relation to the computational procedures implemented in the three loops of the GCD process. Outcomes of each loop can be merged with the input data and written to a separate table (e.g., vox_lvl30_09_upd). This updated voxel-based representation can be merged with the large-scale data (vox_lvl40) and visualized in Rhinoceros.

1.3.3. Site-aligned coordinate systems implemented in the RDB environment

To achieve the goal of multi-scalar data integration within the RDB environment, the concept of a site-aligned coordinate system needs to be implemented. The role of the ontology-aided generative computational design process is to generate site-specific design proposals. The coordinate space of the data to be queried by EIM Ontology 2 and EIM Ontology 3 is aligned with the site boundary dimensions and the rotation of the site outline. These site-specific conditions can be described as a 2D rectangle with fixed dimensions and rotation. By extruding this 2D boundary by a fixed distance, a 3D bounding box that describes the site geometry is created. To support the operation of EIM Ontology 2 and EIM Ontology 3, an interactive reprojection of the RDB-based voxel model data from the original coordinate system to the site-aligned coordinate space was required. The implementation of geometric operations such as translation and scaling in the RDB environment is relatively straightforward. Inclusion of the rotation component was required since it would not be reasonable to limit the generative design process to operate exclusively on north-south oriented volumes for any given site. To include the rotation component in the internal transformation function executed in the RDB environment, custom SQL functions were developed. Those functions are used to map the coordinates between the large-scale voxel data and the site-scale coordinate system. Since the vertical location is not influenced by such a transformation, this problem is reduced to a composite transformation in 2D. In computer graphics, geometric transformations are conventionally utilizing homogeneous coordinates since all common transformation operations can be expressed as 3x3 matrices. In result, these operations can be combined by a simple vector multiplication operation. For this reason, the implemented transformation function required the voxel nodal point coordinates to be expressed as homogeneous coordinates. In homogeneous coordinate space a single point is expressed in a 3x1 matrix. Geometric operations of translation and rotation are represented as 3x3 matrices. Transformation between the two coordinate spaces is presented below as Equation 1.

$$\begin{bmatrix} vox_{x'} \\ vox_{y'} \\ 1 \end{bmatrix} = \begin{bmatrix} cos(\alpha) & -\sin(\alpha) & 0 \\ sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & x_{off} \\ 0 & 1 & y_{off} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} vox_x \\ vox_y \\ 1 \end{bmatrix}$$

$$\begin{aligned} &where: \\ vox_{x'} &= \text{x coordinate of reprojected point} \\ vox_{y'} &= \text{y coordinate of reprojected point} \\ \alpha &= \text{rotation angle} \\ x_{off} &= \text{offset in x direction} \\ y_{off} &= \text{offset in y direction} \\ vox_x &= \text{x coordinate of initial point} \\ vox_y &= \text{y coordinate of initial point} \end{aligned}$$

Equation 1: Matrix representation of the transformation required to transform the large-scale voxel data into the site-scale coordinate system space.

The coordinate transformation needed to be implemented within the RDB environment. Since matrix operations are not implemented as a part of the SQL function syntax, coordinate transformation needs to be expressed as a system of linear equations. Linear equations are presented as Equations 2 and 3 below.

$$vox_{x'} = vox_x \cos(\alpha) - vox_y \sin(\alpha) + x_{off} \cos(\alpha) - y_{off} \sin(\alpha)$$
$$vox_{y'} = vox_x \sin(\alpha) + vox_y \cos(\alpha) + x_{off} \sin(\alpha) + y_{off} \cos(\alpha)$$

Equations 2 and 3: Transformation of the large-scale voxel data into the site-scale coordinate system space expressed as a set of linear equations.

The equations presented above were implemented as SQL functions in the RDB environment. For each required level a new SQL table view utilizing these functions was created. Finally, different site-aligned coordinate systems contain data in different resolutions. To facilitate this functionality, a simple aggregation function was used in the definition of the SQL table view. In result, datasets contained in the ECOLOPES Voxel Model can be queried in multiple resolutions and coordinate systems, both directly in the GH environment and indirectly through the EIM Ontologies implemented in the GraphDB environment.

1.3.4 **Integration of voxel data and EIM Ontologies through GraphDB SQL virtualization**

The integration of the ECOLOPES Voxel Model and the EIM Ontology is facilitated through the Ontop Virtualization technology, which is integrated in the GraphDB software solution. This technique is widely applied in commercial applications of GraphDB technology where the graph reasoning capabilities need to be utilized on pre-existing data stored in an RDB environment. In such cases, the effort of data migration from RDB to GDB is minimized by the application of the SQL virtualization technique. The main task in such a virtualization-based workflow is related to the description of how the tables, columns, and primary keys in the RDB map onto graph structure in the GDB environment. On the technological level, such mapping is declared as a set of ODBA/R2RML mappings, written in a single file. This file is uploaded into the GraphDB instance when the RDB/GDB connection is created. This process has been tested to enable the integration between the RDB-based voxel model and EIM Ontology stored in the GraphDB environment. Initial tests showed that for performance reasons file-based SQL databases, such as SQLite, should be avoided. PostgreSQL and GraphDB server instances hosted on the same machine have shown sufficient performance to execute the operations required for the integration between the ECOLOPES Voxel Model and the EIM Ontology. Currently, each voxel model level contained in the RDB can be interactively linked with the GraphDB instance, based on the provided OBDA/R2RML mappings. As a result, the data contained in the RDB-based voxel model can be transparently queried and reasoned using techniques implemented in the GDB environment. Located on the left side of Figure 6 is a screenshot of the GraphDB interface representing the contents of virtualized voxel data. Located on the right side of Figure 6 is a file that contains exemplary OBDA mappings.

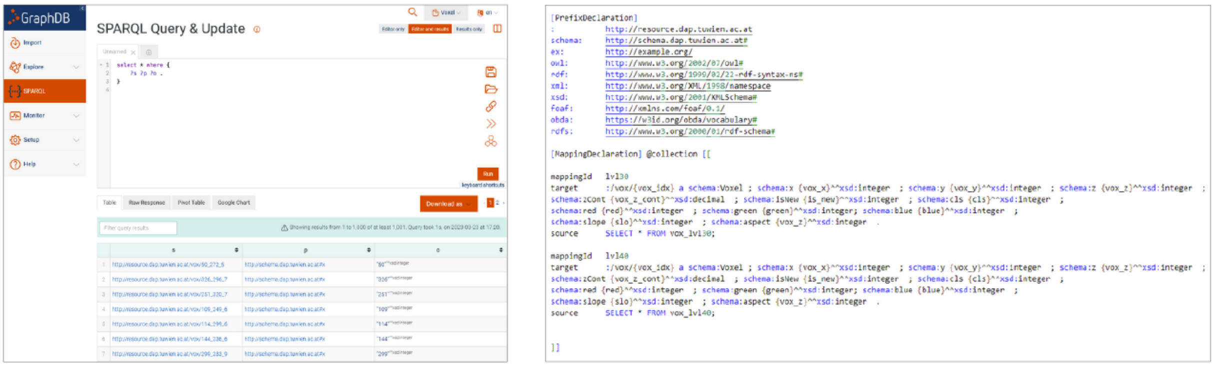


Fig. 6: Left: Screenshot of the GraphDB interface, showing how data contained in the ECOLOPES Voxel Model can be queried and represented in an ontology-based format (RDF triples) Right: Data saved in the RDB-based voxel model can be virtualized in GraphDB, by defining the mapping between the RDB and GDB data structure in an OBDA / R2RML file.

2 INTERACTIONS OF THE ECOLOPES VOXEL MODEL WITH THE DESIGNER AND OTHER COMPONENTS OF THE ECOLOPES COMPUTATIONAL DESIGN FRAMEWORK

The interactions between ECOLOPES Voxel Model, designer and the GCD components are divided into three loops.

Loop 1 facilitates the configuration of *Networks* in a voxelized 3D space, materialized in the Rhinoceros CAD environment. It involves EIM Ontology 1, Rule-Based System 1 (associated algorithms i.e., ASP), and CAD Model 1 as its main components of interaction in the Translational Design Process of selection and distribution. Defining and spatially locating design objectives and implementing design instructions derived from EIM Ontology 1, based on feedback from Loop 2 and Loop 3, are some of the tasks that are addressed.

Loop 2 facilitates the distribution of *Volumes* in a *voxelized 3D space, materialized in the Rhinoceros CAD environment. It in*volves EIM Ontology 2, Rule-Based System 2 (associated algorithms i.e., ASP), and CAD Model 2 as its main components of interaction in the Generative Design Process 1 of volume specification. Guiding the changes in maps (volumetric voxel data) and 3D configuration of volumes, and implementing design instructions derived from EIM Ontology 2, based on feedback from Loop 1 and Loop 3, are some of the tasks that are addressed.

Loop 3 facilitates the generation of *landform* geometry in a voxelized 3D space, materialized in the Rhinoceros 3D CAD environment. It involves EIM Ontology 3, Rule-Based System 3 (associated algorithms i.e., ASP), and CAD Model 3 as its main components of interaction in the Generative Design Process 2 of landform generation. Guiding the geometric articulation of the volume object and implementing design instructions derived from EIM Ontology 3, based on feedback from Loop 1 and Loop2, are some of the tasks that are addressed. Detailed elaboration of the functionalities implemented within these three loops is presented in the report on *D4.2 Interim EIM Ontology*.

The generative computational design algorithms utilize datasets encoded in the voxel models either by directly querying the data in the RDB or by retrieving the virtualized RDB data through the GraphDB interface. The required functionalities implemented in the Loops 1,2 and 3 are described in the following sections.

2.1 Interactions between ECOLOPES Voxel Model, Designer and GCD components

Architectural designers can interact with the ECOLOPES Voxel Model both directly through the dedicated Grasshopper interface and indirectly, while working with other GCD components which are accessing ECOLOPES Voxel Model data in background. Different GCD components are implemented in the three loops, as described in the Deliverables *D4.2 Interim EIM Ontology* and *D5.3 ECOLOPES Computational Model*.

2.1.1 Translational Process: Loop 1

In the first loop, the designer configures *networks* in the 3D viewport of McNeel Rhinoceros software (see report *D5.1 Development Process for ECOLOPES Algorithm*). The node-based programming interface of Rhinoceros software is Grasshopper, which is widely used in architectural design. Continuous validation of the network structure is handled in the background by EIM Ontology 1 (O1), utilizing the GraphDB reasoning functionality (see report *D4.2 Interim EIM Ontologies*). Firstly, the internal constraints related to the spatial configuration of the *User Networks* and the *Ecological Networks* are validated. This process is informed by multiple data layers that are interactively queried from the ECOLOPES Voxel Model (*Dataset Maps)*. Components implemented in the first loop and the role of ECOLOPES Voxel Model in this process is shown in Figure 7.

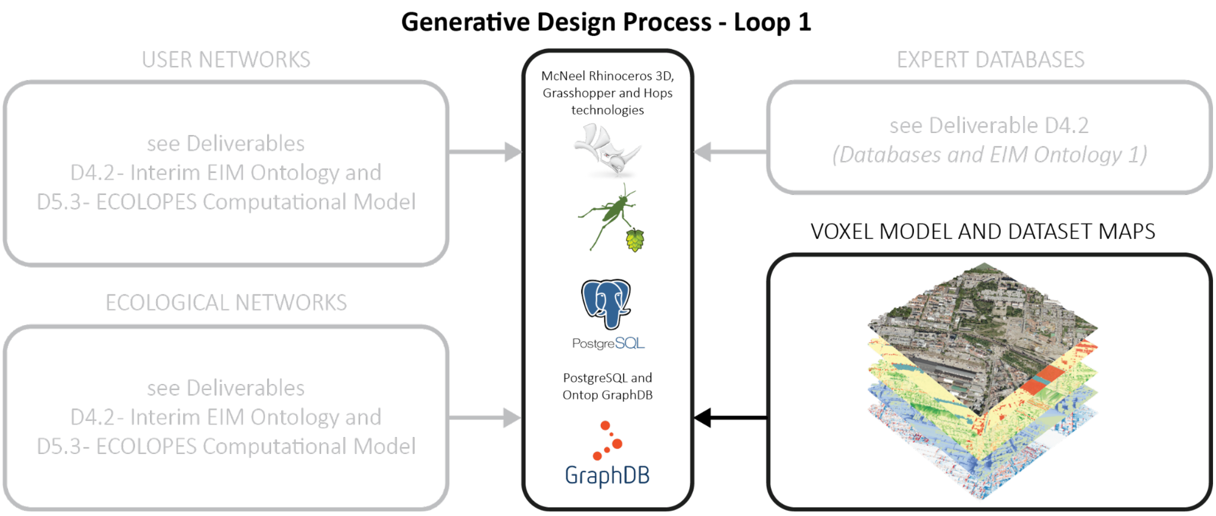


Fig. 7: Illustration of the role of the ECOLOPES Voxel model in the first loop of the Generative Computational Design (GCD) process. The collection of 3D maps (Dataset Maps) is provided through the Ontop SQL Virtualization technology.

The process of creation and modification of *User Networks* is conducted by the designer and the role of the ECOLOPES Voxel Model is to provide relevant spatial data representing environmental conditions on site at the beginning of the design process. As elaborated in report *D4.2 Interim EIM Ontology*, the designer places architectural, ecological, and environmental nodes in the Rhinoceros environment. Ecological and architectural nodes represent planned spatial provisions related to the architecture and ecology. For example, an ecological provision might require high shading availability. In this example, EIM Ontology 1 retrieves the value related to the solar exposure in this location from the ECOLOPES Voxel Model utilizing the SQL virtualization technique. In result, feedback is returned to the designer indicating that the chosen node location does not fulfill the specified requirements for the defined type of provision.

Moreover, to support the designers in the spatial configuration of *networks*, the possibility to directly interact with the ECOLOPES Voxel Model was implemented. Designers can interactively explore datasets contained in the voxel model by visualizing the individual data layers in the Rhinoceros interface. This interface was implemented as a collection of Grasshopper components, presented in Figure 8.

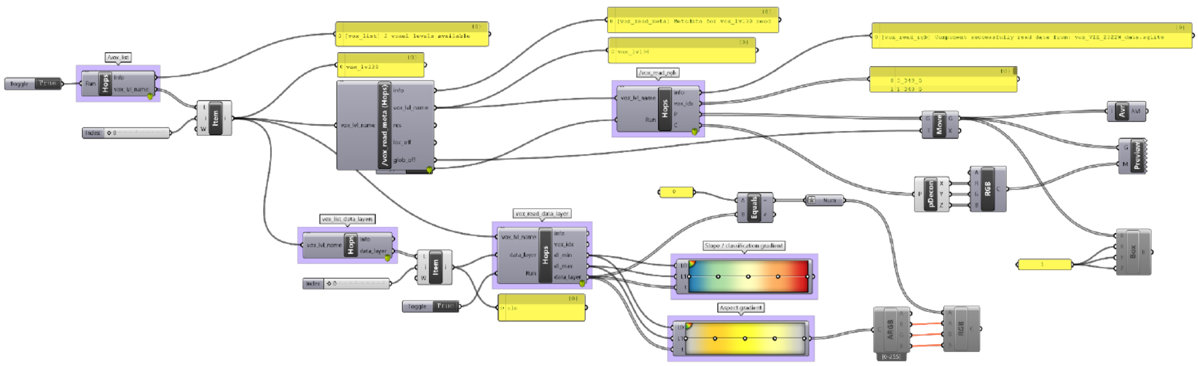


Fig. 8: Example of Grasshopper Hops components implemented to enable the interaction between the designer and the ECOLOPES Voxel Model through the McNeel Grasshopper interface.

The initial integration between the ECOLOPES Voxel Model and the EIM Ontology 1 (introduced technically in Section 1.3.4) has been tested. Placeholder plant data describing three types of plants and their sunlight requirements has been loaded into GraphDB. The left side of Figure 9 shows this dataset consisting of aSunnyPlant, aHalfShadyPlant and aShadyPlant, manually loaded in the GraphDB interface. On the right side of Figure 8a, the representation of the ECOLOPES Voxel Model data in the GraphDB interface is shown. In the middle of Figure 9, an exemplary SPARQL query that utilizes both the dummy plant data and ECOLOPES Voxel Model data is presented. The SPARQL endpoint federation functionality needed to be utilized to enable simultaneous query of two datasets in the GraphDB system.

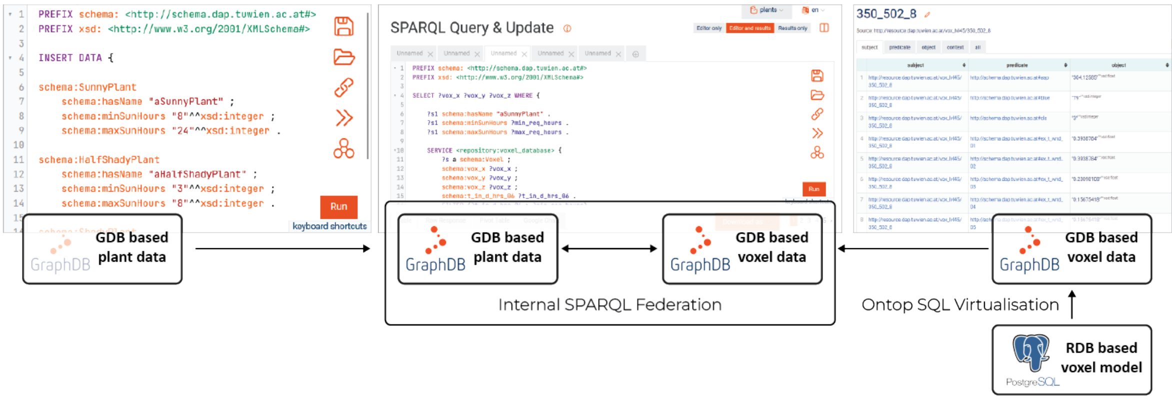


Fig. 9: Initial test of the integration between ECOLOPES Voxel Model and GraphDB. In this example, placeholder data describing sunlight requirements of three types of plant is linked with the data stored in the ECOLOPES Voxel Model. Internal SPARQL federation functionality enables simultaneous query of the two datasets.

This initial test was conducted to determine whether the ECOLOPES Voxel Model can be extended with the query and reasoning capabilities of the SPARQL endpoint, provided by the GraphDB technology. This implies that the results of such an extended query would need to be returned in the format aligned with the structure of the ECOLOPES Voxel Model. This integration was tested via the implementation of a temporary Hops Grasshopper component, which executes a predefined SPARQL Query, presented in Figure 9 above. At the same time, this temporary Grasshopper component transforms the data returned by the SPARQL query into a representation that can be utilized by other components implemented for the interaction with the ECOLOPES Voxel Model. The upper part of Figure 10 shows how the previously introduced components used to visualize ECOLOPES Voxel Model data can be extended with the temporary SPARQL Query component. The lower part of Figure 10 shows how the components shown above can be used to generate a set of 3D voxel maps that illustrate preferential plant locations, based on their solar exposure requirements. From the left, preferential locations for (a) aHalfShady plant, (b) aShadyPlant and (c) aSunnyPlant types.

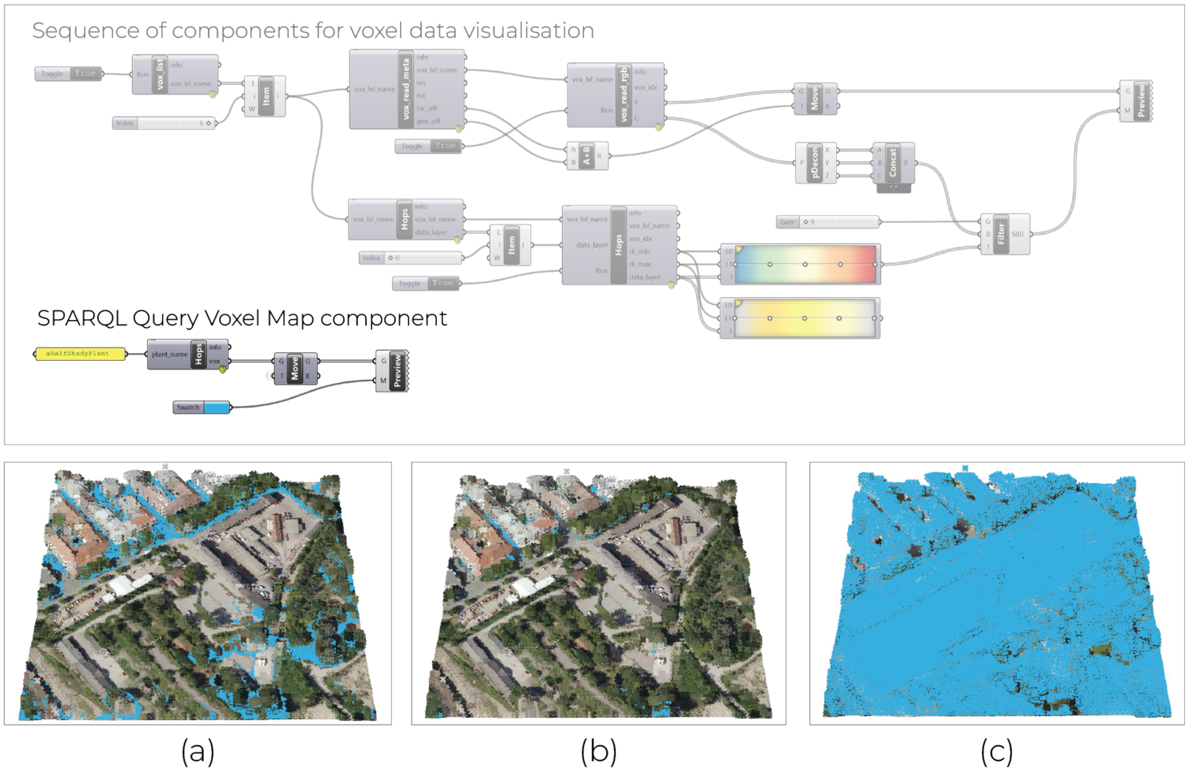


Fig. 10: Integration between the ECOLOPES Voxel Model and an exemplary dataset stored in the GraphDB. Query and reasoning functionalities provided by the SPARQL endpoint can be implemented within the computational setup of the ECOLOPES Voxel Model. Systematic, voxel-based data structuring enables interoperability between the two components, implemented by Grasshopper and Hops.

As mentioned above Grasshopper is a node-based programming interface of Rhinoceros software. Individual components are representing basic functionalities and dedicated algorithms can be built by chaining multiple components together to implement a complex functionality for a given design task (Rutten, 2023). ECOLOPES Voxel Model implementation consists of multiple components that are executing predefined operations in the external Python interpreter and in the RDB environment. Currently, four sequences of components have been outlined for the interaction with the voxel model. Components implementing basic operations, such as listing column names available in an SQL table are utilized in multiple sequences. Given the modular character of this approach, designers can create new component sequences and link the processes outlined in the exemplary sequences with external Grasshopper components. The first sequence implements the functionalities required to read and visualize voxel data as 3D points in real-world colors. The second sequence enables listing, reading and visualizing data layers from a chosen level in a 3D false-color visualization. The third sequence allows the designer to update and insert new data into the ECOLOPES Voxel Model. The fourth sequence introduces the possibility to select and run an SQL query chosen from the predefined set. Implemented SQL queries were constrained to a predefined set, to avoid user mistakes and implement security best practice, related to SQL injection attacks possible in web-facing SQL servers. Advanced users can define new SQL queries in the dedicated configuration file. Those queries are instantly available for execution in the Grasshopper interface.

The introduction of SQL queries enables designers to experiment with the voxel-based data representations and identify promising applications of the voxel modeling approaches. For example, the possibility to efficiently generate 2.5D raster representations of the voxelized geometry was identified. Further applications of filtering and aggregation queries were studied. Notable advantage of this approach is the computational performance of the SQL queries. For example, generation of a 2D top view from a voxel dataset containing 163.812 3D points stored in an SQLite database required only 462ms as compared with an initial Grasshopper implementation that requires multiple hours for completion. This approach was extended to utilize SPARQL queries in the GraphDB environment. The advantage of this extended approach is the possibility to include data that is not available in the voxel model as a part of a query. For example, locations suitable for a plant species described in the GraphDB environment can be queried in a form representing a 2D top view. These possibilities have been further studied in the context of research addressing the role of EIM Ontologies in the design process. Tabular overview of Grasshopper components that were implemented to facilitate the interaction with the ECOLOPES Voxel Model contained in the RDB is presented in a table in Appendix A.

2.1.2 Generative Process: Loop 2 Spatial Organization (Dataset *Volumes*)

As stated above, the generative design process is configured as linked process loops. Loop 2 aids the generation of the spatial organization (volume distribution) for design cases 1 and 2 (*D4.2 Interim EIM Ontology*). Case 1 entails the design of a master plan for the development of a given site. Spatial organization is generated through the distribution of architectural, biomass and soil volumes, which we term for case 1 *primary volumes*. Case 2 entails the design of an individual building for which all constraints are given by a municipal master plan. Since the maximum allowed primary volume is already given by the masterplan, the task is to partition the primary volume into *secondary* and *tertiary* architectural, biomass and soil volumes (see reports *D5.1 Development Process for Ecolopes Algorithm* and *D4.2 Interim EIM Ontology*).

For instance, in case 1 *volumes* are distributed on the selected site for which the ECOLOPES design process is executed. Volumes distributed in Loop 2 are considered as generic and are articulated as cuboid geometry with a fixed edge length that is defined by the designer. Each volume is assigned a predefined class (e.g., architectural volume, biomass volume, etc.). The site is defined as a 3D bounding box, the dimensions of which are defined as multiples of the volume edge size. A detailed description can be found in reports *D4.2 Interim EIM Ontology* and *5.3 ECOLOPES Computational Model*.

The ECOLOPES Voxel Model supports the volume distribution process with data describing pre-existing environmental conditions on the selected site. The datasets contained in the ECOLOPES Voxel Model can be accessed by EIM Ontology 2 through the GraphDB Ontop SQL Virtualisation interface (see section 1.3.4). In the *Volume Distribution* process, EIM Ontology 2 generates the rules that are translated into an ASP program, executed in the Potassco ASP environment (see reports *D4.2 Interim EIM Ontology* and *D5.3 ECOLOPES Computational*

Model). The rules generated in the process capture (1) constraints derived from dataset *networks* that result from Loop 1, (2) site constraints and (3) dataset *maps*, which is voxel data that is interactively queried from the ECOLOPES Voxel Model. The interface between EIM Ontology 2 and the Potassco ASP environment translates the representation of environmental data contained in the ECOLOPES Voxel Model into a format required by the ASP program. This data is merged with other design constraints and sent to the ASP environment to initiate the computation of the possible volume distributions (answers contained in the set). For example, distribution of biomass volumes can be informed by the shading availability, retrieved from the ECOLOPES Voxel Model. Figure 11 shows the role of the ECOLOPES Voxel Model in this process. Further details can be found in report *D4.2 Interim EIM Ontology*.

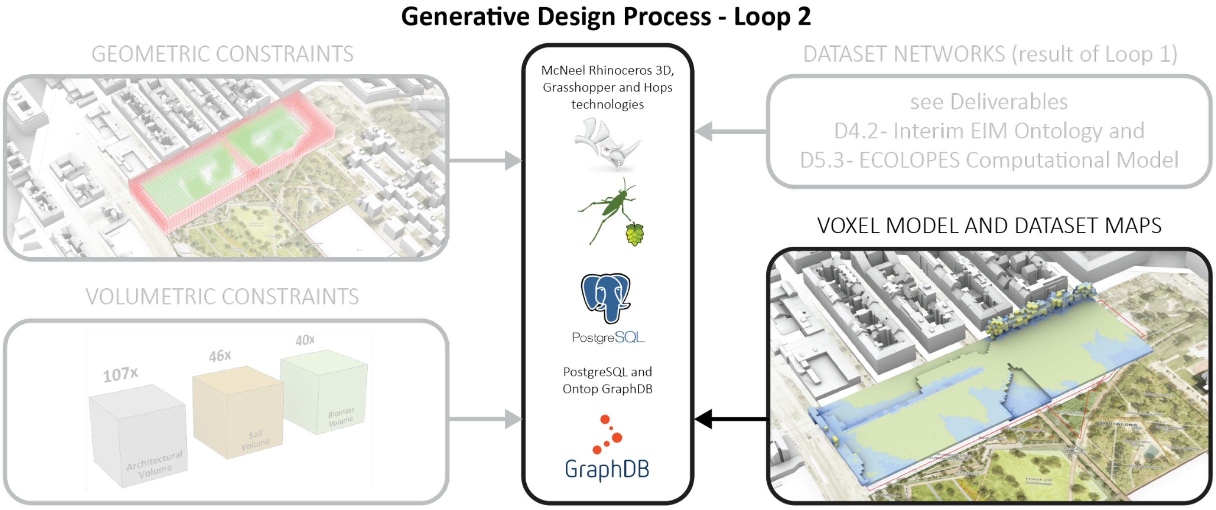


Fig. 11: Illustration of the role of the ECOLOPES Voxel Model in Loop 2 of the Generative Process. The data available in the voxel model is mapped onto the site-specific coordinate system and exposed to Ontology 2 through the Ontop SQL Virtualization interface.

Spatial organization via distribution of the different types of volumes operates within the site boundaries (3D bounding box) and is constrained by the resolution, which is defined by the designer. Data provided by the ECOLOPES Voxel Model needs to be matched with the dimensions and resolution of the site bounding box. Based on the 3D bounding box dimensions and constraints of the design process outlined for the Vienna Case Study, four resolutions (3, 6, 9 and 12 meters) were selected. To accommodate for this functionality a range of dedicated voxel model levels were introduced. Figure 12 shows the levels implemented in the ECOLOPES Voxel Model and the computational techniques that enable interoperability between the ECOLOPES Voxel Model, EIM Ontology 2 and Algorithm 2. Integration of the three components required the introduction of computational procedures to map the voxel data onto the site aligned coordinate space in a chosen resolution. For example, a resolution of 3m can be chosen to test how the *volume distribution process* translates a designer-created set of *User Networks* into a distribution of generic cuboid volumes. The designer indicates in the *User Network*, that a particular location needs to contain an ecological provision related to a tree species that requires high sun exposure. In this process the role of ECOLOPES Voxel Model is to provide the data describing environmental conditions related to solar exposure, which is interactively recomputed to match with the site-aligned coordinate space at the selected resolution. The detailed description of the computational procedure required for this functionality is described in section 1.3.3.

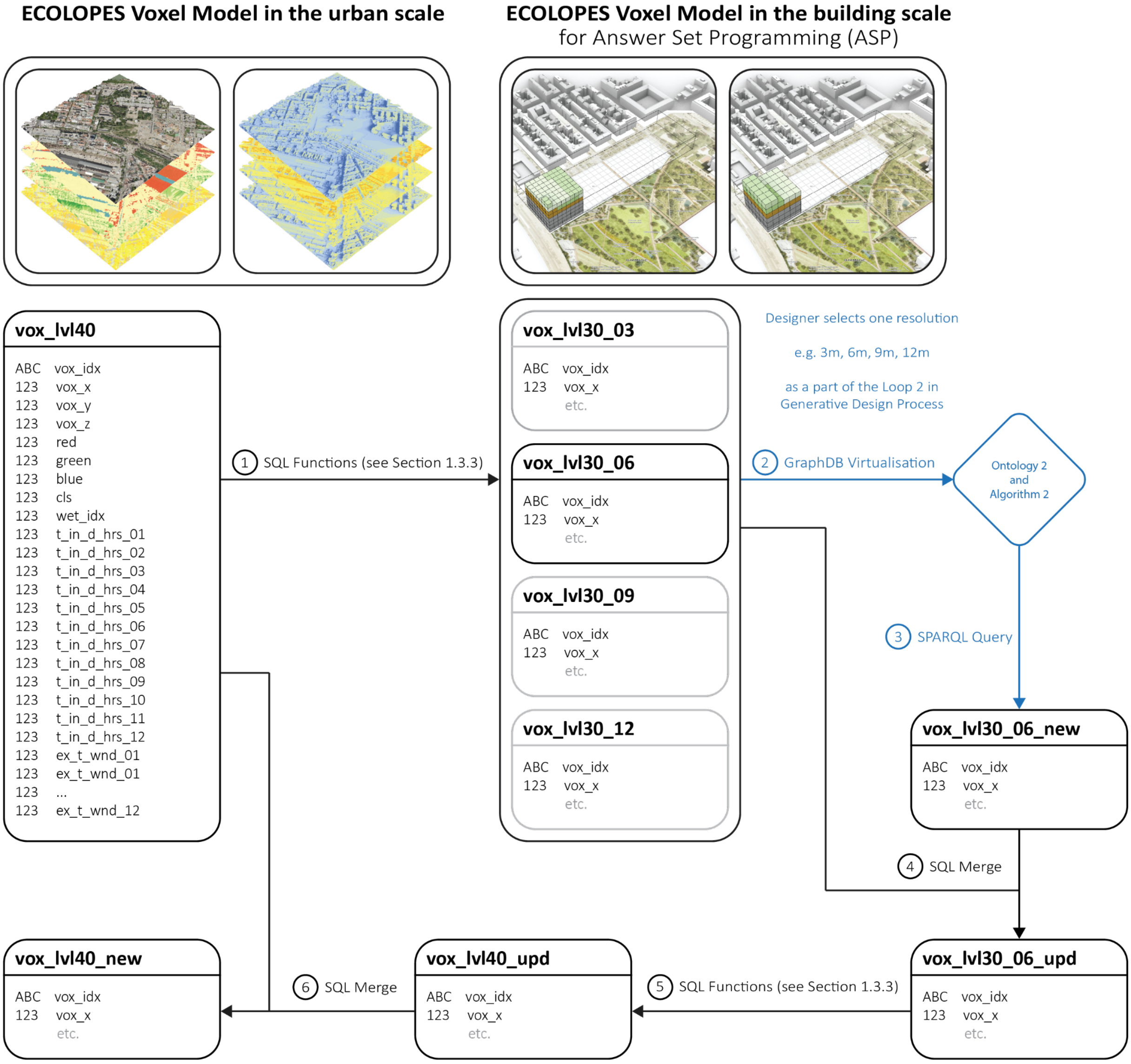


Fig. 12: Detailed representation of the computational process that was developed to enable multi-scalar integration of voxel data, linking base *datasets written in the global coordinate system (vox_lvl40) and site-specific* coordinate *system required for the Volume Distribution process (vox_lvl30_03, vox_lvl30_06 etc.). This figure illustrates how the methods for systematically updating and merging voxel levels described in Figure 5, are applied in the context of Loop 2.*

2.1.3 Generative Process: Loop 3 Geometric Articulation (Dataset *Landform*)

Loop 3 aids the generation of the geometric articulation (dataset *landform*) for design cases 1 and 2. Case 1 entails the design of a master plan for the development of a given site. In the context of this research this entails geometric articulation of site and buildings leading to what we term *primary landform*. Landform can therefore be coherently designed across the entire site, with all volumes adhering closely to the landform scheme. For Case 2 this entails *secondary* and *tertiary landform* (hierarchical nesting of terrain features) to enable accessibility and appropriate provisions for specified species to specified parts of the building envelope (see reports *D5.1 Development Process for Ecolopes Algorithm* and *D4.2 Interim EIM Ontology*). A detailed description of this functionality is provided in report *D4.2 Interim EIM Ontology*. Figure 13 shows the components implemented in the third loop and the role of ECOLOPES Voxel Model in this process.

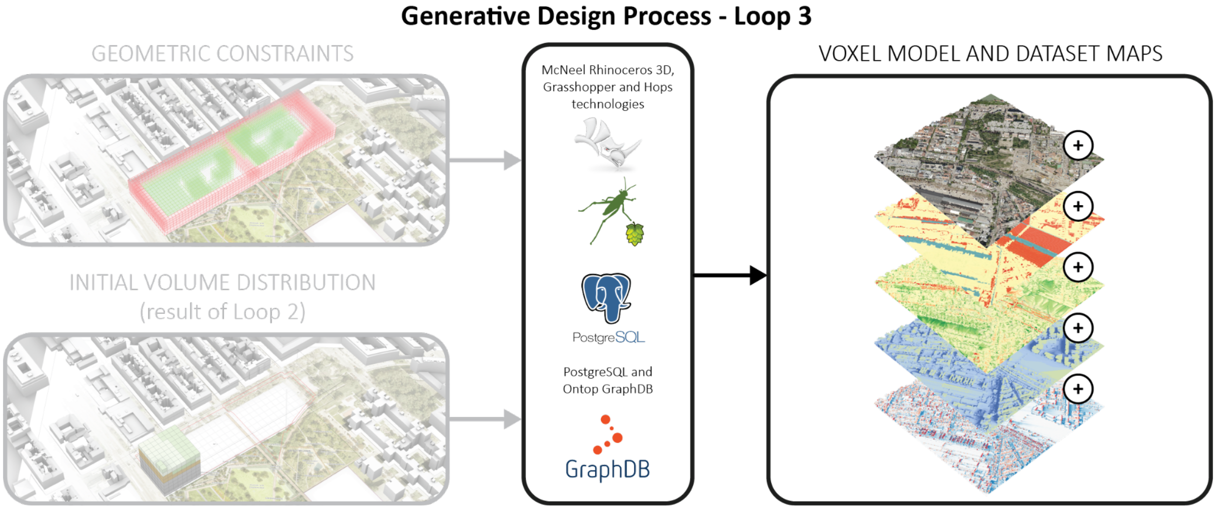


Fig. 13: Illustration of the role of the ECOLOPES Voxel Model in Loop 3 of the Generative Process. The data available in the voxel model is exposed to EIM Ontology 3 through the Ontop SQL Virtualization interface. Datasets provided by the ECOLOPES Ecological Model and ECOLOPES Regional Model can be included in the ECOLOPES Voxel Model and exposed to EIM Ontology 3.

The integration between the ECOLOPES Voxel Model and the EIM Ontology 3 implemented in the Ontop GraphDB environment is facilitated through the Ontop SQL virtualization technique, described in section 1.3.4. Data available in the ECOLOPES Voxel Model can be accessed by EIM Ontology 3 to facilitate the generation of geometric articulation of sites and buildings (dataset *landform*). This algorithmic procedure is operating at multiple levels of hierarchy (primary, secondary, and tertiary landform). For this reason, data contained in the voxel model needs to be queried at multiple resolutions. The technical description of the multi-scalar data available in the ECOLOPES Voxel Model is described in section 1.3.2. It has not yet been determined at which resolutions and in which coordinate system this algorithmic procedure will be executed. A collection of voxel model levels (vox_lvl20_x) has been reserved for the algorithm implemented as a part of Loop 3. Currently the functionality related to the custom coordinate spaces functionality is flexible enough to accommodate for a later choice of resolution and orientation that is required by the algorithm implemented in Loop 3. Technical details of this functionality are described in section 1.3.3.

The primary role of the ECOLOPES Voxel Model in the third loop is to align the outputs of the GCD process with the structure of the inputs used to initiate the GCD process. After the final outcomes of the GCD are generated, their geometric representation will be converted to match the structure of the ECOLOPES Voxel Model. Corresponding environmental analysis data needs to be generated to match the information content of the inputs retrieved from the

ECOLOPES Voxel Model. For this reason, an analogous geospatial analysis workflow needs to be executed, based on the voxel data that describes site conditions resulting from the GCD process. Finally, voxel data representing the geometric and environmental conditions of the design outcomes produced by the GCD will be exported. This exported data will be made available for the ECOLOPES components that are implemented in the next steps of the ECOLOPES computational framework (see Fig. 1 and deliverables *D3.1 Prototype technical requirements report*, *D3.2 Draft ECOLOPES platform architecture*, and *D3.3 Interim ECOLOPES Platform Architecture*).

2.2 Interactions between ECOLOPES Voxel Model and other computational components

Interactions between the ECOLOPES Voxel Model and other components implemented as a part of the ECOLOPES computational framework are facilitated by a range of dedicated interfaces. A description of different datasets and methods required to convert the data into the representation compatible with the ECOLOPES Voxel Model is provided in the following section. The underlying data integration approach partially utilizes interfaces allowing for interaction between the ECOLOPES Voxel Model and EIM Ontology, described in detail in *D4.2 Interim EIM Ontology*. Furthermore, the Ecological Model and KGF are introduced and future directions to initiate possible integration between these components and the ECOLOPES Voxel Model are discussed.

2.2.1 ECOLPES Voxel Model and Databases

Datasets contained in external databases can be converted into a representation compatible with the ECOLOPES Voxel Model. Geospatial datasets in the form of continuous and discrete grids are best suited for such conversion. For example, geospatial simulation and analysis data describing environmental conditions found on site can be easily represented in the ECOLOPES Voxel Model. Open-source GIS software packages, such as SAGA GIS (Conrad et al., 2015) or QGIS (Open-Source Geospatial Foundation Project, 2020), can be used to generate geospatial analysis datasets representing solar exposure, topographic wetness conditions or seasonal wind exposure conditions. The voxel modeling approach has in this case both advantages and limitations. The voxel-based data integration approach is efficient when large quantities of homogenous 3D-grid based spatial data is available. For datasets of other types, direct import into the GraphDB environment might be a better possibility. Figure 14 illustrates different data structuring approaches implemented as a part of tasks 5.1, 5.2, 5.3 and 4.2.

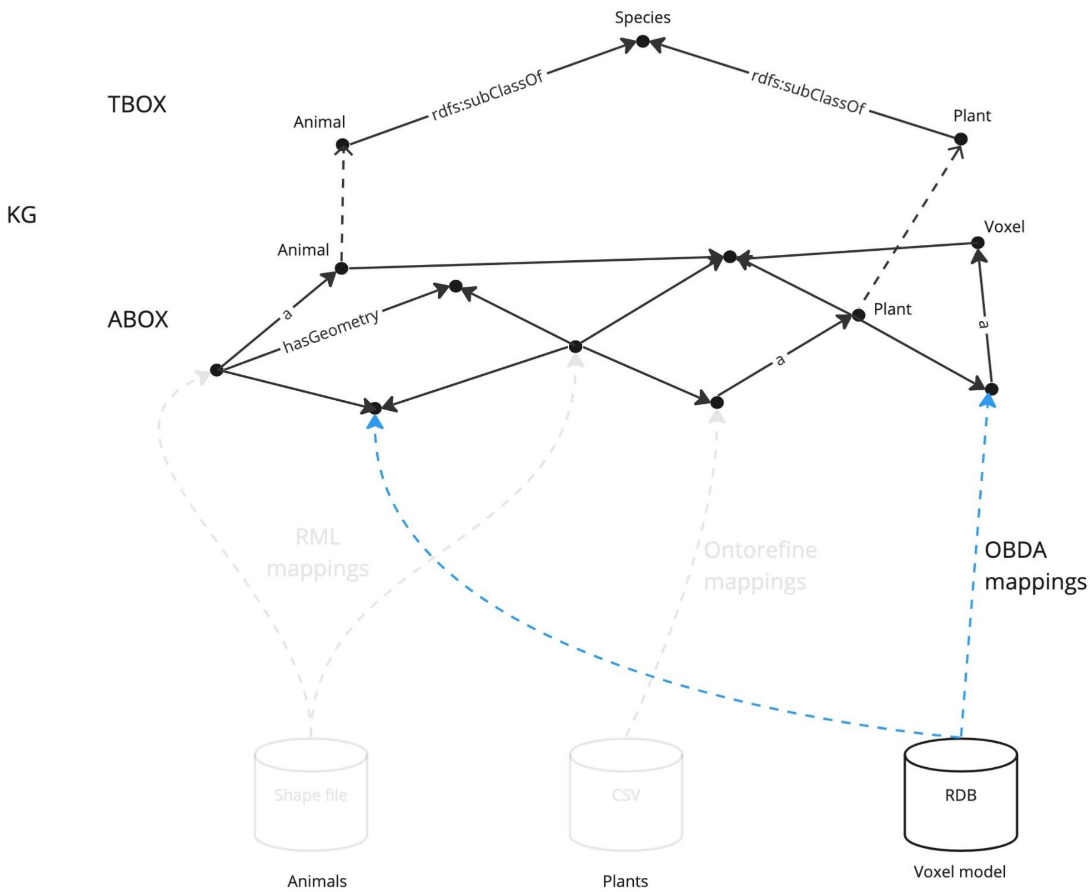


Fig. 14: Heterogeneous data is mapped and converted into a graph form in KG (ABox) by using different mapping languages such as RML, Ontorefine and OBDA. Some of the data is virtualized meaning data is not copied (Voxel model), while some data is copied/materialized. The user can query the KG as a unified interface that encompasses and integrates different datasets combining the results, and, if required, reasoning on top using TBox statements.

The integration of different disciplinary datasets within the RDB structure enables performant queries, utilizing extensively tested logics of SQL language. At the same time, a few limitations of the voxel-based modeling approach have been identified. Firstly, non-continuous data sets (3D grids with only a few points containing data) are not suited for the inclusion in the ECOLOPES Voxel Model. Missing data needs to be explicitly handled, which negatively impacts the performance of the RDB / GDB environment. When the available data is small in quantity (hundreds to tens of thousands) and is not structured as a continuous 3D grid, the advantages of voxel-modeling cannot be fully utilized. The ECOLOPES Voxel Model enables the designer to interactively explore data layers encoded in the RDB, by applying false-color mapping (heat maps) on the 3D points in the Rhinoceros 3D environment. Data that is not suitable for the continuous 3D heat map visualization is not suited to be encoded in the ECOLOPES Voxel Model. Such datasets are better suited to be directly imported into the GraphDB, when the data is directly linked to concepts already represented in the EIM Ontologies. Examples of the datasets that are better suited for direct inclusion in the GraphDB are Regional Plant Pool, Regional Animal Pool, Local Plant Pool, and Local Animal Pool. Further details are presented in report *D4.2 Interim EIM Ontology*.

2.2.1 ECOLOPES Voxel Model and Ecological Model

The implementation of the ECOLOPES Ecological Model was reported in Deliverable *D4.1 Preliminary EIM Ontology.* The ECOLOPES Ecological Model integrates a modified version the FATE-HD plant model (Boulangeat et al., 2012, 2014, 2021) with an original implementation of both animal and soil-microbiota sub-models (see report *D4.1 Preliminary EIM Ontology*). Moreover, definition of PFGs and AFGs based on functional traits data was required to produce exemplary input data. Execution of the Ecological Model requires inputs related to soil classification (see report *D4.1 Preliminary EIM Ontology*), PFGs and AFGs (see report *D4.1 Preliminary EIM Ontology*), as well as the spatial description of site conditions, including geometry, shading and soil depth values. It is already integrated in the 3D CAD Rhino/ Grasshopper, thus ecological analysis of 3D building envelopes is possible now (*see report D3.3 Interim ECOLOPES platform architecture*). It should be noted that data exchange between the Ecological Model and other technical components is made possible through the Knowledge Generation Framework experiments (*see report D3.3 Interim ECOLOPES platform architecture*). The following section discusses similarities between the data structures required to run the Ecological Model and the data contained in the ECOLOPES Voxel Model. Currently the ECOLOPES Voxel Model contains data describing site-specific conditions of the location chosen for the Vienna Case Study. At the end of the ontology-aided generative computational design process, the data in the ECOLOPES Voxel Model is updated to reflect the outcomes of the design process. A detailed description of the datasets contained in the ECOLOPES Voxel Model is available in section 1.3.1. The datasets allowed all ECOLOPES partners to evaluate and experiment with the structure of the RDB-based voxel model, i.e., importing discipline specific data. Initial tests were conducted in the early stages of developing the RDB-based voxel model. Experiments were conducted to evaluate if the overall structure of the data utilized for local and regional ecological modeling implemented in the WP4 can be aligned with the structure of the RDB-based voxel model. Currently, both the Ecological Model and Regional Model are being developed. These two models are addressing different resolutions and are using partially different types of input and output data. Based on the existing specification of data structure implemented so far, a first technological evaluation of the possibility to establish an interface between the Regional Model and ECOLOPES Voxel Model has been discussed.

As discussed in deliverables D4.2, D3.3 and the current progress of the tasks T4.1 – T4.4, T3.3 and T3.4, the Ecological Model is implemented 1) in a 3D CAD system (Rhino/ Grasshopper) by McNeel, SAAD and TUM, and 2) as a standalone executable file, generated from the source code written in the C++ programming language (see report *D4.1 Preliminary EIM Ontology*). The Ecological Model requires as inputs (1) spatial data from a 3D building envelope, such as soil classification, soil depth, shading, parameters linked to the form of the building (2) and definition of PFGs and AFGs. Outputs are biomass and PFGs in a resolution of 1 cubic meter over time. D3.3 reported that soil depth, soil type, shading, inclination, biomass and PFG data is stored in the JSON file format to be analyzed by a Machine Learning Model developed by McNeel. Data structure was optimized and transformed for the ML model that reveals patterns between different input parameters as well as it can make predictions. Further details can be found in Deliverables D4.2, D3.2, D3.3, as well as in the future reports and scientific publications.

2.2.2 ECOLOPES Voxel Model and Knowledge Generation Framework

The ECOLOPES Ecological Model and the Knowledge Generation Framework have been developed in close collaboration by TUM, SAAD, MCNEEL, UNIGE, and TECHNION. The following section briefly introduces the current state of the KGF (reported in *D3.3 Interim ECOLOPES Platform Architecture*) and a roadmap towards a connection between ECOLOPES Voxel Model in the KGF. The KGF is a series of computational experiments that link architectural, environmental, and ecological parameters to generate knowledge about the relationships between architectural form, the environment and ecological performance. The ECOLOPES Grasshopper plugin enables KGF experiments (D3.3). These experiments use as an input a 3D model of a building envelope and output species abundance (soil, plants, animals) in a resolution of 1 cubic meter. Furthermore, metadata such as shading values, soil depth, building geometry (e.g., surface inclination) and biomass, etc. are computed and correlated in a Machine Learning model (D3.3). Thus, the KGF approach aims at defining computational rules and thresholds of Key Performance Indicators (KPIs) for decision support to be used in a generative design and optimization process.

ECOLOPES Voxel Model and the EIM Ontologies have the potential to support each other, for instance, by way of KGF output (rules for design) that can be utilized by the EIM Ontologies and ECOLOPES Voxel Model. Currently both the KGF, the EIM Ontologies and ECOLOPES Voxel Model are further developed and there are possibilities for a future integration for the ECOLOPES platform (WP3).

3 VOXEL DATA FOR THE OPTIMIZATION PROCESS

The datasets contained in the voxel model can be utilized in the processes implemented within the optimization workflow (WP6). At the end of the process implemented in the WP4 / WP5 workflow, both CAD-based and voxel-based representation of the geometry will be saved and passed to the components positioned later in the ECOLOPES Computational Design Workflow (Fig. 1). The results of the GCD process will be exported as a 3D CAD model in the Rhinoceros format (.3dm). Detailed description of the outcomes generated in the GCD process is described in D5.3 ECOLOPES Computational Model. Corresponding voxel-based data will be exported as a single SQLite database file, containing domain-specific data related to the environmental and ecological properties of the design outcome at the end of the ontology-aided generative computational design process. This numerical information can be computed as fitness objectives for the multi-objective optimization. As described in the sections above, these fitness objectives are the KPIs that have been computed in the KGF (WP3). Additionally, the ontological correlations will aid in the definitions of KPI priorities and design strategies. The resulting optimized 3D design alternatives and metadata could also be appended into the database file to enable an iterative process between the generative and optimization design phases.

4 VALIDATION, TRL, FAIR PRINCIPLES, OPEN QUESTIONS AND FUTURE RESEARCH

This section addresses validation of the ECOLOPES Voxel Model, the required TRL, adherence to the FAIR principles, as well as open questions and future research.

4.1 Validation

The different components of the ontology-aided generative computational design process (EIM Ontologies, ECOLOPES Voxel Model, ECOLOPES Computational Model including all algorithms) are closely linked through numerous interfaces. For this reason, we have included a detailed elaboration of the validation process that is described in report *D5.4 ECOLOPES Computational Model*. To avoid considerable repetition across current reports this subsection only summarily addresses the validation of the ECOLOPES Voxel Model and the directly related datasets.

The following aspects were or will be validated:

1. ECOLOPES Voxel Model functionality
2. Interfaces between the components of the ontology-aided generative computational design process: functionality and interoperability
3. Designer & ECOLOPES Voxel Model: Usability of the dataset maps in the context of a design project
4. Designer & ECOLOPES Voxel Model: Usability of the conceptual approach in a practice context
5. Designer & ECOLOPES Voxel Model: Usability of the technical approach in a practice context

The functionality of the ECOLOPES Voxel Model was tested internally by the development team throughout the stages of the development of the voxel model, including the alpha version to ensure that the required TRL was reached (see section 4.2). A final validation step is currently in preparation in the context of the Vienna Case Study, which will be undertaken in the period from October 2023 to the end of January 2024.

The functionality of and interoperability/interfaces between the components of the ontology-aided generative computational design process have been tested, in as far as these interfaces have already been technically developed. Some of the interfaces are still in development and will need to be tested internally by the development team when they have reached a testable state. Validation of all key interfaces will take place in the context of the Vienna Case Study, which will be undertaken in the period from October 2023 to the end of January 2024.

Since the ECOLOPES approach, concepts, methods, and computational tools are developed for robust use in practice a series of validation steps needed to be developed that concern the interaction between the design and the components and the entire process of the ontology-aided generative computational design process. The coverage of validation related to the software implementation is representative of Technology Readiness Level 4. According to the BRIDGE2HE H2020 TRL self-assessment tool (TRL Assessment | NCP Portal Management | Horizon Europe NCP Portal, 2022) this level is defined as the alpha version of the software tested by the software development team. Further development of this approach is considered and for this reason, conceptual and methodological validation of the approach might be extended. Conceptual and methodological validation might extend beyond the scope of the software implementation to include a selected group of end-users (master-level architecture students). This advancement of validation on the conceptual level is intended to support the possible future development of the software components to address higher TRLs after the completion of the ECOLOPES Project.

Currently the GCD approach is being validated in a master-level design studio context at TU Wien, realized in distance learning mode. Participants are working in an uncontrolled software environment, facilitated by individual laptop computers and residential-grade internet connections of unknown geographic spread. For these reasons, extensive validation of the software implementation is constrained by a range of technological challenges spanning beyond the TRL 4. According to the BRIDGE2HE H2020 TRL self-assessment tool (TRL Assessment | NCP Portal Management | Horizon Europe NCP Portal, 2022), the inclusion of selected end-users in controlled environments is assigned to TRL 6, while the inclusion of end-users in non-controlled environments is representative TRL 7. For example, to facilitate higher TRLs controlled remote access to the functionalities implemented as a part of the software solution is necessary. This would require introduction of dedicated computational infrastructure, facilitating data encryption and user authentication at a level of individual interfaces between the GCD components.

Some technological constraints of the software implementation are related to the current state of the development represented by McNeel Hops software components. Currently McNeel Hops technology is primarily developed for internal use in controlled environments of a single institution. For example, the current implementation of McNeel Hops component allows external computation within a local network (LAN), based on unencrypted communication with a group of servers, identified by their IP addresses. This communication is facilitated through an unsecured HTTP endpoint and the Hops client implementation (distributed as compiled binary through McNeel Package Manager) does not facilitate any form of authentication or enforce data-in-transit encryption. It needs to be noted that such implementation is representative for the main use case of the McNeel Hops component and introduction of functionalities spanning beyond the main use case would need to be evaluated. Alternatively, functionalities such as SSL data-in-transit encryption of user credential validation could be handled at the level of computational infrastructure (e.g., multiple levels of HTTP proxying). Such infrastructure-related implementation would need to be separately investigated and would require substantial investment in terms of the computational infrastructure, expert knowledge and personal costs required to implement and continuously operate such infrastructure. The described implementation would be representative of TRL 6-7 and might be addressed in future research to be conducted after the completion of the ECOLOPES project.

This concerns the dataset *maps* from a conceptual perspective (see *D5.1 Development Process for ECOLOPES Algorithm* and *D4.2 Interim EIM Ontology*). Here the question is whether architects with a first degree (BA) can conceptually access and incorporate the dataset *maps* in their designer workflow. Since site analysis and the use of related software i.e., various simulation tools in GIS and CAD environments are already part of common practice in architecture, it seems reasonable to assume that there will be no major conceptual problems. Nevertheless, the conceptual integration of the dataset maps in the ECOLOPES design workflow for design generation was successfully tested in the context of a series of master-level design studios at TU Wien (see *D5.4 ECOLOPES Computational Model Validation*). While the workflow used in the master-level design studios increasingly involved aspects of data structuring and correlation i.e., between architectural, environmental, and ecological data, the full ECOLOPES Voxel Model has yet not been tested in these studios. The aim is to first test and validate the components of the ontology-aided generative computational design process in the context of the Vienna Case Study, as an extended form of alpha testing representative of TRL4 conducted by the software development team. Upon successful conclusion of the Vienna Case Study the ECOLOPES Voxel Model will be conceptually and methodologically introduced to the curriculum of the master-level design studios in the final two runs during the summer semester 2024 and the winter semester 2024-25 (see *D5.4 ECOLOPES Computational Model Validation*). Given the technological constraints described in the previous paragraphs and the formal requirements related to the TRL4, only the elements that are required to introduce the ECOLOPES Voxel Model on the conceptual and methodological level were introduced in the distance learning environment of the ECOLOPES Design Studio.

4.2 **Technology Readiness Level**

The research outcomes presented in this report are based on software implementation of the alpha version that was tested internally by the development team. The researchers that were involved in the development of components directly interfacing with the ECOLOPES Voxel Model have been continuously evaluating the implemented functionalities. The interaction with the EIM Ontologies has been implemented through the SQL visualization technique available in GraphDB (see section 1.3.4). Interactions between the ECOLOPES Voxel Model and designers are primarily implemented utilizing the McNeel Rhinoceros 3D / Grasshopper ecosystem. An Overview of currently implemented components and their description is presented in Appendix A. Consortium participants who are not directly involved in work that utilizes the data contained in the ECOLOPES Voxel Model have been contacted and invited to participate in the process of testing the components at key development stages. Their contribution provided an interdisciplinary perspective and shaped the direction of the ECOLOPES Voxel Model development. According to the TRL self-assessment tool implemented as a part of the BRIDGE2HE H2020 project (TRL Assessment | NCP Portal Management | Horizon Europe NCP Portal, 2022), this level of technological advancement is representative of the Technology Readiness Level 4.

4.3 **Adherence to FAIR Principles**

To adhere to the FAIR principle and promote research reproducibility, datasets produced during this study will be published in one of the most recognizable open access data repositories. According to the practices observed in the field, the Zenodo repository (European Organization for Nuclear Research & OpenAIRE, 2013) has been identified as a repository that promotes discoverability of datasets published in the field of architectural design. The effort related to ensuring data interoperability has been initiated as a part of the data exchange functionality required for the integration of the ECOLOPES Voxel Model data with the components implemented in the later in the ECOLOPES computational workflow (Fig. 1). The initial dataset described in section 1.3.1 and the voxel-based representation of the results created at the end of GCD process (see section 3) will be published in the Zenodo repository.

4.4 Open questions & Future Research

While some interfaces with other components of the ontology-aided generative computational design process still need to be finalized, the ECOLOPES Voxel Model has reached the intended stage of its development. The open questions offered below therefore consider open questions in the context of future research after the completion of the ECOLOPES research project.

The Ecolopes Voxel Model currently contains data from several specified sources in specified formats pertaining to a limited number of disciplines or domains. The related datasets are contained in the voxel model as (1) inputs to the design process and (2) outputs of the design process for each design variant.

4.4.1 Inputs into the Design Process: Data-sources, Domains and Data Correlation

With an increasing understanding of the complexities involved in environmental and ecological planning and design it is likely that the range of data sources, data formats, and involved disciplines and domains will increase. This may impact on the way the data is structured within the voxel model and introduce a greater complexity to data correlation as a distinct functionality of the voxel model as a custom-configured project-specific database. In the steps succeeding the ECOLOPES Project, ongoing search for further fields of study able to support data-integrated design processes will be continued. Research disciplines that are able to contribute insights related to the understanding of complex relations between the data-informed processes in design and planning across different scales will be considered. Research disciplines are often using distinct representations of data and its integration with the structure of the voxel model might pose a challenge. Identification of a promising field of study will be followed by the evaluation of disciplinary analysis and simulation methods. Next, an evaluation aimed at investigating whether the disciplinary methods are providing spatially explicit data that could be represented within the structure of a voxel-based system will be conducted. Finally, initial experiments related to the integration of such datasets in the data-integrated voxel-based design workflows will be executed.

4.4.2 Outputs of the Design Process: Informed Local Databases

Currently, the design output for each design variant consists of a CAD Model, related voxel data, and ontological outputs. Upon completion of the ontology-aided generative computational design process, the data related to the design variants selected for optimization is passed on to the next step in the process. Design variants that are not selected are currently not considered in terms of potential further use. Given that the generated data is representative of possible solutions that could satisfy a different set of benchmarks, requirements or KPIs, it would seem useful to store this data and keep it accessible for further use. In future steps succeeding the ECOLOPES Project, reproducibility and computational effort related to the generation of large amounts of design variants will be evaluated. This computational effort will be evaluated against the storage requirements needed to represent a large collection of design outcomes and the related voxel-based representation of their environmental performance criteria. Regarding the design generation process, performance of the design generation, analysis and evaluation algorithms will be evaluated, and areas of possible improvement will be indicated. Regarding the combined CAD and voxel-model storage requirements, alternatives and possible improvements will be studied. The comparison of the two evaluations is expected to lead to the establishment of strategies for systematic recording of the intermediate design solutions emerging from the ontology-aided generative computational design process. One of the considered possibilities is a hierarchically structured set of databases that are included within or closely linked with the ECOLOPES Voxel Model.

5 Publication Plan

We recently submitted a scientific article for peer-review to Frontiers of Architectural Research journal that focuses on the conceptual framework for an ontology-aided generative computational design process for ecological building envelopes. In the article we describe the conceptual approach and the development of the related components of the ontology-aided generative computational design process (EIM Ontologies, ECOLOPES Voxel Model, ECOLOPES Computational Model).

Secondly, we are in the process of preparing a scientific article on the specific development and utilization of the "ECOLOPES Voxel Model as a *spatial-knowledge representation schemata* in the context of an ontology-aided generative computational design process for ecological building envelopes". We aim to submit this article to *Architectural Science Review* (Taylor & Francis) or to *Technology | Architecture + Design* (Taylor & Francis).

Finally, we will prepare a scientific article on "Validation of the ECOLOPES ontology-aided generative computational design process for ecological building envelopes", which will report the results of the Vienna Case Study, which will commence in October 2023 and be finalized in January 2024.

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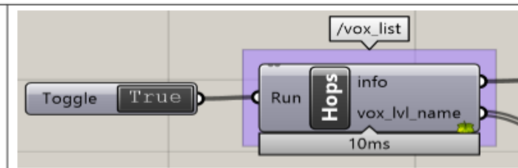
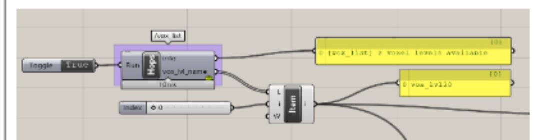
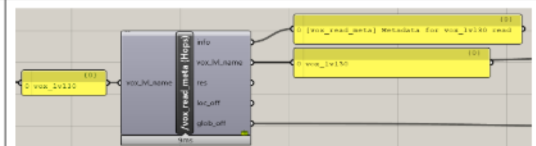
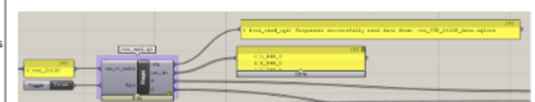
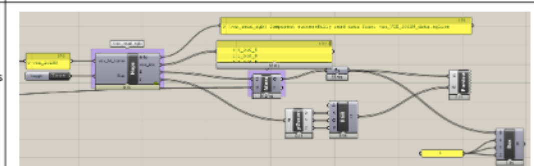
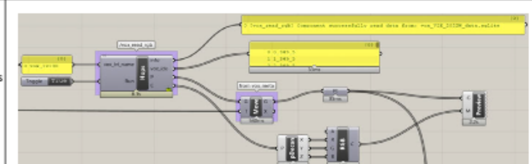
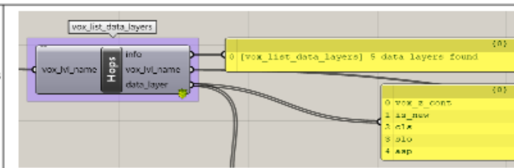
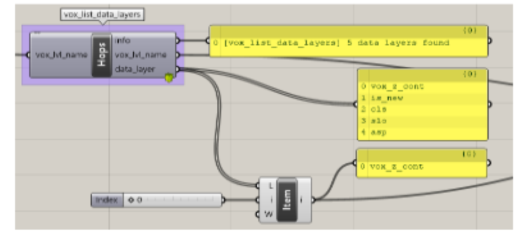
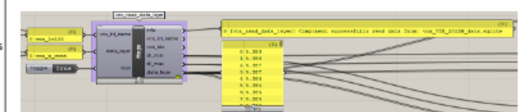
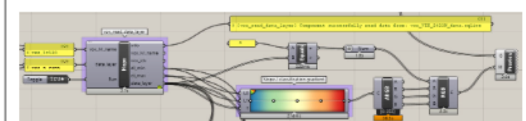
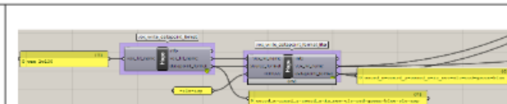
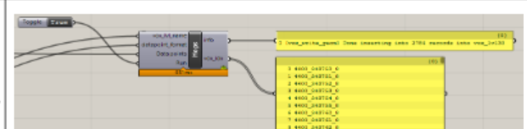
APPENDICES

Appendix A

Overview of the implemented Grasshopper component

	Case	Component name	User Story	Query	User Action after Query	Requirements	Component implementation (Grasshopper canvas screenshot)
A	**Working with voxel model levels**						
A1	Listing voxel model levels available in the database	vox_list	User wants to list available voxel model levels (describing site location and resolution) available in the database.	List voxel levels available in the database (tables and table views), non-relevant tables are filtered out	Choosing voxel model level to work with	• Access to the RDB that stores the voxel data • Reading and filtering of database tables	
A2	Choosing voxel model level to work with	vox_list + GH Item	User wants to choose voxel model level (describing site location and resolution) to work with.	not applicable native Grasshopper function to select a single item from the list	Reading global properties of a voxel model level	• Access to the RDB that stores the voxel data • Reading and filtering of database tables • User feedback - choosing an item - level of the voxel model (GH)	
A3	Reading global properties of a voxel model level	vox_read_meta	User wants to get the resolution and relative locations of data written in a voxel model level to work with the data in Rhino	Read a record from vox_meta that matches selected voxel model level	Reading 3D locations of nodal points from stored in the voxel model	• Access to the RDB that stores the voxel data • Reading and filtering of database tables • User feedback - choosing an item - level of the voxel model (GH)	
B	**Working with voxel model nodal points 3D locations**						
B1	Reading 3D locations of nodal points from stored in the voxel model	vox_read_rgb	User wants to load the 3D locations of the voxel nodal points for the chosen voxel level to visualize the points in Rhino 3D viewport	Read 3D locations of nodal points stored in the chosen voxel model level	Reading voxel data layer, real-world color or visualizing nodal point coordinates	• Access to the RDB that stores the voxel data • Reading and filtering of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model (GH)	
B2	Reading real-world colors of the nodal points stored in the voxel model	vox_read_rgb	User wants to load real-world colors stored in the voxel model	Read real-world colors of nodal points stored in the chosen voxel model level	Visualizing real-world colors assigned to nodal point coordinates	• Access to the RDB that stores the voxel data • Reading and filtering of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model (GH)	
B3	Reading and visualizing real-world colors stored in the voxel model	vox_read_rgb + GH RGB color + GH Preview	User wants to visualize real-world colors in the Rhino 3D viewport	not applicable native Grasshopper functions to create a list of colors and preview geometry	not applicable	• Access to the RDB that stores the voxel data • Reading and filtering of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model (GH)	

	Case	Component name	User Story	Query	User Action after Query	Requirements	User Interface Sketch
C	**Working with voxel model data layers**						
C1	Listing voxel model data layers available in the chosen voxel model level	vox_list_data_layers	User wants to list available voxel data layers.	List voxel data layers available in the chosen voxel model level, non-relevant layers are filtered out	Choosing a voxel model data layer to work with	• Access to the RDB that stores the voxel data • Reading and filtering of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model (GH)	
C2	Choosing a voxel model data layer to work with	vox_list_data_layers + GH Item	User wants to choose voxel model data layer to work with.	not applicable native Grasshopper functions to create a list of colors and preview geometry	Loading data from a single data layer available in the voxel model	• Access to the RDB that stores the voxel data • Reading and filtering of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model and data layer (GH)	
C3	Loading data from a single data layer available in the voxel model	vox_read_data_layer	User wants to load the data saved in a voxel model data layer.	Read data contained in a chosen data layers form the active level in the voxel model	Visualizing voxel data layer as colored heatmap in the Rhino 3D viewport.	• Access to the RDB that stores the voxel data • Reading and filtering of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model and data layer (GH)	
C4	Visualizing voxel data layer as colored heatmap in the Rhino 3D viewport.	vox_read_data_layer + GH Gradient + GH RGB color + GH Preview	User wants to visualize voxel data layer as colored heatmap in the Rhino 3D viewport.	not applicable native Grasshopper functions to create a list of colors and preview geometry	not applicable	not applicable	

D	**Modifying voxel model geometry**						
D1	Listing data layers available in a voxel model level and choosing which dataset will be updated	vox_write_datapoint_format vox_write_datapoint_format_filter	User wants to list data layers available in a voxel model level and letting user which dataset he wants to add will be updated	List voxel data layers available in the chosen voxel model level, filtering out non-relevant, geting user input which data layers need to be updated	Choosing which data layer needs to updated with new data (e.g. Simulation data) available in Rhino	• Access to the RDB that stores the voxel data • Reading, filtering and writing of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model and data layesr (GH)	
D2	Adding new nodal points to the chosen voxel model level (3D nodal points locations) and associated data	vox_write_geom	User wants to add new nodal points and data to the voxel model.	Write 3D locations of nodal points, real-world colors and available data layers stored in the chosen voxel model level	not applicable	• Access to the RDB that stores the voxel data • Reading, filtering and writing of data saved in a table that represents the chosen level • User feedback - choosing an item - level of the voxel model, data layers, Rhino 3D Point geometry and associated data (GH)	

Appendix B

Published literature review on the applications of voxel models

architecture

Review

A Scoping Review of Voxel-Model Applications to Enable Multi-Domain Data Integration in Architectural Design and Urban Planning

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Abstract: Although voxel models have been applied to address diverse problems in computer-aided design processes, their role in multi-domain data integration in digital architecture and planning has not been extensively studied. The primary objective of this study is to map the current state of the art and to identify open questions concerning data structuring, integration, and modeling and design of multi-scale objects and systems in architecture. Focus is placed on types of voxel models that are linked with computer-aided design models. This study utilizes a semi-systematic literature review methodology that combines scoping and narrative methodology to examine different types and uses of voxel models. This is done across a range of disciplines, including architecture, spatial planning, computer vision, geomatics, geosciences, manufacturing, and mechanical and civil engineering. Voxel-model applications can be found in studies addressing generative design, geomatics, material science and computational morphogenesis. A targeted convergence of these approaches can lead to integrative, holistic, data-driven design approaches. We present (1) a summary and systematization of the research results reported in the literature in a novel manner, (2) the identification of research gaps concerning voxel-based data structures for multi-domain and trans-scalar data integration in architectural design and urban planning, and (3) any further research questions.

Keywords: voxel; computer-aided design; volumetric modeling; data-integrated-design workflows; review; bibliometric analysis

check for updates

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1. Introduction

Computer-aided design (CAD) emerged in the 1950s at the intersection of the computer and engineering sciences. Today, it bears central importance in the disciplines of engineering informatics and architectural design and urban planning. CAD is defined as "the use of computers to aid in the creation, modification, analysis, or optimization of a design" (Lalit Narayan et al., 2013, p. 3) [1].

Voxel models emerged in the computer science field in the 1960s and their initial applications in the field of CAD were studied in the late 1980s by Granholm (Granholm et al., 1987) and Jense (Jense et al., 1989) [2,3]. Voxel models are referred to as "spatial-knowledge representation schemata" (Srihari, 1981) [4], implying that they can serve as spatial data structures to encode the knowledge utilized in knowledge-based design processes. This review examines the existing applications of voxel models in the fields of architecture, spatial planning, computer vision, geomatics, geosciences, manufacturing, and mechanical and civil engineering, to identify their possible role in interdisciplinary and knowledge-based design processes.

Section 1.1 outlines the scope of this review. The first paragraph outlines the problem statement and research delimitation. The second paragraph discusses the aim and rationale of this literature review. The third paragraph introduces the research aims followed by the research objectives. This semi-systematic literature review is structured chronologically. Based on the chronological order, Section 1.2 identifies the early definitions of voxels, to establish the review context. Section 1.3 highlights the current state-of-the-art applications of voxel models in the field of engineering sciences. Section 1.4 describes how key parameters for this semi-systematic literature review were selected. Section 1.5 shows how key parameters were translated into a methodological approach. Section 2.1 describes the data collection, search, and selection processes and eligibility criteria. Section 2.2 presents the narrative review methodology. Section 2.3 introduces the scoping-literature-review methodology. Finally, Sections 2.3.1–2.3.5 report details describing the method implementation developed for this semi-structured review required to assure research transparency.

1.1. Outline of the Review Scope

Today, voxel models are used in various scientific fields to study man-made and natural artifacts [5–7]. This is often carried out in relation to the spatial context and environment [8–10]. Adopting this approach in architectural design and urban planning can help to advance the addressing of interdisciplinary design problems, such as increasingly complex sustainability requirements [11,12]. However, the digital-architecture and urban-planning context lacks multi-domain data integration approaches and data structures that can facilitate the embedding and visualization of the spatial representation of knowledge in computer-aided urban planning or architectural-design processes. This article focuses on the potential role of voxel models as "spatial-knowledge representation schemata" (Srihari, 1981) [4] to address this gap. This involves examining voxel models as multi-domain data structures for architectural design and urban planning. More specifically, this paper addresses voxel applications in computer-aided design related to architectural design and spatial planning, covering a wide range of voxel model applications, spanning design, simulation, and the analysis of architectural objects across scales.

Literature reviews focusing on the voxel concept in relation to CAD processes are sparse. Recent thematic reviews focused on the voxel applications for the structural analysis of CAD models [5], four-dimensional (4D) printing [6], and additive manufacturing [7]. The potential of voxel models in the CAD field was stated in one of the earliest literature reviews addressing these models [3]. The first literature review addressing application of voxel models in CAD conducted by Jense (Jense, 1989) discussed applications, including prosthesis design and interactive surgical and tool path planning in digital manufacturing processes. Historically, possible voxel model applications were derived from 3D data sources available at that time, such as computed tomography (CT) and magnetic resonance imaging (MRI). At present, 3D scanning techniques, such as photogrammetry, time-of-flight cameras, and light detection and ranging (LiDAR) are widely adopted across a wide range of scientific disciplines. These technologies can be used to three-dimensionally capture objects that differ in scale by orders of magnitude. At the same time, LiDAR sensors are utilized in the computer vision discipline to capture objects commonly found in building interiors and urban scenes. These technological advancements led to the emergence of novel voxel model applications in CAD, in the construction industry [8], solar radiation modeling in forested areas [9] and in species distribution modeling [10]. However, an interdisciplinary semi-systematic literature review that integrates the elements of bibliometric analysis to scope different voxel applications has not yet been conducted. While significant amounts of research concerning the voxel model application in medical sciences exist, a detailed comparison between the application of voxel models in medical studies and in the CAD field is beyond the scope of this study. Applications of voxel models in medical studies are based on data collection techniques such as CT and MRI imaging, and do not present substantial novelty for a scoping literature review addressing the field of architectural and urban planning. This is largely due to the scale of objects studied in this field, which encompasses buildings as well as urban and natural landscapes.

This review addresses the following objectives:

- Identification of the scope of existing voxel model applications in the context of CAD and linked fields, based on existing interdisciplinary approaches and categorization of the identified approaches based on the dominant sub-discipline related to the interdisciplinary field of CAD;
- Analysis of each identified category to identify the existing discipline-specific applications of voxel models that can offer a key utility to the field of knowledge-based computational methods and tools in architecture and urban planning;
- Discussion of novel approaches to voxel models as spatial-knowledge-representation schemata in the context of computational architectural design and urban planning;
- Identification of further research questions based on the outcomes of the semi-systematic literature review.

The methods selected for this review reflect these objectives. The first objective is addressed through a narrative literature review methodology. The emergence of voxel models is traced by searching for the earliest voxel definition. The reference tracing strategy is used to create an initial understanding of the scope of the voxel model applications. Scoping literature methodology is used to identify the scope of the research addressing the application of voxel models in the CAD context. This step concludes with the definition of thematic categories expressed as clusters in the bibliographic network. The resulting categorization is further studied and synthesized by utilizing the narrative review methodology, thereby addressing the third research objective.

1.2. Emergence of the "Voxel" Term

This section examines the definition of, and the theory related to, voxel models, through a literature study, to identify the earliest publications mentioning or referencing voxel models. The term "voxel" emerged in the 1970s in the field of computer science to describe methods for volume rendering and early experiments in the 3D visualization of medical images. Early attempts to work with 3D grids containing data can be traced back to the time preceding the wide availability of computers. Efforts to generate 3D visualizations of datasets constructed by utilizing medical imaging were published as early as 1970 [13]. In this context, terms such as "three-dimensional image" (Greenleaf et al., 1970) [13], "three-dimensional array" (Artzy et al., 1980) [14], and "volume rendering" (Drebin et al., 1988) [15] are often interchangeably used with the term "voxel". In the 1980s, a series of works [14,16,17] were published that sought to systematize concepts related to 3D arrays and the introduction of voxels as a mathematical concept.

Srihari [4] explained that "the term voxel is short for "volume element" analogous to pixel for "picture element" in two dimensions". He also pointed toward the potential interdisciplinary application of voxels, "ranging from organs interior to the human body to rock microstructures (. . .)" [4]. The growing availability of computers led to a convergence of the theoretical concepts related to voxels and volumetric rendering techniques. Arie Kaufman [18–20] explained that "each voxel is a unit of volume and has a numeric value (or values) associated with it that represents some measurable properties or independent variables of a real object or phenomenon." [21]. In the CAD field, early voxel applications were studied by Jense and Huijsmans and initially related to 3D-object reconstruction and visualization based on multiple two-dimensional (2D) sections [22]. Jense and Huijsmans presented a literature review that outlined pioneering voxel applications in the CAD context [3].

At the beginning of the 1990s, the term "voxel" was widely recognized in the field of computer graphics and primarily linked to solid modeling and spatial-partitioning representation [23] (p. 549). Subsequently, voxels were recognized as standalone concepts in the field of computer graphics related to the field of volumetric models [24] (p. 349). Finally, a shift from the analytical to the representational character of voxels occurred, whereby "voxels have gone in and out of favor for rendering, especially in entertainment" [24] (p. 349). However, the early definition of voxel models as "spatial-knowledge representation schemata" [4] is of particular interest for this literature review. Voxel-based spatial data integration and further abstraction toward spatial knowledge representation might indicate a possibility for further development of voxel models that could lead toward knowledge-based and data-integrated design and multi-domain decision support for architectural design and urban planning. To gather detailed insights, an in-depth literature review is needed to understand the diverse disciplinary approaches that can contribute to using voxel models as knowledge representation schemata in the CAD context.

1.3. Contemporary Voxel Applications in the CAD Field

Voxel models are used to study the properties of constructed objects ranging in scale from the physical properties of a building material to the environmental properties of urban neighborhoods. They also serve to integrate different spatial data representations. This approach can be instrumentalized for knowledge-based and data-integrated design and multi-domain decision support in architectural design and urban planning. To prepare the grounds for this, a scoping review encompassing a selected range of disciplines related to the CAD field is needed, to derive the possible future directions for interdisciplinary applications of voxel models in architectural design and urban planning.

Kaufman et al. explained that a "voxel is a unit of volume and has a numeric value (or values) associated with it that represents some measurable properties or independent variables of a real object or phenomenon." [21] Srihari, who primarily works in the fields of pattern recognition, machine learning (ML), and computational forensics, stated that "developing systems for processing and displaying these [3D] images has revealed the need for developing new data structures, and more generally, for developing spatial-knowledge representation schemata" [4]. The "spatial knowledge" term is used both in the contexts of cognitive science and artificial intelligence (AI). Galton [25] offered a detailed elaboration of the spatial knowledge representation in the AI context. In the CAD context, Jense stated that "it is useful to note (...) the duality that exists between the interpretation of voxel models as sets of cuboid volume cells, or as sets of 3D points, each representing a discretized point-sample, taken from some continuous space" [3]. The early voxel definitions are different from the common understanding of voxels as collections of boxes arranged in a 3D grid related to the cuboid representation of voxels used, for instance, in computer games. In general, voxel models containing numeric variables describing the properties and variables of real objects or phenomena are data structures that encode spatial knowledge.

1.4. Identification of Key Parameters and Suitable Review Methodology

A general distinction between systematic, semi-systematic and integrative literature reviews was introduced by Snyder [26]. Semi-systematic literature reviews can be conducted "when wanting to study a broader topic that has been conceptualized differently and studied within diverse disciplines, [which] can hinder a full systematic review process" [26] (p. 334). This methodology addresses the practical constraint where "to review every single article that could be relevant to the topic is simply not possible" [26] (p. 335). Snyder elucidated that "a potential contribution [of a semi-systematic literature review] could be, for example, the ability to map a field of research, synthesize the state of knowledge, and create an agenda for further research or the ability to provide an historical overview or timeline of a specific topic" [26] (p. 335). According to Snyder, semi-systematic literature reviews require adaptation and the development of customized approaches for each study. Transparency of the process and the appropriate coverage of literature can be achieved through the development of individual standards and detailed research plans. As a result, such a method can very effectively provide answers to research questions addressing a widely defined research scope and overcome the limitations of the more narrowly defined systematic literature reviews [26] (p. 336). Methods applied in semi-systematic literature reviews "often have similarities to approaches used in qualitative research in general (...) [and are] usually followed by a qualitative analysis" [26] (p. 335). Based on this description, this literature review can be classified as a semi-systematic review. Regarding the choice of methods, we considered Paré and Kitsiou [24] (p. 169) who further distinguish literature review methods. For the qualitative part of this semi-systematic literature review, we chose the scoping review method. Quantitative analysis was covered by the narrative literature review method. Paré and Kitsiou [27] (p. 169) provided an overview of the methodological requirements for scoping and narrative literature reviews. However, example literature reviews implementing this methodology in the field of architectural design and urban planning are sparse. A notable exception is the study of Ullah [28], who proposed a "simplistic yet reproducible" method for systematic reviews, based on the PRISMA guidelines [29], to construct a conceptual framework for studies of the built environment. Table 1 compares the critical parameters of six literature reviews [30–35] that are similar in scope and address different CAD-related domains, to identify the methodological state of the art in the field.

Table 1. Overview of the literature reviews related to the CAD field that apply a similar methodology. The critical parameters are presented in columns. Each studied review is evaluated in relation to the identified parameters.

	Datasets, Tools, and Methods				Analysis Types		
	Databases Used *	**Screening Reported**	**Deduplication Reported**	**Software Tools ***	**Keyword Co-Occurrence**	**Keyword Burst Analysis**	**Yearly Publication Trend Analysis**
Sharifi et al. [30]	WoS	no	no	VOS CS	yes	yes	yes
Guo et al. [31]	WoS	no	no	VOS CS	yes	yes	yes
Al-Mashhadani et al. [32]	Sco	yes	yes	VOS	yes	no	yes
Sharifi [33]	WoS	no	no	VOS SciM	yes	no	yes
García-Leónet al. [34]	Sco	no	no	VOS Bibl	yes	yes	yes
Makabateet et al. [35]	Sco	yes	no	VOS	yes	no	no
Tyc et al. (this study)	WoS Sco	yes	yes	VOS NLP	yes	yes	yes

* WoS—Web of Science database; Sco—Elsevier Scopus database; VOS—VOSViewer software; SciM—SciMAT software; Bibl—Bibliometrix software; and NLP—natural language processing (computational technique).

The table shows that simple keyword search strategies are used, and the time span often covers multiple decades. Methods such as keyword co-occurrence analysis and the yearly publication trend are frequently utilized. At the same time, the inclusion of more than one data source, screening, and deduplication is rarely reported. Echchakoui [36] suggested using both Scopus (Sco) and Web of Science (WoS) databases, while Liberati et al. [29] advocated the inclusion of gray literature, referring to preprints and other publications not indexed in the most popular databases. The method used in this study adopted the PRISMA guidelines for the scoping-literature-review methodology addressing the interdisciplinary field of CAD and the identified shortcomings. To decide on the time span for this literature review, key publications were identified and mapped onto the timeline shown in Figure 1.

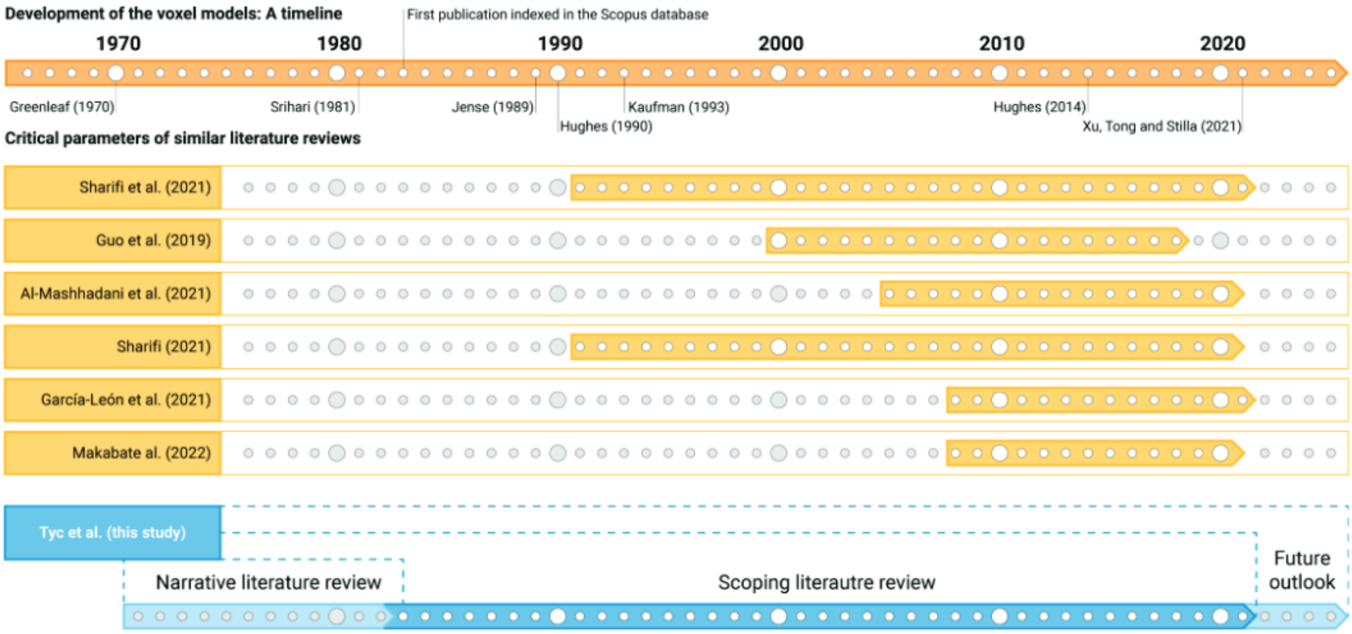

Figure 1. Timeline comparing the time periods of literature reviews from similar disciplines [30–35]. The reviews listed in the table are related to the interdisciplinary field of study covered by this publication, although none of the reviews address the topic of voxel models directly. The time span for the scoping review part in this study is chosen based on this comparison. The periods for the narrative parts of this review are chosen based on the initial research summarized in the voxel-model-development timeline at the top [3,4,8,13,21,23,24]. This figure is available in Supplementary Materials (Figure S1) as a high-resolution, full-page illustration.

1.5. Outline of the Review Scope

While a range of discipline-specific reviews have been published, no scoping review investigating the possible intersections among disciplinary approaches to voxels exists. The existing methods related to the literature reviews in different CAD-related domains were studied, and are summarized in Table 1. Based on the listed references, a keyword co-occurrence analysis was undertaken by utilizing VOSViewer as a software tool for "constructing and viewing bibliometric maps" [37]. This analysis was performed to understand the knowledge components and structure and research trends [38], and to map the trends in the research field development [39].

The initial screening showed that 82% of the 56.052 publications related to voxels was published in the field of medicine. To address this issue, an ML and natural language processing (NLP)-based screening method was developed to identify the publications relevant to the scope of this study. The method builds on the algorithms implemented in state-of-the-art open-source software developed for bibliometric analysis and systematic literature reviews. The applicability of existing open-source literature-review tools, such as revtools [40] and ASReview [41], was investigated herein. However, their application in this interdisciplinary scoping review was unsuccessful because they operate on the assumption that reviewers are starting the review process with a priori knowledge of the exact scope of the study. For example, in the ASReview, reviewers were asked to select some papers that were within the scope of the study and some papers that were outside it. This selection was used to suggest the records for reviewer classification in the next stages. While such a strategy can be useful in systematic reviews, the initial paper pre-selection can increase the bias risk. In this scoping literature review, the exact definition of the scope is the study result, not the a priori assumption made by the reviewers. The topic-modeling-based classification method implemented in revtools was selected in this context. The constraints related to the manual choice of the topic count and the dataset size were identified. The topic-modeling algorithm implemented in revtools required making choices regarding the topic count, which directly affected the result quality. In the context of this scoping literature review, this arbitrary defined parameter can increase the risk of introducing bias. Therefore, the iterative coherence score method of choosing the optimal number of topics was identified in the literature [42]. The dataset used in this scoping literature review comprised 117,908 records, and was two-to-three orders of magnitude larger than the datasets conventionally used in the systematic literature reviews conducted with revtools. The iterative character of the coherence score method and the long processing times of this implementation are currently limiting the applicability of revtools in similar scoping literature reviews. To address these issues, the initial classification was derived from a widely recognized literature database and iteratively validated by the reviewers supported by the computational techniques implemented in ASReview and revtools. The initial classification resulted in literature collections dominated by medicine-related publications unsuitable for quantitative analysis. Based on the published scientific description of the algorithms implemented in the ASReview software, the functionalities needed for this study were implemented as described in the Materials and Methods Section. The scoping literature review was complemented with the elements of a narrative literature study to gain an initial understanding of the scope of the voxel model applications and the existing disciplinary approaches. The narrative literature review methodology was also used for a detailed study of the clusters generated by the keyword co-occurrence analysis. These clusters are grouping disciplinary applications of voxel models used to initiate an in-depth analysis of the possible contributions of discipline-specific voxel model applications to CAD design and urban planning.

2. Materials and Methods

2.1. Data Source Description

The dataset used herein was created from the Web of Science Core Collection and Elsevier Scopus databases, which were searched for all publications containing the word "voxel" in title keywords or the abstract. Gray literature was retrieved from the CORE database [43], using the same search criteria. The database search resulted in a dataset containing papers published between 1981 and 2021. A subset of the Sco dataset containing classification data was used in the training step of the AL-based record screening process. In the next step, a dataset for the keyword co-occurrence analysis was created by classifying and merging the complete Sco and WoS datasets. Finally, the CORE dataset was classified, and the relevant publications were added to the final dataset used in the expert evaluation phase. Figure 2 presents detailed information about the size of individual datasets and the publication counts used in the final dataset.

The eligibility criteria were defined after the dataset retrieval, based on the manual reviewer's evaluation of the dataset quality. The initial inclusion criteria were set to limit the publications to quantitative study types (i.e., journal and conference papers, books and book chapters, and review and data papers), considering the quantitative character of the keyword co-occurrence analysis. Publications containing incomplete metadata, particularly the keyword and publication-date fields, were rejected, due to the keyword-co-occurrence analysis requirements. Those that did not contain publication dates (e.g., preprints) and other types of gray literature were reintroduced into the study by merging the CORE database after the keyword-co-occurrence analysis step. In the last step, reviewers were required to summarize the identified clusters based on the detailed study of the relevant publications; hence, the dataset was limited to English publications.

The preliminary study showed that 82% of the research publications concerning voxels were related to medical sciences. This was calculated based on the Scopus All Science Journal Classification Codes (ASJC Codes), which were not available for all publications in the Scopus database. This limited the method's applicability to 77% of the records from the Scopus database. The ASJC Codes assigned multiple research disciplines to each publication, thereby allowing the preliminary exclusion of publications related to medical studies. Figure 3 shows the results of this preliminary study.

2.2. Narrative Review Methodology

The elements of a narrative literature study were introduced herein to extend the timeline of the reviewed literature and trace back the emergence of publications on voxels and the initial concepts that drove the voxel model development. This was performed to facilitate the search for the early and interdisciplinary definitions of the voxel models. Narrative literature-review methods combined with the reference-tracking method were applied to identify the publications that would otherwise not be found through a systematic database query. Furthermore, narrative elements were used to conduct a detailed analysis of the clusters generated by the keyword co-occurrence analysis.

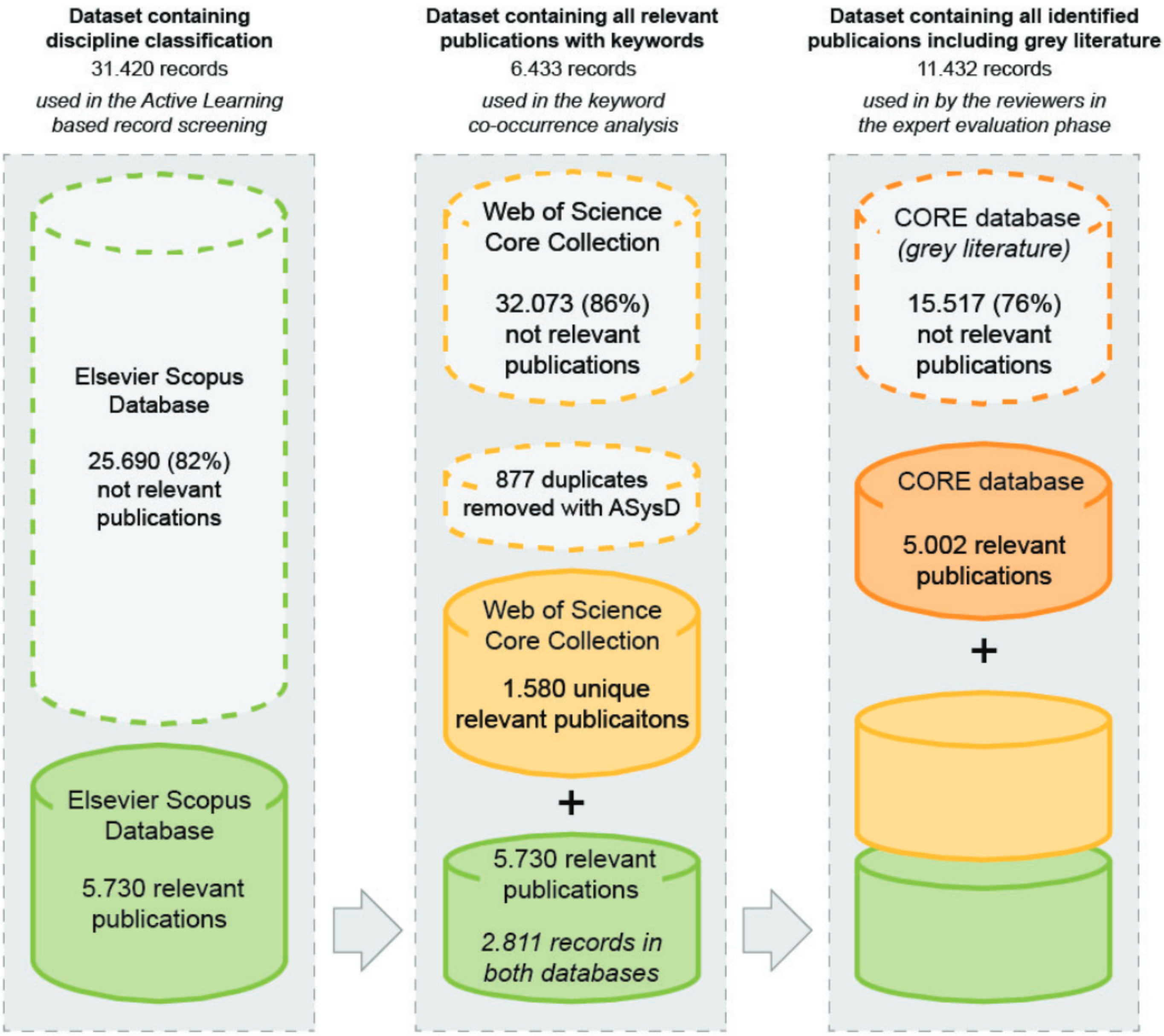

Figure 2. Datasets constructed different steps of this and the distribution of relevant publications in the Web of Science, Elsevier Scopus, and CORE databases.

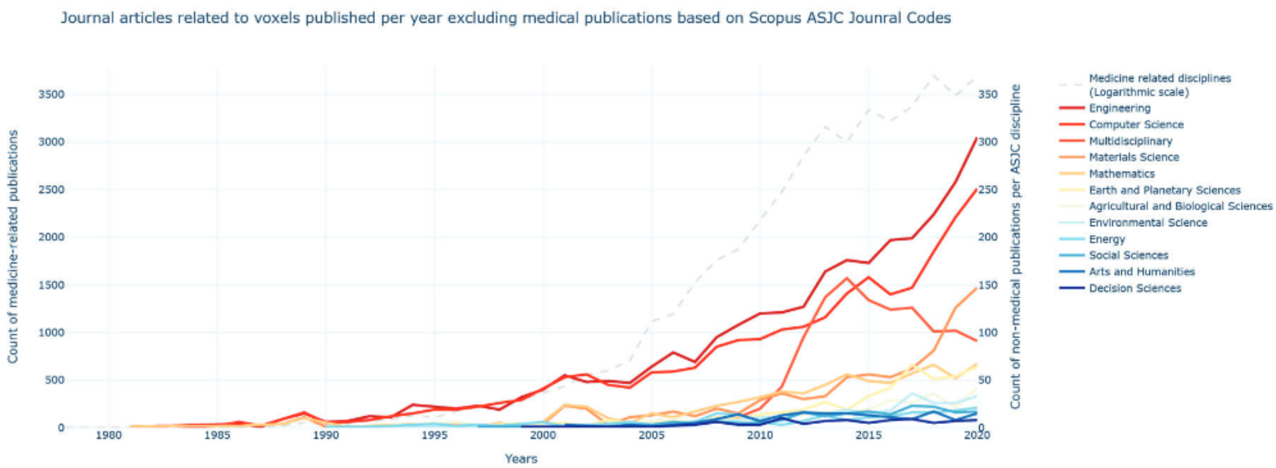

Figure 3. Disciplinary distribution of the voxel-related papers related to the year of publication based on the Scopus All Science Journal Classification Codes. The medicine-related publications are indicated by the gray dashed line plotted on a logarithmic scale to compensate for the publication volumes of a different order of magnitude. This figure is available in Supplementary Materials (Figure S2) as a high-resolution, full-page illustration.

2.3. Scoping Review Methodology

Reviewing extensive collections of publications retrieved from publication databases poses a challenge for reviewers, which is related to the inclusion of records irrelevant to the target question [40], (p. 609) and overlapping content [44], (p. 2). To address some of these challenges, a semi-automated deduplication AsySD algorithm is currently being developed for extensive literature collections [44]. Active-learning (AL) algorithms are applied in literature review studies for interactive sorting and publication filtering [41]. Topic-modeling algorithms, such as the Latent Dirichlet analysis (LDA), are also applied to assist reviewers in screening extensive literature collections [40]. The open-source implementations of AL algorithms, LDA-based topic modeling, and the semi-automated deduplication algorithm were evaluated in this review. The de-duplication with the AsySD algorithm was only possible after the initial screening, due to the size of the literature collection. A dedicated implementation was developed after the initial experiments (Figure 4).

This entailed relating the steps required by the PRISMA method to the abovementioned algorithms. The implementation prepared for this review utilized the scikit-learn implementation of the MultinomialNB algorithm [45] and the SciBERT transformer model [46] for the semi-automated publication screening. The probabilities predicted by the two independent ML models were combined by applying the Query-by-Committee approach based on consensus entropy [47]. This strategy was taken to mitigate bias and generate datasets for the user-driven LDA-based topic modeling. The LDA component uses Gensim [48] and Mallet [49] libraries for optimal topic number calculation based on the coherence score [42]. Software implementation was developed in Python, utilizing the widely adopted ML and NLP libraries, such as huggingface [50], PyTorch [51], and SpaCy NLP [52]. The development method required considerable computation time, partially on specialized ML hardware. A mobile workstation equipped with Intel i7-9750H CPU, 16 GB RAM, and NVIDIA RTX 2070 with 8 GB GPU memory was used. More advanced ML workloads utilized a single cloud instance equipped with NVIDIA Tesla P100 with 16 GB GPU memory. We report the hardware specifications of the two platforms used in this study and refer to them in the subsequent paragraphs for future reference and to secure research reproducibility.

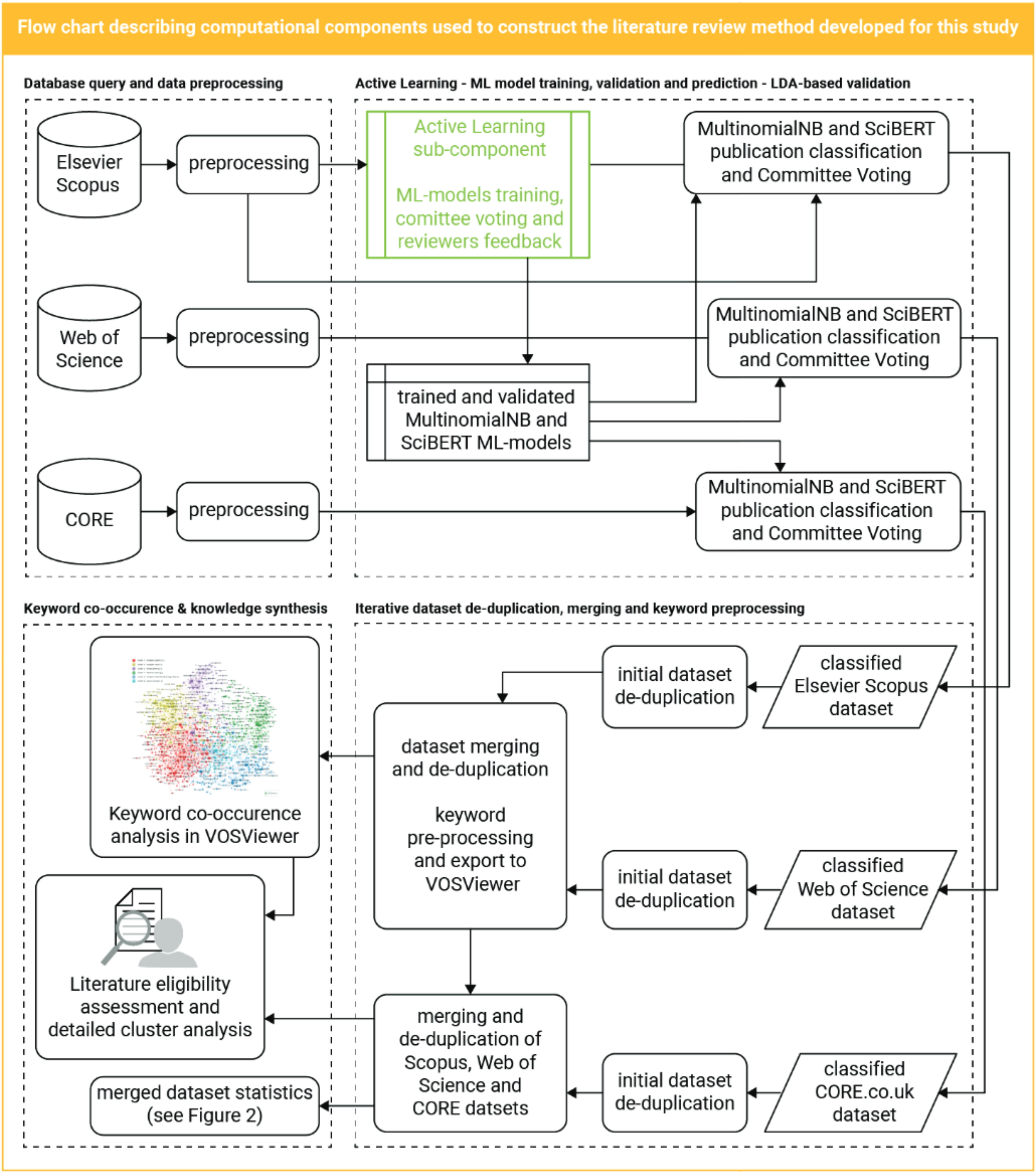

Figure 4. General workflow describing the NLP-based screening method applied in this study for the initial screening, followed by the keyword co-occurrence network analysis and a detailed study of the clusters. This figure is available in Supplementary Materials (Figure S3) in an alternative, horizontal layout.

2.3.1. General Description of the Method Implementation

Figure 2 (Section 2.1) depicts the publication counts retrieved from each database. Due to the interdisciplinary character of this review, the conventional methods for defining the screening criteria were unsuccessful. A manual screening of the whole dataset was practically impossible, and unexpected challenges regarding the keyword-based filtering criteria were observed. For example, the same abbreviation might simultaneously refer to different concepts, depending on the disciplinary context. For instance, the abbreviation "CAD" refers to both computer-aided design and diagnosis. The methods used in medicine, such as CT, are applied in the CAD context (e.g., imaging techniques in additive manufacturing processes). Each filtering attempt was evaluated by the reviewers through a manual checking of individual records. The initial attempts to generate a keyword co-occurrence network based on conventional screening approaches were unsuccessful, resulting in a keyword co-occurrence diagram, in which most of the CAD-related terms were rejected, due to a higher occurrence of medicine-related terms. Accordingly, a multi-step screening strategy was developed to address this problem (Figure 4). This method utilized the partially incorrect classification derived from the Scopus ASJC Codes and the NLP-based screening method to distinguish the papers related to the scope of this study.

The Scopus, WoS, and CORE databases were queried. The resulting datasets were pre-processed to unify the bibliographic data formatting. The pre-processing step included the unification of field names and their contents based on the ris file format specification and the generation of the internal record index for the consistency validation in the subsequent processing steps. In the second step, an AL-based method was introduced to assist the reviewers in screening the collected datasets. The classification data derived from the ASJC codes were used to train the SciBERT and MultinomialNB ML models. The ML models were used to classify the remaining datasets. Following the AL principles, the iterative process of the reviewers' validation and classification was based on consensus entropy and repeated training. The reviewers validated the outcomes by a manual classification of the LDA topics derived from individual publications. The iterative validation procedure was applied both in the training and classification steps to assure that the final results produced by the presented method were validated by the reviewers. The datasets were then merged and deduplicated using the AsySD tool [44]. The datasets for the keyword co-occurrence analysis in VOSViewer [37] and for the manual reviewers' evaluation were prepared. The VOSViewer dataset preparation required keyword processing and file format conversion. The dataset for the reviewers' evaluation was created by the merging and deduplication of the previously described dataset with the records from the CORE database. Finally, the keyword co-occurrence analysis was executed. The resulting clusters were evaluated by the reviewers. The reviewers manually browsed the dataset for relevant publications based on the keyword co-occurrence analysis and the resulting assignment of individual keywords to the thematic clusters. Finally, the reviewers analyzed and described the clusters, based on their expert knowledge.

2.3.2. Description of the AL-Based Classification Component

Undertaking AL required several stages (Figure 5). First, publications, abstracts, and a preliminary classification were used to train SciBERT on the cloud instance and MultinomialNB models on the mobile workstation, to classify papers relevant to the scope of the study. Each training iteration required 4 h of computation on the cloud instance, excluding the time required for additional data processing and transfers between the cloud infrastructure and the local system.

In the training step, the updated publication classification was used to train a new iteration of SciBERT on the cloud instance and MultinomialNB models. This process was repeated until the reviewers no longer reported any misclassified LDA topic. These stopping criteria occurred after three iterations. The last iteration of the ML models was used to classify the remaining papers retrieved from the WoS and CORE databases. This final classification step was conducted on the mobile workstation because the SciBERT prediction step requires less GPU resources than the SciBERT fine-tuning (training) procedure. In the classification step, the updated publication classification was used to update the dataset partitioning and iterate over the LDA-based reviewer evaluation procedure until the stopping criteria were reached.

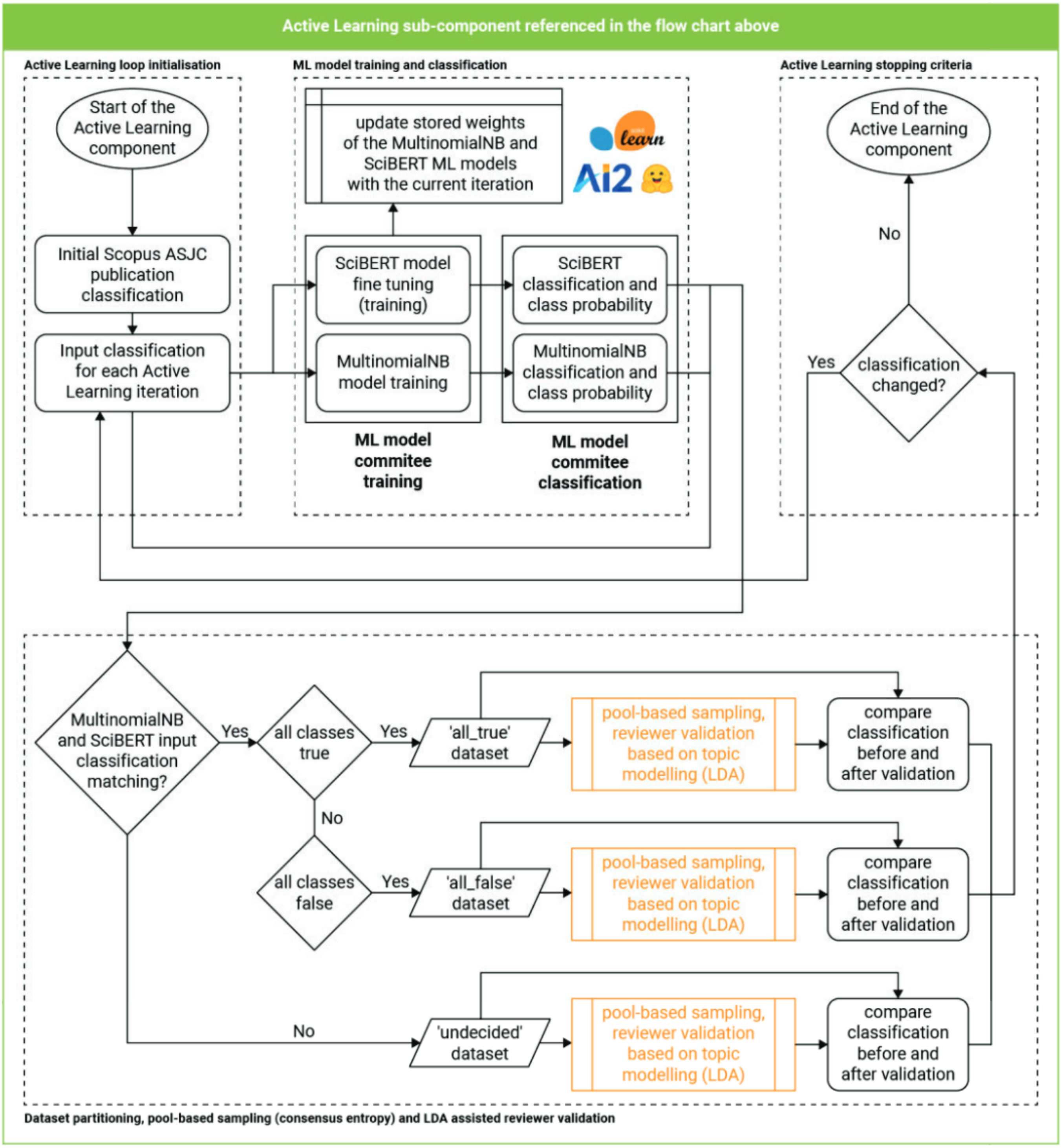

Figure 5. Flow chart describing the algorithmic implementation of the active-learning component. This figure is available in Supplementary Materials (Figure S4) in an alternative, horizontal layout.

2.3.3. Description of the Reviewer Evaluation Component

The following step was concerned with the pool-based sampling and the LDA-based reviewer validation procedure (Figure 6). The reviewers used the LDA-based topic-modeling method implemented on the mobile workstation to review papers whose uncertainty was larger than the 75th-percentile threshold. The Mallet implementation of the LDA algorithm for topic modeling was used. The optimal number of topics was calculated based on the coherence score method [42]. In this method, the LDA procedure was iteratively run for different topic numbers, and the coherence score was recorded.

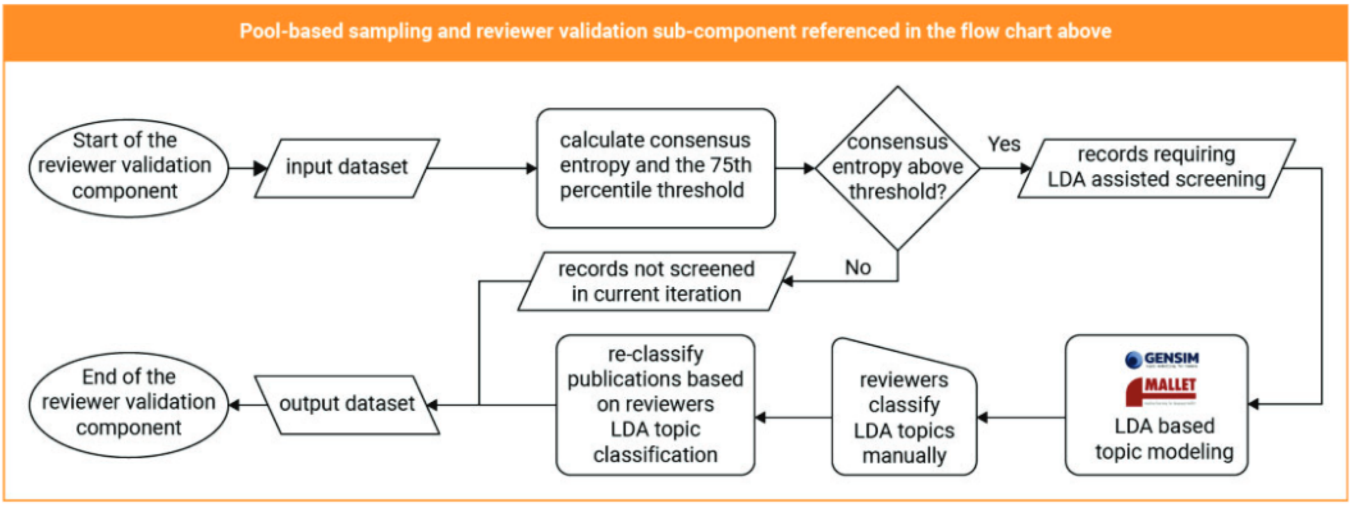

Figure 6. Flow chart describing the algorithmic implementation of the pool-based sampling and the topic-modeling-based reviewer validation component. This figure is available in Supplementary Materials (Figure S5) in an alternative, horizontal layout.

The relation between the topic number and the coherence score was plotted in a similar manner as in the "elbow method", widely used with the k-Means algorithm. The number of topics was chosen for the last value of the coherence score, after which the coherence score started to linearly decrease. This required running 35 iterations of the LDA algorithm and resulted in 6 h of computation on the mobile workstation, excluding the time required for additional data processing and user interaction. The 75th-percentile threshold was chosen based on the manual quality assessment, and resulted in 40.372 records requiring manual validation. Thus, the reviewers classified the LDA topics instead of individual publications, and the updated topic classification was extrapolated to the individual publications.

2.3.4. Integrating Results of the AL-Based Screening with the Keyword Co-Occurrence Analysis

At this stage, the number of publications was reduced from 79,830 to 10,119, and semi-automated deduplication with AsySD was possible. The Sco and WoS datasets containing keywords were merged and exported for the semi-automatic deduplication with AsySD [44]. This procedure identified 877 duplicates, which was 12% of the whole dataset. This quantity of duplicated entries can directly affect the results of the qualitative keyword co-occurrence analysis because the keywords of the duplicated records would occur multiple times in the keyword co-occurrence analysis. To address this issue, the dataset was carefully deduplicated and validated. The resulting deduplicated dataset was converted for the keyword co-occurrence analysis with VOSViewer [37]. Different spellings of the same keyword can negatively influence the results of the keyword co-occurrence analysis. For example, in this study, multiple keywords containing the words "three-dimensional", "3d", "3D", and "3-dimensional" were identified, and their spelling was unified into the "3D" form. VOSViewer allows users to supplement the analysis with a thesaurus file. This file maps each keyword to its unified form, and must be manually created.

The dataset used in this step contained initially 35.173 unique keywords, and a manual generation of the thesaurus file was not plausible. Therefore, the keywords were manually filtered and selectively processed using purpose-written Python regex expressions and selectively lemmatized using the SpaCy NLP Python library [52]. To assess the quality of this process, the reviewers selectively validated the keywords list. In this iterative process, the keywords were alphabetically sorted, based on occurrence. The list was updated after each regex operation. In the next step, the dataset was exported to VOSViewer, and the keywords were visually evaluated in the co-occurrence network. This step was completed when the reviewers did not report any duplicate keywords visible in the VOSViewer network, and by selectively checking the keyword list. The resulting dataset was used to generate the keyword co-occurrence network with VOSViewer (Results Section). The keyword co-occurrence analysis generated thematic clusters and revealed patterns related to individual keywords. In the following step, the gray literature from the pre-processed CORE dataset was merged with the processed Scopus and WoS datasets, resulting in the final combined dataset. The reviewers manually searched for all the metadata contained in this dataset and identified relevant clusters and related keywords in relation to the research aim. In the next step, the reviewers identified the key literature and analyzed the individual clusters, based on the final combined dataset and their expert knowledge.

2.3.5. Evaluation Metrics and Manual Validation of the AL Component

Confusion matrices and the improvement in the accuracy score for each new generation of the ML models were needed to evaluate the results of the NLP-based screening method (Figure 7). Compared with the initial classification of the pre-classified part of the Scopus dataset, this process identified 790 relevant publications that would otherwise be excluded from the scope, and 2.027 irrelevant publications which would negatively affect the quality of the keyword co-occurrence analysis. A total of 40.372 publications were screened by the reviewers using the topic-screening method. However, the wide application of the described method is currently limited, given the technical complexity, cumulative computation time, and reviewers' effort required for the result validation. A detailed description of the computational method is not the aim of this study, and will be considered for a separate publication. A further adaptation of this method for future literature reviews is possible, given the growing availability of computational resources.

Paré and Kitsiou pointed out that scoping and narrative literature-review methodologies do not require formal statements of bias-mitigation strategies [27] (p. 170). The PRISMA methodology developed for the systematic literature reviews in the field of medical sciences is still attracting wide recognition and use. Consequently, literature reviews in the engineering sciences are often required to comply with the PRISMA methodology. The strategies applied to minimize the risk of bias in this scoping literature review are illustrated in Figure 8 and reported below, to support the transparency and reproducibility of this research.

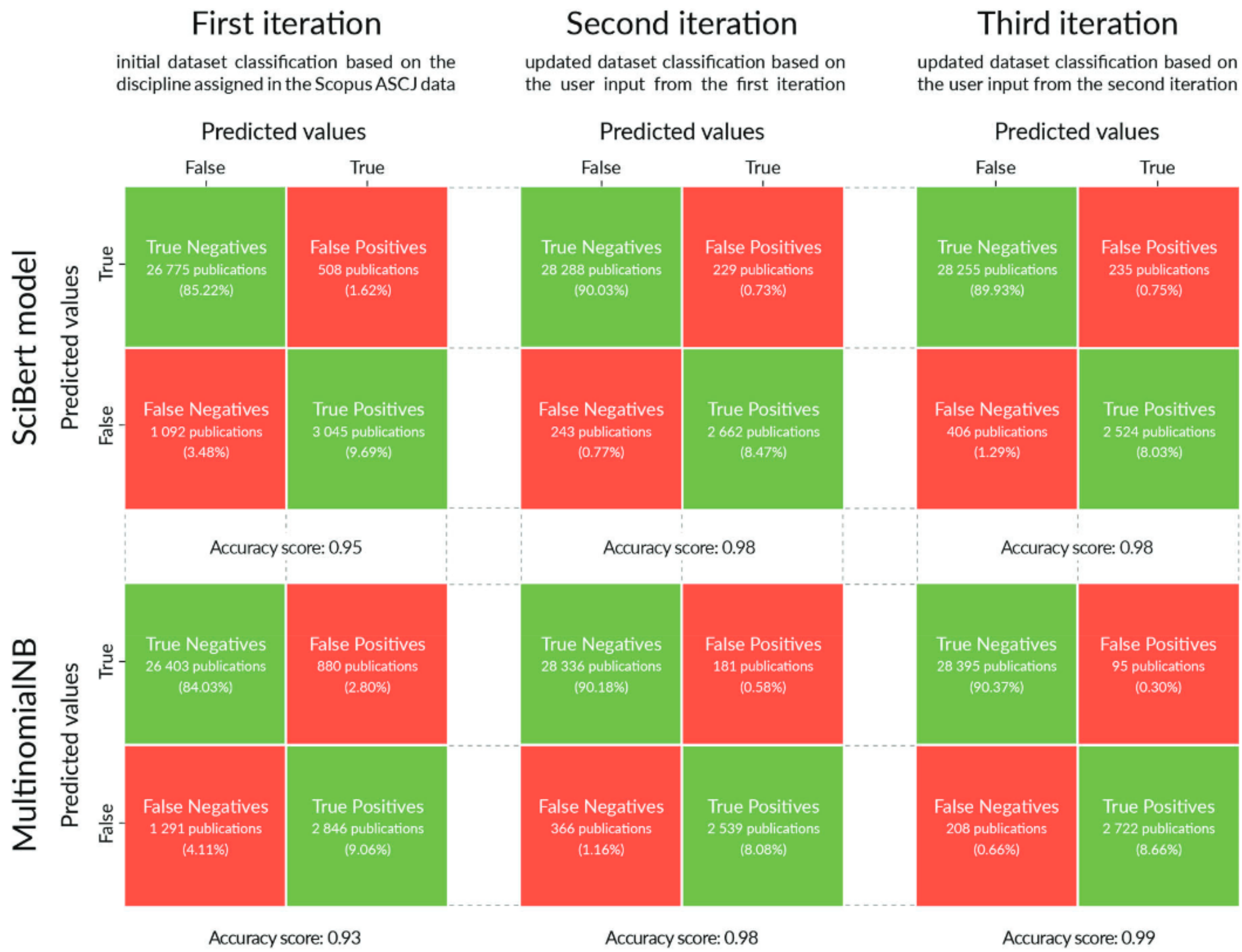

Figure 7. Evaluation metrics of the SciBERT and MultinomialNB models. The confusion matrices for both models are aligned on a common grid representing the three active-learning iterations. The classification improvement in each iteration is reflected in the increasing accuracy score.

First, the WoS, Sco, and CORE datasets were pre-processed to match the bibliographic data formatting. The bibliometric data consistency was manually validated by the reviewers. Custom indexing aligned with the partial dataset lengths was introduced. The custom index was introduced to prevent duplicated or missing records and possible data processing errors in the next steps. The reviewers manually validated the custom index values after each processing step.

Next, the reviewers iteratively validated the AL process results with the LDA-based topic-modeling method (Section 2.3). In this step, the potential risks are related to (1) the bias inherent in the chosen ML models and choice of the method to combine the ML predictions, and (2) the method for validating the outcomes of this algorithmic procedure. Two possibly different state-of the-art ML models were identified, and the Committee Voting strategy was applied. The AL strategy utilizing topic modeling for reviewer validation was introduced. The inherent bias of the LDA algorithm and the bias introduced by the choice of the topic number were considered. The available implementations of the LDA algorithm were also tested for this dataset. The reviewers qualitatively evaluated the resulting topics and the recorded coherence scores for the different topic counts generated by the LDA algorithm. As a result, the Mallet implementation of the LDA algorithm [49] was chosen, and the coherence score [42] method combined with the selective reviewers' evaluation was applied to select the optimal topic number.

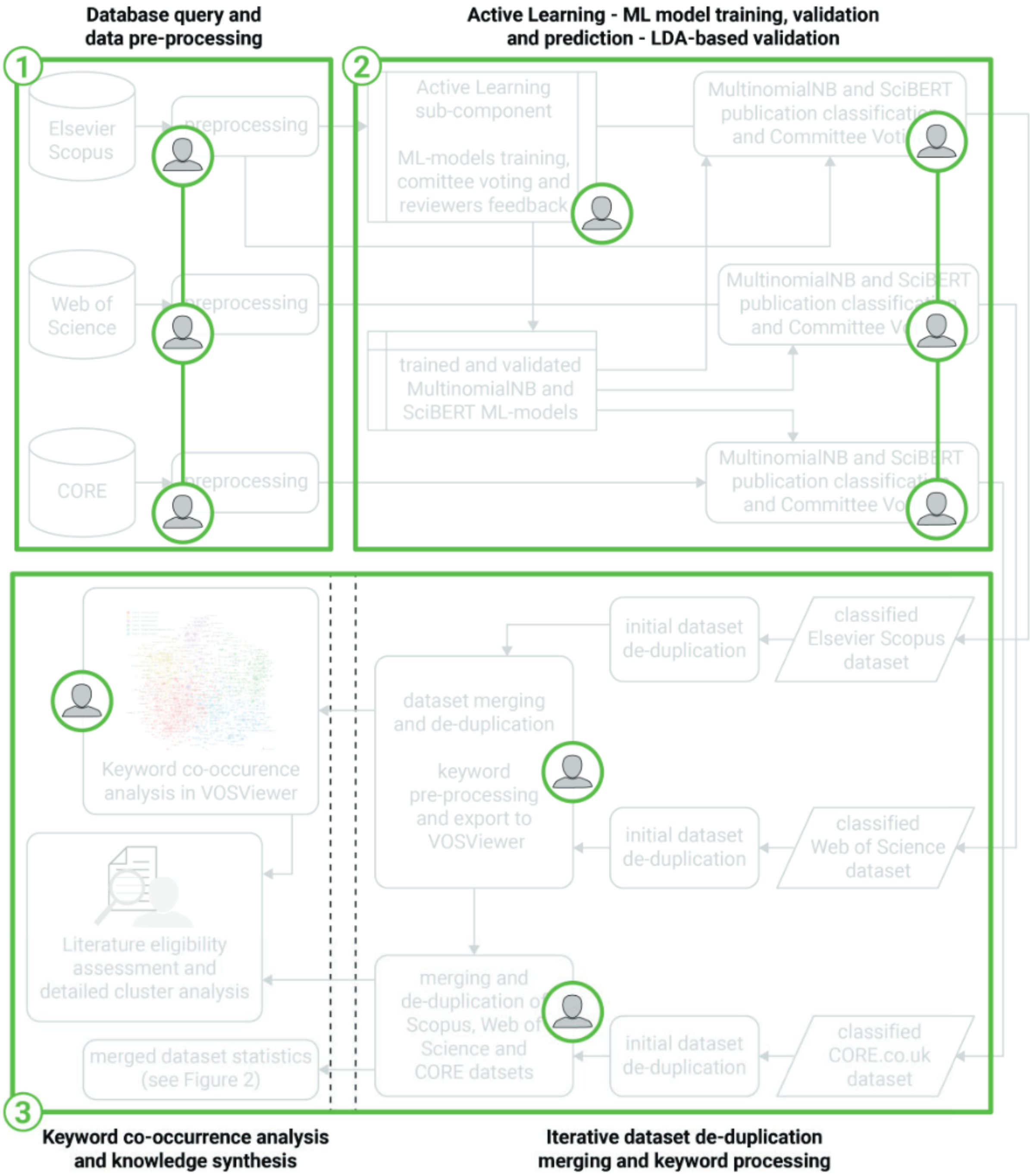

Figure 8. Role of the reviewers in validating the outcomes of the NLP-based screening method to minimize the risk of bias. The validation steps are linked to the workflow components from Figure 4, and assigned with the numbers used in the detailed description below. This figure is available in Supplementary Materials (Figure S6) as a high-resolution, full-page illustration.

Deduplication and keyword processing for the keyword co-occurrence analysis were subsequently undertaken. The semi-automatic AsySD deduplication procedure assigned 91 publication pairs for manual screening. This step showed that the duplicates accounted for 12% of the whole dataset, directly affecting the qualitative keyword-co-occurrence analysis. In relation to the keyword processing, the procedure resulted in a 17% reduction of the total keyword count. Finally, the quality of the keyword co-occurrence network was analyzed by the reviewers.

3. Results

Figure 9 shows the steps taken in the AL-based screening procedure. In the first step, 79.830 records were identified from the databases, while 38.078 gray-literature items were identified from other sources (e.g., CORE database). Deduplication was conducted in the later step. Based on the inclusion criteria, 5.373 records were removed from the WoS and Sco datasets, due to the publication type and the language criteria. Accordingly, 17.559 records were removed from the CORE dataset, due to the language criteria. In the second step, 94.979 records were screened with the NLP-based method. As a result, 92.410 records were classified as irrelevant in the AL-based screening.

In the next step, the results of the AL-based screening were combined with the keyword co-occurrence analysis by the reviewers. A dataset describing the keyword cluster assignment and the weighted importance of individual keywords within each cluster was created using VOSViewer software [37]. This dataset was visualized as a keyword-co-occurrence network diagram (Figure 10) and used by the reviewers in the next steps. Further record exclusion and knowledge synthesis required the systematic combination of the keyword dataset with the literature collection. The reviewers separately selected the studies to be included in the next step for each cluster. The filtered literature collection was queried by the reviewers, based on the selected keywords derived from the weighted keyword occurrence in the studied cluster. All publications containing the chosen keyword in the title, abstract, or keywords were recorded, resulting in a dataset containing 2.569 records. The reviewers manually screened all records in this dataset based on titles, keywords, and abstracts and marked 487 publications for full-text retrieval. They then studied the retrieved publications, to summarize the cluster descriptions. Each cluster description contained a table, in which all the publications listed in the description were further categorized based on the keyword used in the retrieval process. Particular attention was given to the existing literature reviews. The reviewers were then asked to identify the literature reviews related to the studied cluster and to commence the cluster description with the overview of the existing literature reviews.

3.1. Results of the Keyword Co-Occurrence Network Analysis

The merged dataset containing records from the Scopus and WoS datasets was used to create the keyword co-occurrence network (Figures 10 and 11). The different colors in Figure 10 represent the thematic clusters generated with the unified mapping and clustering approach implemented in VOSViewer. The proximity between two keywords reflects the close relations of both terms, even if the terms are assigned to different clusters. The color scale in Figure 11 shows the average publication year assigned to each keyword. The average publication year analysis presents information that is similar to the one in the keyword burst analysis, in which the development of certain concepts in relation to the studied topic can be matched with a particular time. The most recent trends can be traced back to individual keywords and thematic clusters.

The node distribution in the network illustrated in Figure 10 is balanced, and the six clusters can easily be identified. This network diagram does not contain keywords related to medical sciences, which is the main aim of the NLP-based screening step. VOSViewer software enables users to exclude the most frequent keywords from the network visualization, allowing for informed decisions on excluding selected keywords to achieve fine-grained and balanced clustering and mapping results. For example, the first and second clusters contained the “computer graphics” and “computer vision” terms, respectively, which suppressed most of the keywords in the respective clusters. Hence, they were excluded from the visualization and chosen as the cluster names to reflect their relevance in their respective clusters. The names of the remaining clusters were chosen based on the reviewers’ expert knowledge, matching the name of the scientific discipline with the keywords in the cluster. The nodes of the sixth cluster were scattered. This cluster was assigned to the general concepts related to the voxels present in a wide range of disciplines. The clusters that emerged from the keyword co-occurrence analysis were assigned for analysis by the reviewers.

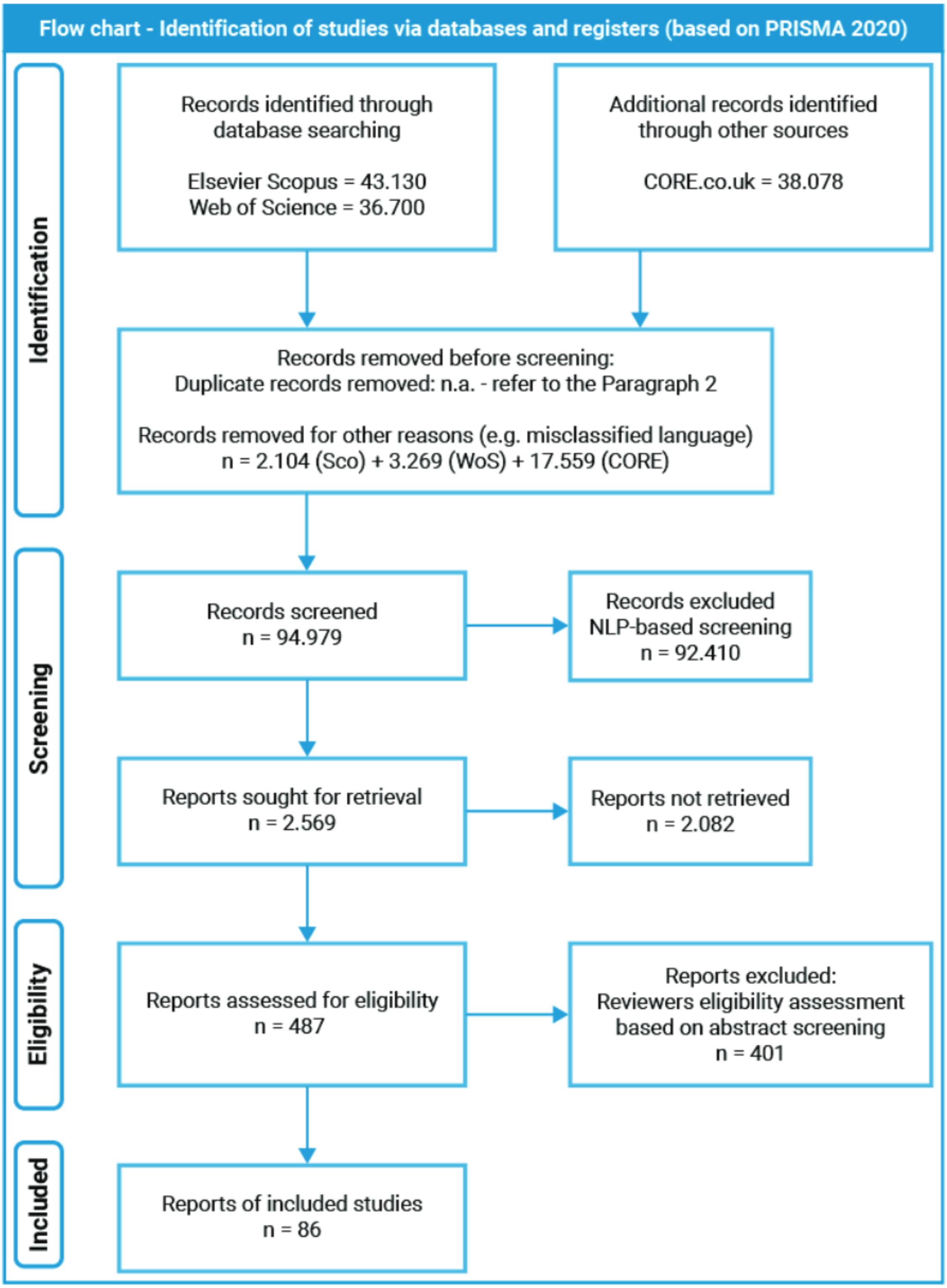

Figure 9. Flow chart describing the results of this literature review adapted from the PRISMA methodology for this scoping review.

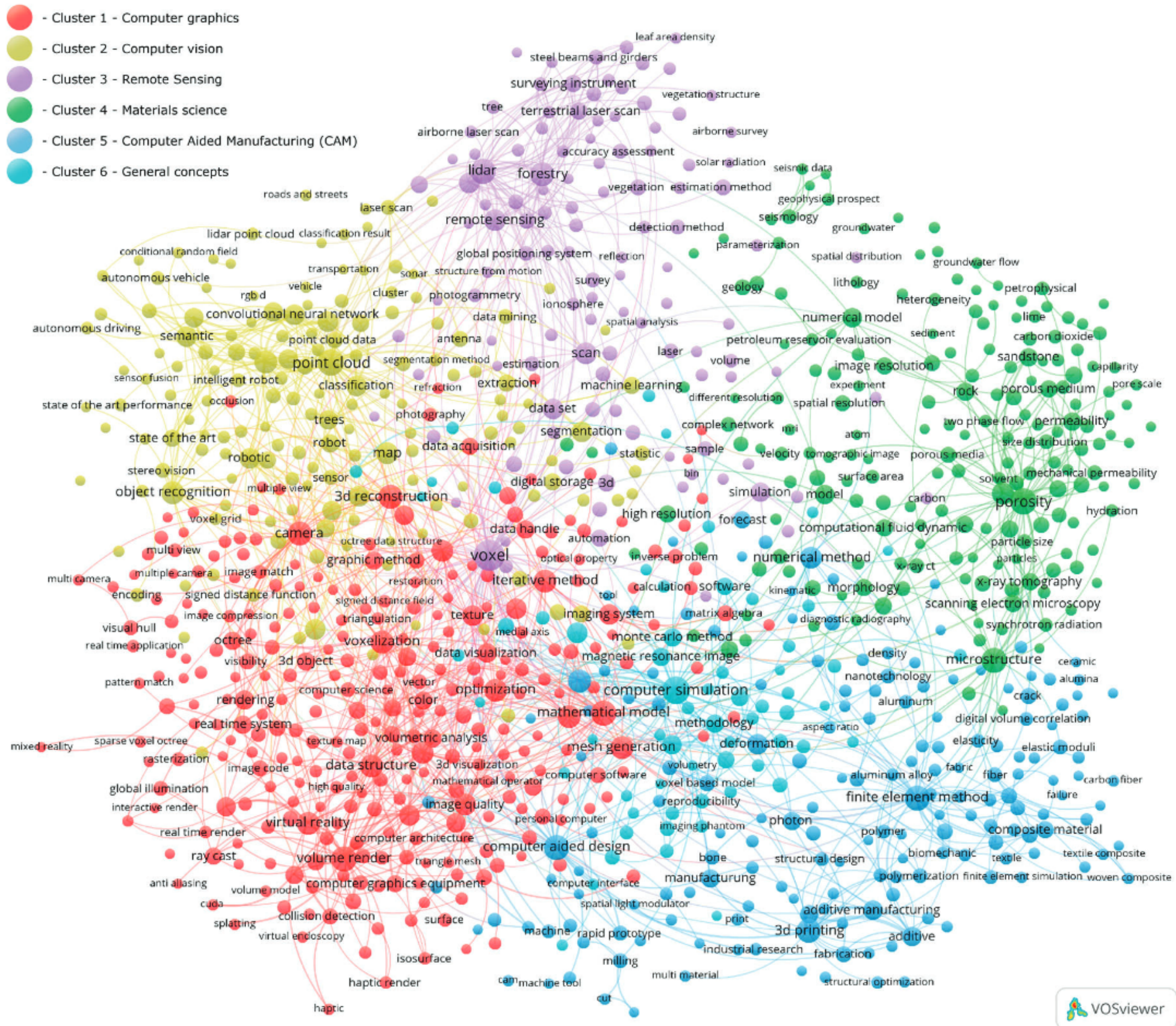

Figure 10. Keyword co-occurrence analysis and clustering presented as a network diagram.

3.2. First Cluster—Intersections between CAD and Computer Graphics

The first cluster represents research on computer graphics (Table 2). Keywords such as "visualization" and "virtual reality", describe the technologies relevant to digital design and planning. Figure 11 shows that the keywords in this cluster have the lowest average publication year. The applications related to the role of voxel models as spatial data structures for encoding knowledge for knowledge-based design processes were not identified in this cluster. Therefore, the discussion in this cluster was limited to the description of the role of the voxel models in dedicated visualization techniques. Most contributions in this cluster were related to the voxel model applications for visualizing large datasets describing buildings [53] and large territories [54]. Experiments with preliminary design exercises both on-screen [55–57] and in virtual reality [58,59] exist. Voxel-based generative-design interfaces have also been proposed [60,61].

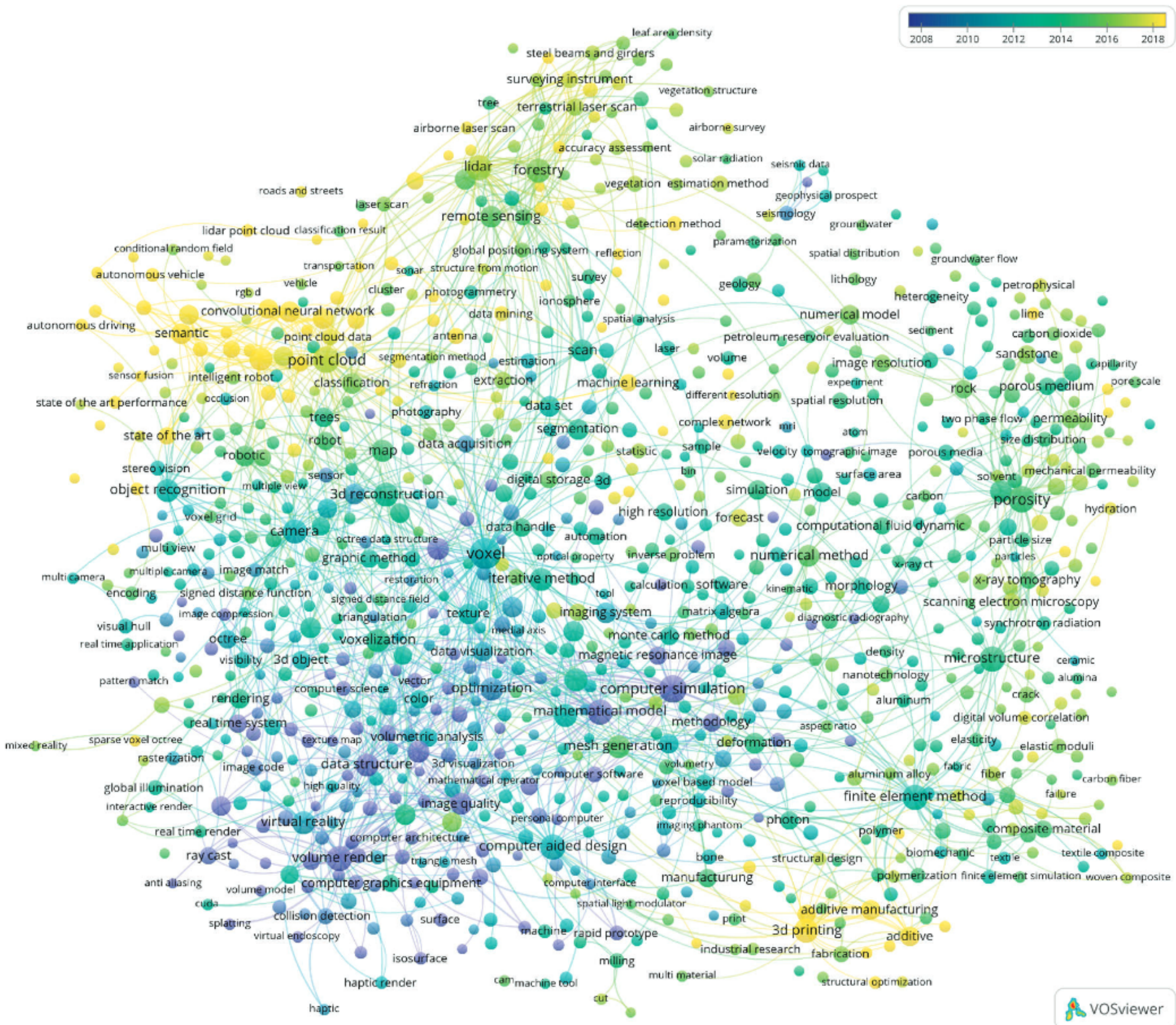

Figure 11. Overlay visualization of the average publication year mapped to the keywords in the network diagram.

Table 2. Selected keywords and representative publications related to the first cluster.

Keywords	Identified Publications
Visualization and volume rendering	Liu et al. [53], Andres et al. [54]
Human–computer modeling interfaces	Strehlke [55], de Vries and Achten [56], Savov and Tessmann [57]
Virtual reality	De Klerk et al. [58], Chen et al. [59]
Cell-based generative-modeling interfaces	Fischer [60], Erioli and Zomparelli [61]

3.3. *Second Cluster—Intersections among CAD, Computer Vision, and Urban Planning*

The second cluster related to the field of computer vision shows multiple overlaps with the computer graphics cluster. Keywords with a higher average publication year are less related to the computer graphics cluster. The most recent research is related to point cloud classification and semantic segmentation, autonomous vehicles, and multimodal data fusion. Table 3 lists the representative publications from this cluster. Different methods of real-time 3D mapping and ML-based scene understanding are present in this cluster, including "machine learning", "convolutional neural networks", "object recognition", "intelligent robot", and "stereo vision" keywords. The keywords occurring in this cluster are related to data acquisition and integration methods, such as "multimodal data fusion", "RGB D", and "stereo vision." The intersection between this cluster and the remote sensing cluster contains terms describing urban environments, such as "roads and streets", "trees", "transportation", and "urban planning".

Table 3. Selected keywords and representative publications related to the second cluster.

Keywords	Identified Publications
Urban green spaces	Susaki and Kubota [62], Wakita and Susaki [63], Anderson et al. [64]
Tree identification and modeling	Schmohl et al. [65], Guan et al. [66], Vonderach et al. [67]
Urban analysis and simulation	Fisher–Gewirtzman et al. [68], Morello et al. [69]

Xu, Tong, and Stilla [8] recently reviewed voxel-based point cloud representations for their potential role in the construction industry. Their review presented a detailed overview of the algorithmic approaches addressing point cloud pre-processing, registration, segmentation, classification, and modeling. They primarily focused on the datasets acquired through laser scanning and stereo vision applied for 3D urban-scene mapping, which aligned well with the cluster described in this paragraph. Table 2 summarizes the publications that went beyond the scope of the review published by Xu, Tong, and Stilla [8] and focuses on the voxel model application in digital architecture and planning. In this context, the voxel models were applied to quantify green space [62], estimate the local landscape index [63], and communicate the importance of urban green volume to non-expert stakeholders using digital fabrication technologies and different visualization techniques [64]. Voxel-based methods can be applied to distinguish individual trees in urban locations [65], predict individual tree species [66], and estimate individual tree volumes and the amount of carbon stored in a single tree [67]. Voxel models were also applied in an urban context to study visibility in complex-terrain conditions [68] and extend Lynch's isovist theory into quantifiable, 3D metrics describing urban landscapes [69].

3.4. Third Cluster—Intersections among CAD, Geomatics, and Architectural and Spatial Planning

The third cluster summarized in Table 4 overlapped with the computer vision cluster. The spatial data acquisition through autonomous vehicles, an understanding of the urban scene, and the application of these concepts to urban planning were identified in the second cluster. A similar synergy among data acquisition, the generation of information, and the knowledge applied to design and planning was visible in the third cluster, extending toward non-urban environments. The keyword 'architectural design' is assigned to this cluster. The application of voxel models and generative adversarial networks (GANs) in architectural form design [70] was identified. Furthermore, voxel models were applied to design hospital layouts [71], connect the voxel-based simulation with the network analysis for building-evacuation modeling [72], and integrate pathfinding and heat transfer for the building-performance simulation [73]. The integration of the building-information modeling (BIM) and voxel-based modeling approaches is gaining popularity. Combined BIM and voxel environments allow the automatic monitoring of the daily construction site progress [74] and crowd-behavior simulation during fire and toxic-gas expansion [75]. The voxelization of BIM models for cell-based path planning [76] and the automatic annotation of exterior building elements [77] were recently studied. The conversion of 3D scans to BIM objects can also utilize voxel models [78]. In addition, photogrammetric 3D scans of lattice structures can be automatically converted into line-based 3D skeleton models used for structural analysis [79].

Table 4. Selected keywords and representative publications related to the third cluster.

Keywords	Identified Publications
Architectural design and planning	Asmar [70], Cubukcuoglu et al. [71], Gorte et al. [72], Goldstein, Breslav and Khan [73]
Building information modeling (BIM)	Golparvar-Fard et al. [74], Scherer et al. [75], Wang et al. [76], Deidda [77], Liu et al. [78], Chen et al. [79]
Building interiors	Hübner et al. [80], Previtali et al. [81]
Building facades	Truong–Hong et al. [82], Chen et al. [83], Thariyan [84]
Solar analysis	Bremer et al. [85], Heo et al. [86]
Geographic Information Systems (GIS)	Karssenberg and De Jong [87], Gebbert and Pebesma [88], Sahlin et al. [89], Orengo [90], Andersen et al. [91], Nolde et al. [92]
Spatio-temporal analysis	Jjumba and Dragićević [93–95], Shirowzhan et al. [96]

For building interiors, voxel models are used to reconstruct the semantic labels of the building interior from the data collected with the 3D scanning sensor of a mobile augmented-reality device [80]. The curvilinear walls, irregular slabs, stairs, and ramps were successfully classified in the abovementioned example. Internal doors and windows can also be reconstructed from incomplete point clouds using a voxel-based approach [81]. A similar approach was applied to building facades, where voxel models were used to reconstruct the building facade geometry and directly use the results in structural analysis software [82]. GANs could be utilized with voxelized facade models to generate the fragments of the facade that are missing in the acquired datasets [83]. Voxel models were also used to design building envelopes based on simulated solar radiation [84].

A voxel-based solar analysis was applied in the urban planning context [85] and in a fine scale through single-laser scanner acquisition [86]. In the context of the Geographic Information Systems (GIS), voxel models are widely utilized when 3D data and temporal change must be introduced [87,88]. The identified applications spanned marine environments [89], volumetric recording of archaeological sites [90], urban planning support in relation to 3D geological modeling [91], and underground energy storage [92]. In the GIS field, the generative capabilities of voxel models were utilized by introducing voxel-based geographic automata [93,94] applied, for example, to simulate the dispersal of airborne pollutants [95]. The application of the voxel automata was recently reviewed in relation to the spatio-temporal change of a built-fabric 3D density in urban contexts [96].

3.5. Fourth Cluster—Intersections among CAD, Materials Science, and Geosciences

The fourth cluster focused on the internal structure of the Earth's surface and on studying the processes happening on this surface (Table 5). Knowledge regarding structure and processes was applied in CAD when planning terrain modifications and in large-scale planning. The fourth cluster contained keywords, such as "porosity", "permeability", "flow simulation", "erosion", and "microstructure". In this context, voxel models were applied to simulate and visualize the spatio-temporal change driven by natural processes and model the multi-layered structure of the Earth's surface.

Table 5. Selected keywords and representative publications related to the fourth cluster.

Keywords	Identified Publications
Terrain modeling and visualization	Graciano et al. [97], Nonogaki et al. [98], Shoaib Khan et al. [99]
Scientific visualization of landscapes	Starek et al. [100], Mitasova et al. [101]
Soil properties and root modeling	Ishutov et al. [102], Rabbi et al. [103], Teramoto, Tanabata and Uga [104], Sengupta et al. [105]
Habitat modeling	Sasaki et al. [106], Loraamm and Downs [107], Downs et al. [108], Loraamm et al. [109]

Dedicated voxel-model visualization techniques contained stack-based terrain representations [97] related to geotechnical-modeling applications [98]. A voxel-based earthwork modeling methodology incorporating the geotechnical properties integrated with the BIM processes was proposed [99]. Different natural processes can be modeled, analyzed, and visualized through space–time cube representations [100] and collaborative, tangible interfaces [101]. Digital rock physics (DRP) is a methodology for studying the petroleum reservoir structure with a focus on the porosity of the Earth's subsurface layers in relation to pore interconnectivity and fluid–rock interaction on multiple scales. Voxel models were applied to model the porosity of laboratory samples based on CT scans and integrate large-scale data describing the geological structure of the studied territory. Integrating 3D printing and DRP [102] allowed the physical manufacture of tangible samples of the digital rock voxel models with different materials. These digital rock twins could be tested using the same laboratory procedures as real rock samples. Moreover, voxel models were applied to study the relations between various soil properties and plant roots [102]. Semi-automated root vectorization techniques were also developed for CT scan-based voxel models [104]. A similar approach was taken to study the 3D spatial distribution and relations among hydrological, geochemical, and microbiological processes [105].

Finally, voxel models were applied to study the relations among land-use patterns, habitat classification, and their use by animals. These methods can support conservation and management planning in urban parks [108]. The application of voxel-based probabilistic space–time prisms (STP) [107] can further advance studies that address urban-habitat-use patterns at high-resolution temporal scales [108]. Voxel-based STPs utilized GPS tracking data to map and predict the probability that the tracked agent (animal) can be found at a specific location at a given time. This information can be overlaid with land-use data to uncover otherwise unobserved daily use patterns related to urban habitats [109]. The temporal range can cover a few days [108] to multiple months [109], depending on the tracking resolution data.

3.6. Fifth Cluster—Intersections between CAD and Computer-Aided Manufacturing

The fifth cluster summarized in Table 6 contained terms such as "3D printing", "finite element method", "topology optimization", and "concrete and thermal conductivity". Bacciaglia et al. [7] published a systematic review addressing the voxelization in additive manufacturing. Momeni et al. [6] reviewed 4D-printing processes, addressing the design and fabrication of shape-changing 4D-printed structures. In the structural analysis context, Schillinger et al. [5] reviewed the finite cell method (FCM) for the structural analysis of the CAD and image-based geometric models. Table 6 summarizes the representative publications from this cluster.

Table 6. Selected keywords and representative publications related to the fifth cluster.

Keywords	Identified Publications
Subtractive manufacturing	Peddireddy et al. [110], Yousefian and Tarbutton [111], Wang et al. [112], Kukreja et al. [113]
Additive manufacturing	Momeni et al. [6], Bacciaglia et al. [7], Huang et al. [114], Greminger [115], Chi et al. [116]
Material performance and failure	Nguyen et al. [117], Taraben and Morgenthal [118], Yang et al. [119], Li et al. [120], Barazzetti et al. [121], Kudela et al. [122], Bitelli et al. [123], Van De Walle et al. [124], Maaroufi et al. [125]
Conventional construction materials such as concrete and wood	Vantyghem et al. [126], Leder [127], Xiao [128], Hosny et al. [129], Naboni and Kunic [130]
Advanced materials and material performance	Schillinger et al. [5], Michalatos and Payne [131,132], Green et al. [133], De Schampheleire et al. [134]
Topology optimization and generative design	Baron et al. [135], Mekki et al. [136], Ambrozkiewicz and Kriegesmann [137], Craveiro et al. [138], Aage et al. [139]

In subtractive manufacturing, voxel models were applied in combination with ML to automatically identify the conventional machining processes from CAD models [110], predict the cutting force [111] and resulting deformations [112], and generate efficient toolpaths [113]. In additive manufacturing, voxel models and ML were applied to predict the 3D-printed-shape accuracy [114], enforce manufacturing constraints on topology optimization [115], and design 3D-printed, self-organizing, and functionally graded materials [116]. The material performance and failure can be studied with the voxel model application. Meanwhile, the mechanical damage on concrete can be studied at the micro scale [117] and by using 3D-imaging techniques and autonomous platforms to monitor buildings [118,119] and other civil engineering structures [120]. The voxel model application for the structural analysis of existing buildings is studied in the context of heritage preservation, considering that the 3D scanning of historical monuments is widely practiced. However, the conventional cloud-to-BIM-to-FEM workflows [121] require sophisticated 3D modeling techniques and expert knowledge. The direct structural analysis of voxelized point clouds with the FCM methods is currently under study [122]. Accordingly, a semi-automated voxelization method was developed to assess the structural stability of a partially collapsed heritage building [123]. Aside from the structural performance, the thermal conductivity of building materials [124,125] can also be studied with voxel-based methods.

In the context of digital architecture and planning, voxel modeling approaches were applied to conventional building materials. An integrated voxel-based workflow addressing digital design, structural analysis, and 3D printing with concrete was recently proposed [126]. Non-cuboid voxel models were used to propose a reconfigurable slip formwork system for materializing continuous, modular concrete structures [127] and constructing voxel-based aggregation structures materialized as stacked MDF units connected by tenon and mortise joints [128]. Furthermore, voxel models were used to integrate topology optimization into the digital design and fabrication process by utilizing concrete and customized foam molds [129]. A similar approach accommodated voxel-based design methods to construct structurally optimized and highly specified tectonic configurations of wooden modules [130], combining multi-material topology optimization, robotic fabrication, and the encoding of design properties in individual voxel cells for the complex multi-material configuration of the proposed voxel assembly.

Progressing beyond the materials widely adopted in architecture, Michalatos and Payne [131] observed that the surface modeling paradigm currently predominant in 3D architectural modeling does not permit incorporating multi-scalar material properties and fine-grained material performance. Their contribution resulted in a software prototype that made designing within the volumetric paradigm possible, and incorporated the internal complexity of solid objects related to the hierarchical complexity of physical materials [132]. A series of deformable physical objects were fabricated to explore the potentials of multi-material 3D printing based on the analysis components implemented in their software. The applicability of this modeling approach can be extended because voxel models were applied to study the performance of complex materials, such as 3D woven composites [133] or open-cell metal foams [134], in relation to their unique structural and thermal performances.

The advantages of combining voxel models, genetic algorithms (GA), and finite-element analysis in the context of topological optimization are well studied [135]. Voxel-based design processes utilizing GA can be combined with computational fluid dynamics algorithms to simulate thermal and airflow performances. These concepts were recently applied to design an organically shaped heat exchanger by utilizing a single-objective GA for optimizing pressure drop and heat transfer, consequently combining two opposing objectives [136]. Voxel-based generative processes can be used to design optimized, fail-safe structures [137] and functionally graded and resource-efficient building components [138]. The growing availability of computation resources has led to a point where generative voxel-based morphogenesis processes can reach giga-voxel resolutions and be applied to generate objects incorporating structural details in scales ranging from millimeters to tens of meters. Aage et al. [139] described this generative-material optimization process, whereby a complete structure of a plane wing emerged from a computational process constrained by the typical aerodynamic load cases and a 3D outline of a typical plane wing. The generated multi-scalar structure showed similarities with the structural patterns observed in bird bone structures. Aage et al. stated that: this "methodology (. . .) is directly applicable to similar morphogenesis problems in other engineering disciplines, as well as in architecture and industrial design." [139] (p. 86).

4. Discussion

The chronological structure of this study is informed by the timeline of the voxel model development shown in Figure 1 (see page 5). The choice of methodologies follows this structure, and the discussion is organized accordingly. The main findings of this study have been listed below, to initiate the discussion on novel applications of voxel models in the context of architectural design and spatial planning:

1. A useful starting point for developing novel applications of voxel models is the observation that the widely adopted definition of a voxel model as "the 3D conceptual counterpart of a 2D pixel in an image" [21] should be seen in its original context and be complemented with the definition of a voxel model as "spatial-knowledge representation schemata" [4].
2. Various applications of voxel models in architectural design developed over time, shifting from human–computer interaction studies towards computational experiments that reflect the generative dynamics of natural systems.
3. The growing availability of high-resolution, 3D data capturing urban scenes and large territories has been instrumentalized in spatial planning, where voxel models are used to integrate and enrich the raw data with the outcomes of analysis and simulation.
4. In various disciplines, spatio-temporal dynamics of the natural and man-made environment are studied using voxel-based methods. Design approaches addressing the challenges of climate change and sustainable development can benefit from the application of identified voxel-based approaches.
5. Applications of voxel models addressing all architectural project phases have been identified. In urban planning projects, identified applications of voxel models are covering initial design phases.

4.1. Existing Voxel Model Defintitions and Their Relevance for Future Research

The following is the most widely adopted definition of a voxel: it is the 3D conceptual counterpart of a 2D pixel in an image [21]. From today's perspective, this creates a misconception by analogy between a static 2D digital image and a voxel as its 3D equivalent. Voxel models emerged at a time when digital photography was not as omnipresent as it is today, and the majority of digital 2D images were computationally generated or acquired through specialized scientific equipment, such as early CT and MRI devices. At that time, the analytical character of a digital image was more evident, and the analogy between 2D pixels and 3D voxels conveyed a different meaning. This initial understanding of voxel models can be re-established by understanding their analytical character, which can extend beyond the 3D geometry in integrating diverse datasets created with 3D mapping, analysis, and simulation, as well as through the design process itself. The growing availability of computational resources makes it possible to encode multidimensional datasets in voxel models and represent the spatio-temporal changes of various parameters for datasets, increasing in scale and resolution.

By extension, one of the interesting ways in which voxels can be used is to encode different datasets, which leads to new insights and allows voxels to be considered as "spatial-knowledge representation schemata" [4]. Nelson and Stolterman [140] posited that design is inquiry for action. In this context, voxel models can be utilized to encode the spatial knowledge encoded in voxel models such as to be actionable in the context of a design-driven inquiry. This voxel model application is particularly suitable for interdisciplinary design environments, where different disciplinary datasets must be spatialized and integrated to support an interdisciplinary design process. Therefore, we foreground herein the integrative approaches that use voxels as knowledge representation schemata. This review outlined several research topics in which voxel models were utilized to structure disciplinary datasets and link them with a discrete geometric representation. In the context of architectural design, voxel models are used for design and analysis of the scales of architectural objects and urban systems. Advancing into a wider scope of computer-aided design, contributions from material science, mechanical engineering, robotics, 3D scanning, and automated object classification were identified. This extended scope outlines the possible directions for future research, where the identified approaches can be utilized to inform the design process. Designers are confronted with the growing complexity of both the object of their design and the environment in which their design exists. In the context of the built environment, the urgent need for innovative sustainable design and construction practices drives the need for novel approaches to informed design methods. The potential of voxel models relating to their interdisciplinary character and the possibility to integrate multi-scalar data were identified in this review. The multi-scalar character of voxel models allows the integration of diverse knowledge domains and the incorporation of temporal change within one composite, spatial model. Composite voxel models understood as "spatial-knowledge representation schemata" [4] could be used to advance spatial information into spatial knowledge, following the line argumentation proposed by Srihari [4]. These models could be combined with expert knowledge to tackle contemporary design challenges, such as climate change and sustainable development. Based on this, targeted multi-domain decision-support systems can be developed and utilized to support designers and decision makers.

4.2. Existing Voxel Model Applications in Computer-Aided-Design Studies

The early voxel model applications in architectural design utilized basic human–computer interfaces, and were studied in pedagogical contexts [55,56]. Over time, they evolved toward generative voxel-based design environments, such as Zellkalkül [60] and Emergent Reefs [61]. These applications integrated computational logics with natural growth processes, and initially involved links with manufacturing processes and environmental simulations. This line of inquiry more recently developed into a combined application of voxel models and GANs in architectural design [70]. Such experiments are often conducted in an abstract design space that disregards the spatial context inherent to architectural interventions.

Advanced voxel-based methods currently existing in the field of CAD can be used to integrate a wide range of physically measured or simulated properties directly related to the affordances of the designed objects. Affordances incorporate relations among the object, its user, and the environment. Voxel models can describe both occupied (the object) and empty (the environment) spaces on a wide range of scales; hence, they can be applied to design objects based on their desired affordances. This could be achieved by utilizing ML-based affordance-detection algorithms to learn function-to-form mapping and generate objects by combining the desired affordances [141]. Alternatively, non-geometric design knowledge formalized as a SysML model can be used to represent the spatial conflicts across multiple design domains in a voxel model space [142]. Spatial conflicts can be addressed through the computational definition of the intended empty spaces related to the design requirements defined by multi-domain design stakeholders that might change throughout an objects' lifecycle. These emerging voxel model applications demonstrate the differences between the understanding of voxel models as the 3D equivalents of pixels versus the analytical character of spatial-knowledge-encoding voxel cells that can be harnessed in computational-design processes.

Findings described above indicate the strength of voxel models in providing approachable and playful interfaces for spatial interactions. It is possible to extend the capacity of such voxel-based design interfaces to incorporate informed, generative-design environments. Moreover, abstract concepts such as affordances and spatial conflicts, can be expressed in geometric terms. Lastly, the multi-stakeholder perspectives and temporal change can be introduced into voxel interfaces. On the other hand, weaknesses of the existing voxel-based design experiments are related to the fact that they often operate in an empty, abstract space, disregarding the constraints of pre-existing geometry and environmental conditions. Moreover, the introduction of abstract concepts, such as affordances or spatial conflicts, requires highly specialized approaches, and has been currently tested only with small-scale objects. From here, the following research gap can be derived. The direct integration of interactive voxel-based environments with data-driven, generative-design processes has not been extensively studied in the field. In particular, concepts such as affordances and spatial conflicts have not been considered in the context of voxel-based methods in architectural design. Lastly, it is important to consider the role of different stakeholders and the temporal change, while developing new voxel-based design approaches. Based on this, the following further research questions arise. How can the user-centered and data-driven, multi-temporal, voxel-based design processes converge to support the architectural design processes? What are the challenges of incorporating affordances and spatial constraints into such voxel-based design approaches? How can different stakeholder perspectives be instrumentalized in such a design process?

4.3. Existing Voxel-Model Applications in Spatial-Planning Studies

By contrast, voxel models are ideally suited for integrating 3D scanned data representing urban scenes and large territories. Xu, Ting, and Stilla [8] extensively reviewed this topic, showing that individual objects can be segmented, semantically classified, and converted to geometric representations directly usable in the CAD context, through diverse ML-based methods. Looking beyond the ML-based urban-scene understanding and analysis, voxel models can be applied to integrate acquired and simulated geospatial data [143] to support generative, performance-oriented design processes in non-urban contexts [144].

In urban contexts, conventional spatial-analysis methods, such as isovists, can be extended to their 4D counterparts through voxel-based methods [69]. At the same time, urban trees can be located [65], identified [66], and quantified in terms of carbon storage [67]. Similar concepts can be applied at a larger scale to quantify the green space in cities [62,63] and analyze and communicate the importance of urban green spaces through digital visualizations and tangible models [64].

The strengths of the voxel models' applications in this context are related to the capacity to represent objects found in the physical world as objects in the abstract space of the voxel model. These voxel-based representations can encode diverse datasets describing physical properties of the physical objects captured. Weaknesses of such approaches can be derived from the technological constraints of the devices used to capture the 3D scan data. Physical resolution of the sensors, acquisition constraints and in-process errors limit the direct use of such data in voxel-based design processes. Moreover, computational techniques to process the acquired data and augment them with additional information are actively developed, and an in-depth understanding of the techniques is required to integrate voxel models in the design processes. This leads to the emergence of a research gap, formulated as follows. The convergence of information-rich, voxel-based representations of our physical environment and data-driven, architectural-design processes has not been extensively studied. Understanding and the continuous development of technological processes is needed for the convergence of the voxel-based methods and architectural-design processes. Based on this, the following research questions arise. What are the open challenges for the integration of information-rich, voxel-modeling approaches in introducing physical environment constraints into the architectural-design process? How can the development and dissemination of knowledge required for the integration of voxel modeling and architectural design be accelerated?

4.4. Existing Voxel-Model Applications from the Interdisciplinary Perspective

The identified voxel-model applications in urban contexts bring together natural and man-made elements. Voxel-model applications for ecological modeling and urban-habitat characterization [106,108] were also identified. These spatio-temporal analysis methods cover a wide range of scales and knowledge domains [145]. However, the voxel-based integration of these methods in computational design processes that integrate urban and architectural design with natural elements and urban ecology has not yet been fully explored. Some research projects focusing on this integration are underway [146,147]. Natural growth processes can also be modeled with voxel models, both in a design context [61] and to study the plant root growth [104]. The convergence of these two approaches is observed in the field of Baubotanik, where voxel models were recently applied to reconstruct a skeleton model from 3D scanned examples of living architectures [148]. The integration of living architecture in urban contexts could be facilitated through a voxel model to leverage the data integration potential, combining different scales, disciplinary datasets, and methods.

The unique quality of voxel-model applications in this context is the ability to spatialize expert data coming from other disciplinary contexts and possibly enable the data for integration with voxel-based design processes in architectural design. The discussed studies are contributing insights that can expand the impact that architectural design and the spatial-planning profession can have on addressing the current sustainability challenges. The perceived weaknesses of the discussed methods are the complexity of individual disciplinary voxel-modeling approaches, requirements for expert data input and the interdisciplinary expertise required for the validation of modeling results. Moreover, existing voxel-model applications are often operating in different spatio-temporal scales and resolutions, the application of which in architectural-design processes is conceptually challenging. From there, the need to understand and integrate voxel-modeling approaches coming from the field of earth sciences within the future design and planning activities can be seen as a possible research gap. Moreover, an understanding of the spatiotemporal scales and resolutions utilized in other disciplines is required to succeed in interdisciplinary design and planning approaches. Future research can focus on the following questions: what are the constraints limiting the possible integration of voxel-modeling approaches from the fields of earth sciences and ecology into design and planning activities? How can the interdisciplinary, voxel-based data relating to different scales and resolutions be integrated into and made an integral part of a design process?

4.5. Distribution of the Identified Voxel-Model Applications across AiA Project Phases

Voxel models can be linked with different architectural and urban-planning stages to address sustainable development. Table 7 assigns the identified voxel-model applications to the categories derived from the project phases, as described in this paragraph. The division of the architectural planning process into phases is conventionally standardized by national bodies, such as the Royal Institute of British Architects (RIBA), the American Institute of Architects (AiA), and other national equivalents. The RIBA and AiA project phases were established to standardize contracts signed between practices and clients and specify project deliveries that architectural offices must submit at the end of each phase. The context of this study extends beyond the understanding of the design process as a procedure to plan and construct a building, by encompassing the relations between natural and man-made environments. This is performed to enable holistic design processes toward sustainable development. As presented through clear indicators, the architectural-design profession recognizes the need for more holistic design processes to address, for instance, the relations between buildings and the environment (e.g., through building life-cycle analysis). This study establishes four categories derived from the building life-cycle [149] (p. 14) and design phases [149] (p. 22) established by the AiA. The first category combines “Pre-design” activities and building “Use and Maintenance” to underline the fact that each constructed building becomes a part of the building stock. The term “building stock” describes a group of buildings, while each constructed building is seen as a stock of raw materials that can be adapted or recycled throughout its lifecycle. From this perspective, the “Use and Maintenance” activities naturally blend with the “Pre-design” activities in the process of the constant change of buildings and cities. The first category collects the voxel-model applications that can be used to capture, quantify, and analyze the objects constituting man-made and natural environments. The following two categories refer to the “Schematic Design” and “Design Development” AIA project phases. Table 7 presents the voxel-model applications related to the design activities assigned to the two project phases listed in those categories. The fourth category contains the contributions related to the voxel-model applications addressing the physical aspects of the architectural design process, including building construction and the constraints related to materials and manufacturing.

The first category in Table 7 contains the voxel-model applications related to both architectural and urban design. Nearly all voxel-model applications in the urban context fall into this category, which can be explained by the adoption of diverse 3D-data-acquisition and analysis techniques utilizing voxel-based representations. The applications related to architectural design are related to the similar techniques applied to both building exteriors and interiors. The category related to the “Schematic Design” phase involves different approaches for design experimentation, utilizing voxel representations. The “Design Development” category contains approaches addressing the analysis and optimization of internal building organization and those for combining generative-design processes with voxel-based representations. The last category identifies the voxel-model applications related to digital manufacturing processes and material properties. The listed publications show growing interest in incorporating material-performance and manufacturing-process constraints in the design processes.

Table 7. Selected voxel model applications assigned to categories based on the project phases derived from the AIA Guide to Building Life Cycle Assessment in Practice [149].

Project Phases	Architectural Design	Urban Planning
Pre-design/ Use and Maintenance	Liu et al. [53] Deidda [76] Hübner et al. [80] Previtali et al. [81] Truong–Hong et al. [82] Chen et al. [83] Orengo [90] Shoaib Khan et al. [99] Taraben and Morgenthal [118] Yang et al. [119]	Susaki and Kubota [62] Wakita and Susaki [63] Anderson et al. [64] Schmohl et al. [65] Guan et al. [66] Vonderach et al. [67] Fisher–Gewirtzman et al. [68] Bremer et al. [85] Heo et al. [86] Andersen et al. [91] Nolde et al. [92] Graciano et al. [97] Nonogaki et al. [98] Sasaki et al. [106] Li et al. [120]
Schematic Design	Strehlke [55] Savov and Tessmann [57] De Klerk et al. [58] Fischer [60] Erioli and Zomparelli [61] Asmar [70] Thariyan [84] Leder [127] Xiao [128] Michalatos and Payne [132]	Morello et al. [69] Mitasova et al. [101]
Design Development	Cubukcuoglu et al. [71] Gorte et al. [72] Breslav and Khan [73] Wang et al. [77] Baron et al. [135] Mekki et al. [136] Ambrozkiewicz and Kriegesmann [137] Aage et al. [139]	
Materials and Manufacturing/ Construction	Golparvar-Fard et al. [74] Peddireddy et al. [110] Wang et al. [112] Yousefian and Tarbutton [111] Kukreja et al. [113] Huang et al. [114] Greminger [115] Chi et al. [116] Van De Walle et al. [124] Maaroufi et al. [125] Vantyghem et al. [126] Hosny et al. [129] Naboni and Kunic [130] Michalatos and Payne [131] Green et al. [133] De Schampheleire et al. [134] Craveiro et al. [138]	

In reference to Table 7, the strength of the voxel-model applications in architectural design can be assigned both to the large number of contributions related to the last design phase and to the good coverage of all project phases. The advantage of voxel-modeling approaches in spatial planning can be seen in the strong concentration in the initial design phase. At the same time, the large fragmentation of architectural-design approaches can be seen as a weakness, since the individual studies are conventionally perceived as disjointed approaches to instrumentalize voxel models to solve the problem at hand, instead of constituting a larger picture of the voxel-modeling approaches in architectural design. While the voxel-model applications in spatial planning are more concentrated, the lack of voxel-model applications in the later project phases can be seen as a disadvantage. The above-mentioned observations can constitute a research gap, expressed as a need to further systematize the voxel-model applications in each of the architectural project phases. Moreover, the transition of voxel-modeling approaches found in the later project phases of architectural design into the domain of spatial planning might lead to new findings. These observations suggest new research questions. In reference to each of the AiA Project Phases, what are the existing voxel-modeling approaches, and how they can be extended? How can the applications of voxel models from different AiA Project Phases and across the architectural design and urban-planning activities be reapplied in different phases and activities?

4.6. Summary of New Questions and Possible New Research Steps

Finally, the main findings of this study derive from the definition of voxel models as "spatial-knowledge representation schemata" [4]. Research gaps emerging from the findings and the following research questions have been presented for each of the main findings. This engenders new further research steps:

- Focus needs to be placed on the investigation of the possible convergence of user-centered and data-driven, multi-temporal, voxel-based design processes in the context of architectural design. This includes the role of affordances and spatial conflicts and ways of expressing them in a voxelized design space, incorporating stakeholder interactions.
- A second line of inquiry needs to focus on the integration of data-driven, voxel-modeling approaches that incorporate physical-environment constraints into architectural-design process. This can serve to underpin the development and dissemination of expert knowledge related to the data-driven voxel-modeling approaches in architectural design.
- Further focus needs to be placed on the promotion of interdisciplinary collaboration between the disciplines of architectural design, spatial planning, earth sciences and ecology, through the development of interoperable voxel-modeling approaches and the instrumentalization of disciplinary datasets ranging in scale and resolution.
- Finally, it will be useful to undertake systematic studies of voxel-modeling approaches in architectural design and urban planning, addressing each of the AiA Project Phases and possible innovations emerging from the application of identified methods in different project phases or design activities.

5. Conclusions

This paper presented a semi-systematic literature review with the aim of uncovering and discussing the possible intersections of diverse disciplinary methods related to voxel models regarding their possible contribution to digital architecture and planning. This study used scoping and narrative literature-review methods to map and summarize the findings and trace the development of voxel models over time. The first part of the review concluded with a keyword co-occurrence analysis. The analysis of the keywords contained in the clusters revealed numerous voxel-model applications, and covered a wide range of topics studied in computer-aided design. This analysis revealed the gap in examining how voxel models could serve as data structures for multi-domain and trans-scalar data-integrated workflows. A detailed examination was conducted to identify the existing and emerging research directions, based on the reviewers' expert knowledge. According to Snyder [26], a semi-systematic literature review aims to identify the scope of topics encompassing a particular knowledge domain. The resulting description of the possible research directions is not meant to be fully exhaustive, but aims instead to provide the possibility for the research community to examine the outcomes of the scoping study and revisit different parts in the separate, systematic literature reviews. The discussion initiated in this review concluded with the observation of numerous voxel-model applications understood as "spatial-knowledge representation schemata" [4] in computer-aided design. However, attempts to integrate this type of voxel model and architectural design are sparse and fragmented. Notable exceptions can be found in generative design [61], geomatics [121], material science [131], and computational morphogenesis [139] (p. 86). However, the full potential relating to the interdisciplinary, integrative, and holistic design approaches addressing sustainable design challenges based on voxel models is only starting. The possible future research directions identified in this review include the voxel-model application for the data-driven design approaches, leveraging analysis and acquisition methods from the field of geomatics. These processes might incorporate the identified generative-design elements and be executed in both urban and non-urban contexts. The identified environmental-modeling methods addressing the field of urban ecology often utilize spatio-temporal, voxel-based representations. The application of such approaches in the context of integrated design and planning processes will be further studied.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/architecture3020010/s1 Figure S1: Timeline comparing the time periods of similar disciplinary literature reviews. (high-resolution, full-page illustration), Figure S2: Disciplinary distribution of the voxel-related papers related to the year of publication based on the Scopus All Science Journal Classification Codes (high-resolution, full-page illustration), Figure S3: General workflow describing the NLP-based screening method applied in this study for the initial screening, followed by the keyword co-occurrence network analysis and a detailed study of the clusters (high-resolution, full-page illustration), Figure S4: Flow chart describing the algorithmic implementation of the active learning component (high-resolution, full-page illustration), Figure S5: Flow chart describing the algorithmic implementation of the pool-based sampling and the topic modeling-based reviewer validation component (high-resolution, full-page illustration), Figure S6: Role of the reviewers in validating the outcomes of the NLP-based screening method to minimize the risk of bias (high-resolution, full-page illustration).

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