Data-driven design for Architecture and Environment Integration

Convergence of data-integrated workflows for understanding and designing environments

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Abstract

Rapid urbanization and related land cover and land use changes are primary causes of climate change, and of environmental and ecosystem degradation. Sustainability problems are becoming increasingly complex due to these developments. At the same time vast amounts of data on urbanization, construction and resulting environmental conditions are being generated. Yet it is hardly possible to gain insights for sustainable planning and design at the same rate as data is generated. Moreover, the complexity of compound sustainability problems requires interdisciplinary approaches that address multiple knowledge fields, multiple dynamics and multiple spatial, temporal and functional scales. This raises a question regarding methods and tools available to planners and architects for tackling these complex issues. To address this problem we are developing an interdisciplinary approach, computational framework and related workflows for multi-domain and trans-scalar modelling that integrate planning and design scales. For this article two lines of research were selected. The first focuses on *understanding environments* for the purpose of discovering, recovering and adapting land knowledge to different conditions and contexts. This entails an analytical data-integrated computational workflow. The second line of research focuses on *designing environments* and developing an approach and computational workflow for data-integrated planning and design. These two lines converge in a combined analytical and generative data-integrated computational workflow. This combined approach aims for an intense integration of architectures and environments that we call *embedded architectures*.
In this article we discuss the two lines of research, their convergence, and further research questions.

Keywords

Data-driven Design, Data-integrated Workflows, Architecture and Environment Integration, Understanding Environments, Designing Environments

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Context

Human intervention impacts substantially on the global climate and the biosphere (Turner et al.,1990). This includes land cover and land use change (Turner & Meyer, 1991) resulting from rapid urbanization and construction. The latter are key drivers of climate change and environmental and ecosystem degradation (Trusilova & Churkina, 2008). As a result, sustainable development is swiftly becoming more complex and demanding (Underdal, 2010) due to the compound nature of sustainability problems (Hensel & Sunguroğlu Hensel, 2020). Recent decades have witnessed a considerable increase in studies that focus on the environmental impact of urbanization and construction and calls have emerged for the development of a science of urbanization (Solecki et al., 2013). At the same time Big Data has risen to prominence and vast amounts of data are being generated and analysed across many fields related to sustainable development (UN Big Data for Sustainable Development), cities (Batty 2016) and city planning (Batty, 2013). In parallel, a broad spectrum of approaches to data-driven urbanism (Kitchin, 2018) and data-driven architectural design and construction (Deutsch, 2012; Bier & Knight, 2014; Hensel & Sørensen, 2014) have emerged. However, a key question remains as to how data and data-driven design processes could be instrumentalized across knowledge fields and beyond discrete domains and scales to achieve a better understanding and more sustainable transformation of the environment.

The complexity of sustainable development and design requires a broad interdisciplinary approach that builds on multiple domains of knowledge and expertise, and addresses multiple dynamics across spatial, temporal and functional scales (Martens, 2006). Operating on discrete domains or scales significantly limits any approach to tackling the complexity of sustainable development in an effective manner. Therefore the focus needs to shift to trans-scalar approaches, methods and workflows. We are seeking to address this through our research. To illustrate this we discuss two lines of ongoing research: (1) *understanding environments* and (2) *designing environments*. *Understanding environments* involves discovery, recovery and adaptation of land knowledge for use in different conditions and contexts. This entails an analytical, data-integrated computational workflow. *Designing environments* focuses on developing an approach, a methodological framework and a computational workflow for trans-scalar, data-driven planning and design of environments. This work extends our long-term research into, and development of, multi-method approaches for research-based design in architecture, landscape architecture, and urban planning and design (Hensel, Santucci, Sunguroğlu Hensel & Auer, 2020; Hensel, Sunguroğlu Hensel & Sevaldson, 2019; Hensel & Sørensen, 2019). The two lines of research discussed in this article converge in a combined data-integrated computational workflow for analysis and design. This combined approach aims to achieve an intensive integration of architectures and environments that we term *embedded architectures* (Hensel & Sunguroğlu Hensel, 2020a, 2020b).

Innovations

The aim of this research is to develop trans-scalar, data-driven processes for architecture and environment integration along two specific research trajectories: (1) advancement of *understanding environments* through data-integrated analyses, and (2) development of data-integrated methods for *designing environments*. These lines of inquiry are based on interdisciplinary and transdisciplinary approaches, seeking to incorporate related fields of knowledge and expertise, and seeking to capture and address dynamics that span spatial, temporal and functional scales.

Understanding Environments

The first line of research entitled *understanding environments* seeks to advance the understanding of socio-ecological systems by way of knowledge discovery, recovery and adaptation. This includes in particular sustainable traditional agricultural systems and practices. The selected example focuses on viticulture, an important European socio-economic sector that is experiencing the impact of climate change (Fraga et al., 2016). More specifically, this research focuses on high-altitude terraced vineyards in Lamole in Tuscany. This research, which is ongoing, involves numerous collaborators, in particular, since 2016, the Geomatics for Environment and Conservation of Cultural Heritage Laboratory at the University of Florence (Hensel, Sunguroğlu Hensel & Sørensen, 2018). The goal of this research is to gain insights into how for centuries it has been possible to cultivate high quality red wine at this altitude. In this case the interdisciplinary research extends to a transdisciplinary one that engages local viticulturists and winemakers in the task of recovering and adapting traditional land knowledge. The research involves knowledge and data integration through coordinated methods of inquiry, data-acquisition and integration, and computational modelling and analysis. In the Lamole project, data is obtained through various remote sensing methods, geospatial analysis and computational simulations. This data is incorporated into an information model (computational ontology) and integrated in a voxel model that is linked with a CAD model of individual vineyards. Together these elements form the computational framework of a decision support system (DSS) for the adaptation of the viticultural system under consideration to different conditions and contexts.

In order to acquire a better understanding of such systems it is necessary to transcend not only disciplinary boundaries, but also the limits of discrete spatial, temporal and functional scales. In the case of the research project in Lamole, the range of scales includes: (1) the *territorial* scale (the Lamole valley together with its specific climate, ecosystem, land use mosaic, etc.), (2) the *site* scale (individual terraced vineyards together with their green borders), and (3) the *feature* scale (individual items such as drystone walls, plants, etc.). On the territorial scale a point cloud and digital elevation and digital surface models based on airborne LiDAR data was obtained for the entire Lamole Valley. These datasets were provided by Servizi Imprese e Territorio S.R.L. Additionally, open-access Geographic Information Systems (GIS) data was obtained from the GEOscopio portal run by RegioneToscana for the purpose of land use analysis, identification of terraced vineyards for future research, and environmental analysis of the wider territory. Since 2016 numerous UAV-based surveys in RGB and thermal-infrared (TIR) ranges have been conducted using entry-level and dedicated platforms. Photogrammetric reconstructions of three terraced vineyards in Lamole have been made, delivering precise terrain models and three-dimensional data on the thermal performance of the drystone walls and the soil on the terraces. To obtain insight into the microclimatic performance of individual features of the vineyards, in this instance individual drystone walls, five weather stations and, more recently, two ground-based TIR cameras were installed in a selected vineyard. The weather stations served to obtain long-term data pertaining to ambient temperature and humidity, soil temperature and humidity, solar radiation, wind speed and direction, and precipitation. This was done at different distances from a selected drystone wall to understand the contribution of the wall to modulating the microclimate of the terraces. Data from the nearby meteorological station served as control data and to calibrate the installed weather stations. Ground-based TIR cameras generated data of high temporal resolution, capturing temperature data relating to individual vines and portions of the drystone walls at 10 minute intervals. Insights gained from this study will facilitate better understanding of the thermal performance of the drystone walls in creating an advantageous microclimate for the grape vines.

The resulting datasets on the site and the feature scale indicate that the terraces and drystone walls modulate the microclimate of the high-altitude vineyards in an advantageous way for growing high quality red wine. However, to enhance this understanding requires the correlation of data and the integration of the datasets. For this purpose we selected a voxel model approach. A voxel is a data point that can comprise multiple and heterogeneous datasets, i.e. spatial and temporal data. In a voxel model such data points are organized as a regular grid in three-dimensional space. In order to accomplish this we structured the point cloud of a selected vineyard as a three-dimensional grid to act as a voxel model (Fig. 1) (Tyc, Sunguroğlu Hensel, Parisi, Tucci & Hensel, 2021). This enabled the integration of different datasets pertaining to the solar performance of terraces and drystone walls at the territorial, site and feature scale (Fig. 2).

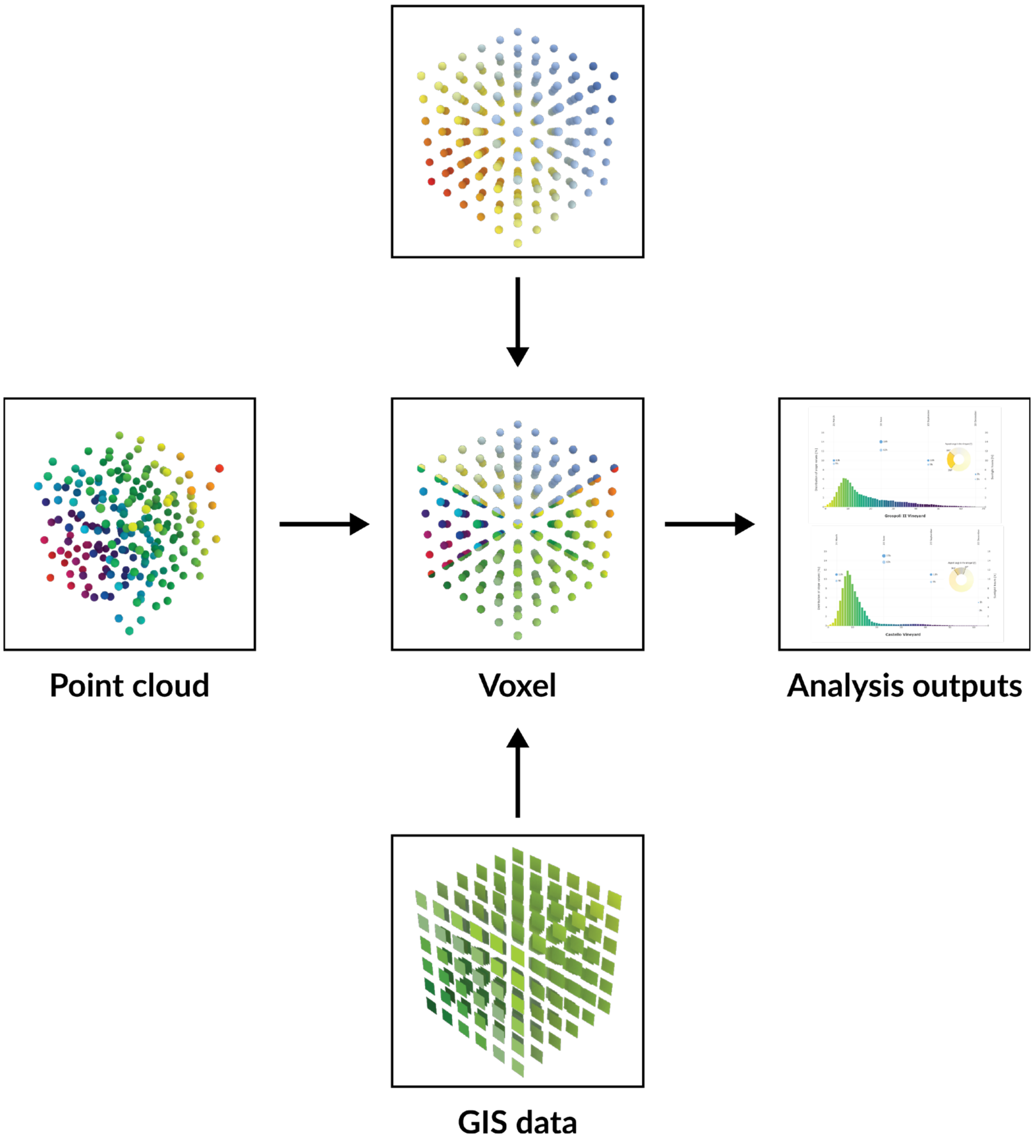


FIGURE 1 This diagram shows the main steps in the creation of a composite voxel model. Photogrammetric point clouds are voxelized and fused with datasets derived from GIS and diverse simulation tools. Data points of the voxel model can be both interactively queried by the users and accessed by ML algorithms to generate analytical outputs describing objects at different scales.

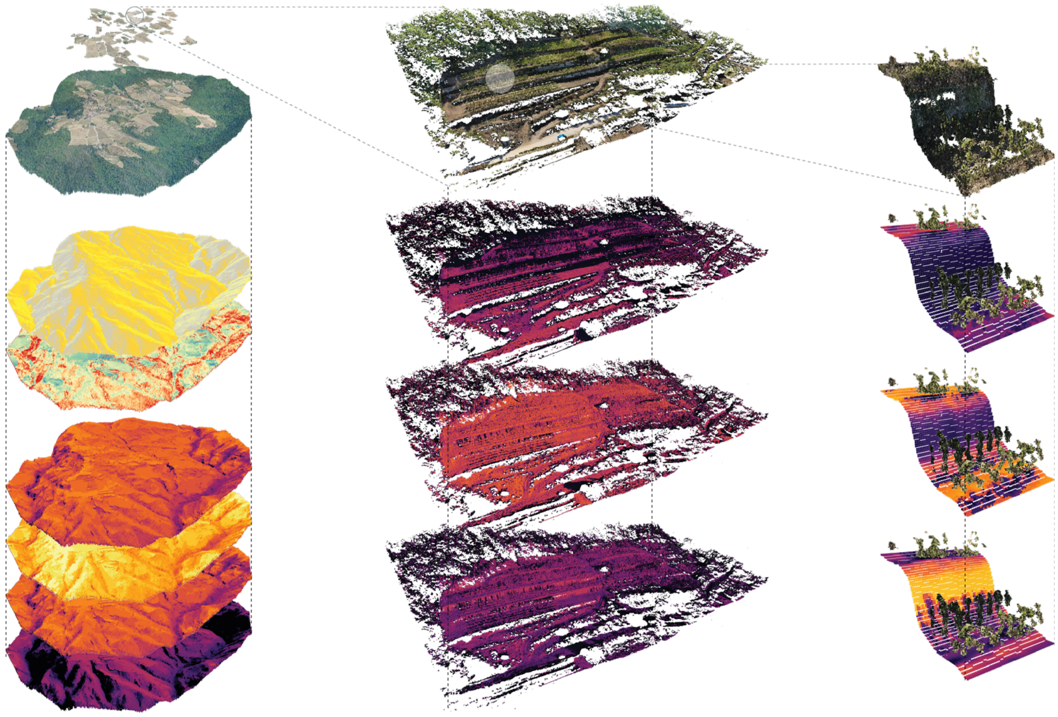
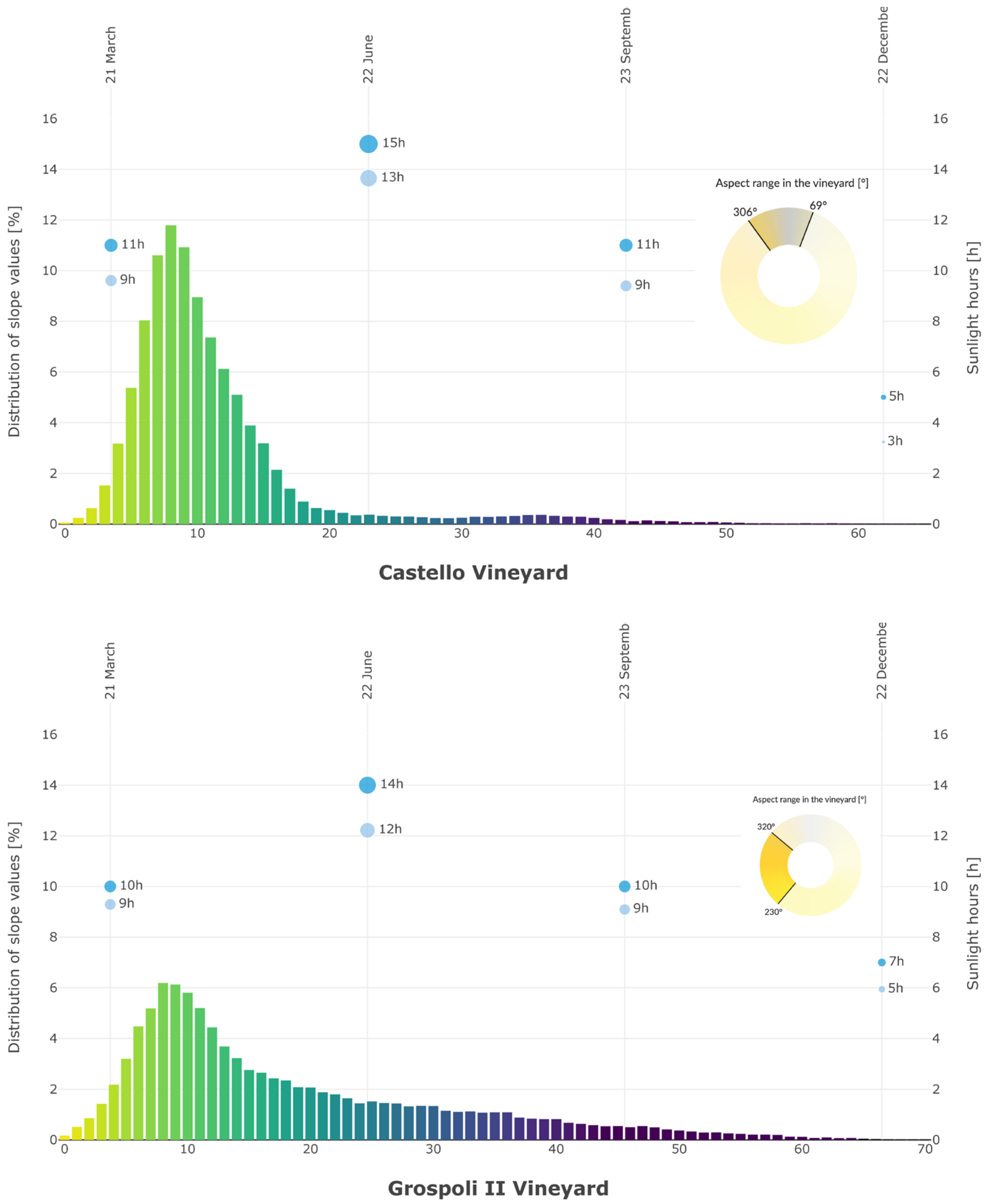


FIGURE 2 Integration of territorial, site and feature scale data in a composite voxel model. Geometric and multispectral data acquired with UAV photogrammetry and airborne LiDAR is augmented with outcomes of computational analysis and simulations at different scales.

In parallel, we undertook environmental performance analyses with an interdisciplinary toolset, developed originally in the field of geomatics and digital architecture for studies at discrete scales. That toolset includes SAGA GIS Incoming Solar Radiation for the territorial and vineyard scales, as well as Grasshopper Ladybug Tools for the feature scale. Integration of the data derived from measurements and simulations pertaining to different spatial and time scales made it possible to develop insights into how the environmental performance of different features of the vineyard combine and correlate in modulating microclimate (Fig. 3).

Furthermore, we linked the voxel model to a parametric CAD model of individual terraced vineyards that can be adjusted to meet different requirements or to modify microclimate differently. The next phase of the research will focus on the further development of this workflow to facilitate data-driven DSS to assist interdisciplinary teams with the task of adapting sustainable traditional agricultural systems and practices to different conditions and contexts. The DSS will be based on an information model (computational ontology) that links the expertise of the different disciplines and knowledge fields, i.e. viticulture, ecology, plant physiology, soil science, microclimatology, landscape architecture, et cetera, as well as the related datasets. The ontology will describe and represent domain-specific entities, their properties and relations, to capture and translate data into actionable information for design. To develop this information model and the related DSS constitutes the next phase in our research. While DSS have been discussed and used in the context of agriculture (Perini & Susi, 2004; Rose et al., 2016; Zhai et al., 2020) and precision farming (Castrignanò et al., 2020), there exists a gap in recovery and adaptation of land knowledge related to traditional sustainable agriculture and horticulture. While current research like the *Ecological Prototypes* research project is beginning to address this gap (Sunguroğlu Hensel, 2020), there is still some way to go.



b

FIGURE 3 Interactive graphs showing the slope distribution and yearly distribution of the sunlight hours in a vineyard. The graphs incorporate data from the airborne LiDAR and open-access GIS data and represent an intermediate step in the feature engineering for a K-Means-based vineyard classification.

Designing Environments

In a second line of research we focus on developing a data-driven computational design approach that aims at architecture and environment integration. This is done with specific emphasis on topographical, climatic and ecological conditions and with the aim of developing a data-driven trans-scalar design process that combines planning and design scales. The research is pursued in parallel in OCEAN, the practice of two of the authors of this article, and in master-level design studios in the research department for Digital Architecture and Planning at Vienna University of Technology.

An example of such work is the development of an alternative densification strategy and related computational methods for suburban settings. One such project commenced in OCEAN in 2018 for a site in Nesodden municipality located on a peninsula in the Oslo fjord close to Oslo city. Guided by a strategic development plan, Oslo is densifying and expanding its metropolitan area. This development places considerable pressure on neighbouring municipalities, like Nesodden, to densify as well and to construct the required new housing and related facilities. Nesodden municipality is currently characterized by a low-rise suburban fabric, agriculture, forestry and natural areas. The peninsula features a largely intact terrain sloping steeply down to the sea. In Norway, as in many other places, terrain is typically levelled prior to development. This inevitably entails the wholescale removal of vegetation and topsoil, and the levelling of bedrock, with all the related consequences for soil and water regimes, as well as for ecosystems and biodiversity. Moreover, this presents a marked increase in risk of severe flooding and accelerated soil erosion resulting from the expected considerable increase in precipitation due to climate change. In order to address this problem we searched for ways of extending and densifying the suburban fabric with minimal vegetation removal and by keeping the existing terrain intact.

For the project in OCEAN and the subsequent work in the master-level design studios at Vienna University of Technology we obtained a high-resolution LiDAR-data-based point cloud of the site via the open-access national spatial data infrastructure (Høyedata) of the Norwegian Mapping Authority, Norway's national geodata coordinator. The point cloud was converted into a detailed terrain model of the selected site. Based on this model, an extensive terrain analysis was undertaken that included slope, aspect, orientation, water runoff and sun exposure. This was done in Bison, a landscape architecture plugin for Grasshopper and Rhino (Fig. 4). The work in OCEAN proceeded by examining whether the existing terrain suggests a latent circulation system that can be derived from the terrain without major modification. In a subsequent step a series of dwelling typologies were developed that are specific to terrain features (Fig. 4).

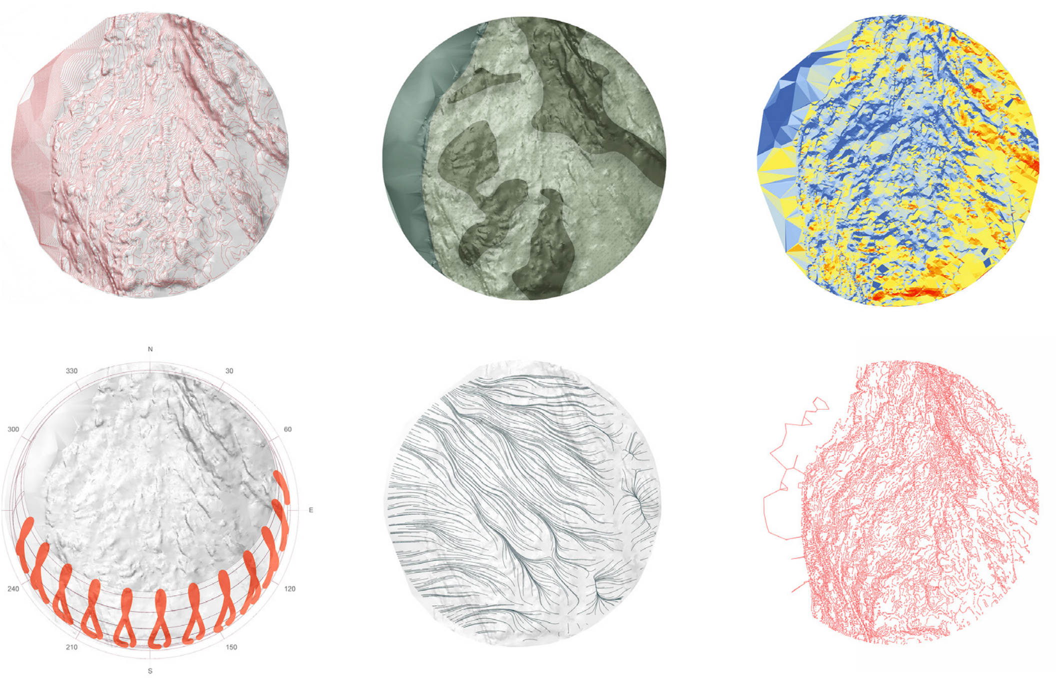


FIGURE 4 Analysis of terrain morphology, slope, vegetation distribution, sun path and water run-off, and closest points. Copyright: OCEAN Architecture | Environment, 2018.

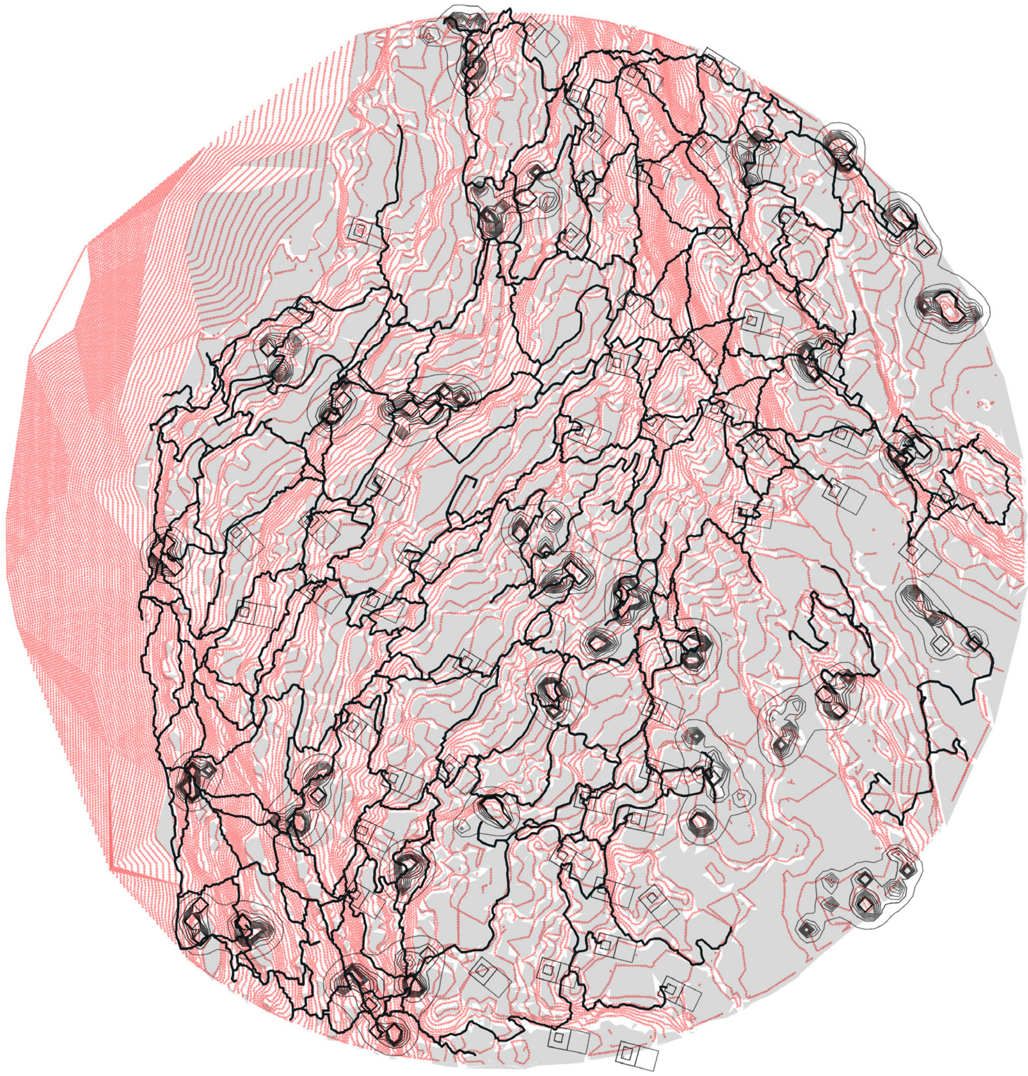


FIGURE 5 Terrain-specific circulation and dwelling typology distribution plan. Copyright: OCEAN Architecture | Environment, 2018.

These were subsequently located according to the terrain-specific circulation system and the typology-matching terrain features, as well as minimal removal of vegetation. Subsequently the building volumes were oriented in relation to solar exposure and views afforded by the terrain (Fig. 5).

In the master-level design studio a similar process was pursued. In this context the workflow was extended by including a series of computational optimization routines, which were deployed in order to locate and orient the buildings and to ensure that the requirements laid down by the Norwegian building regulations were adhered to, i.e. daylight requirements for all buildings. In the studio the relation between terrain and terrain-specific dwelling typologies was further detailed (Fig. 6) and a greater range of types deployed in the computational process (Fig. 7, Fig. 8).

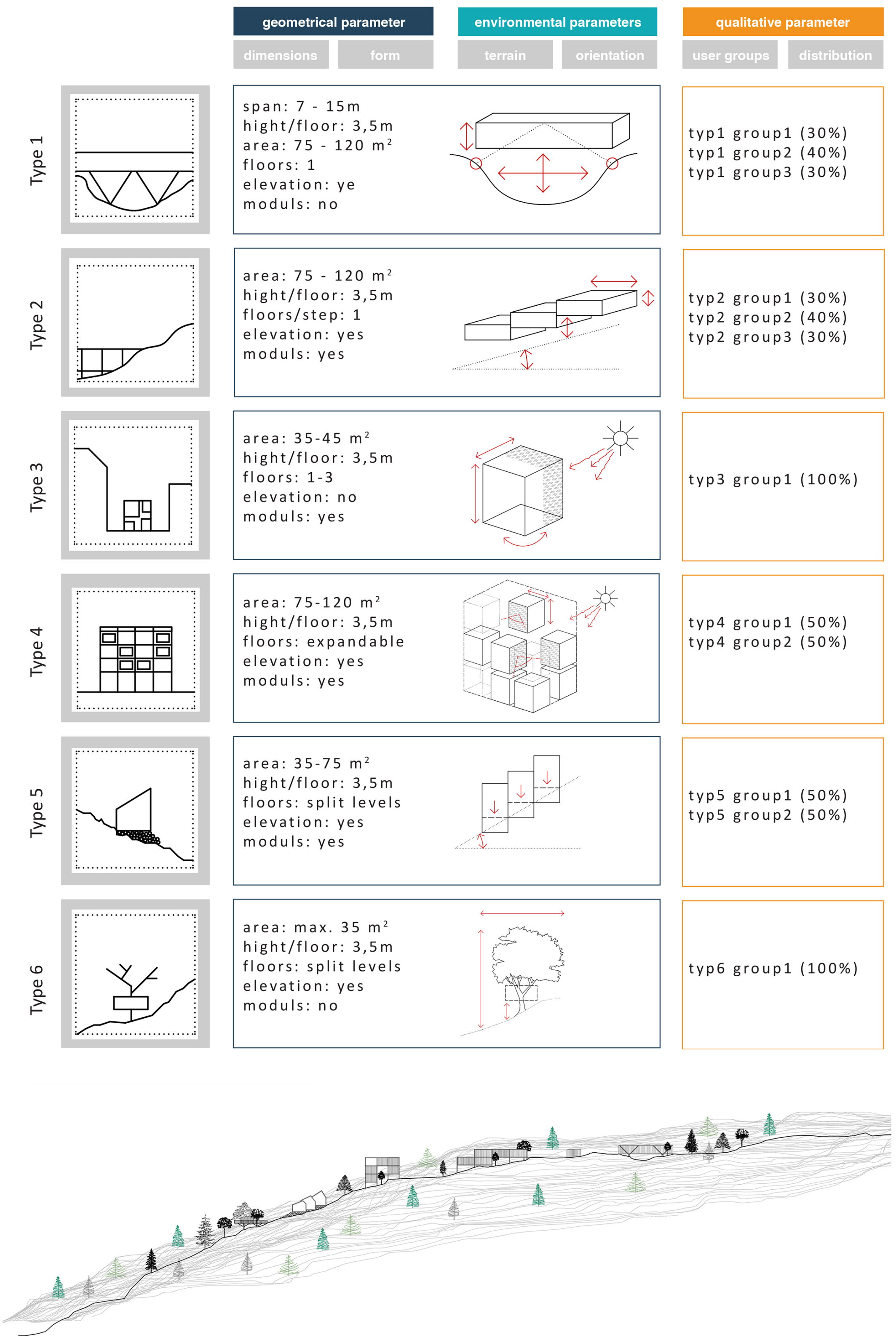
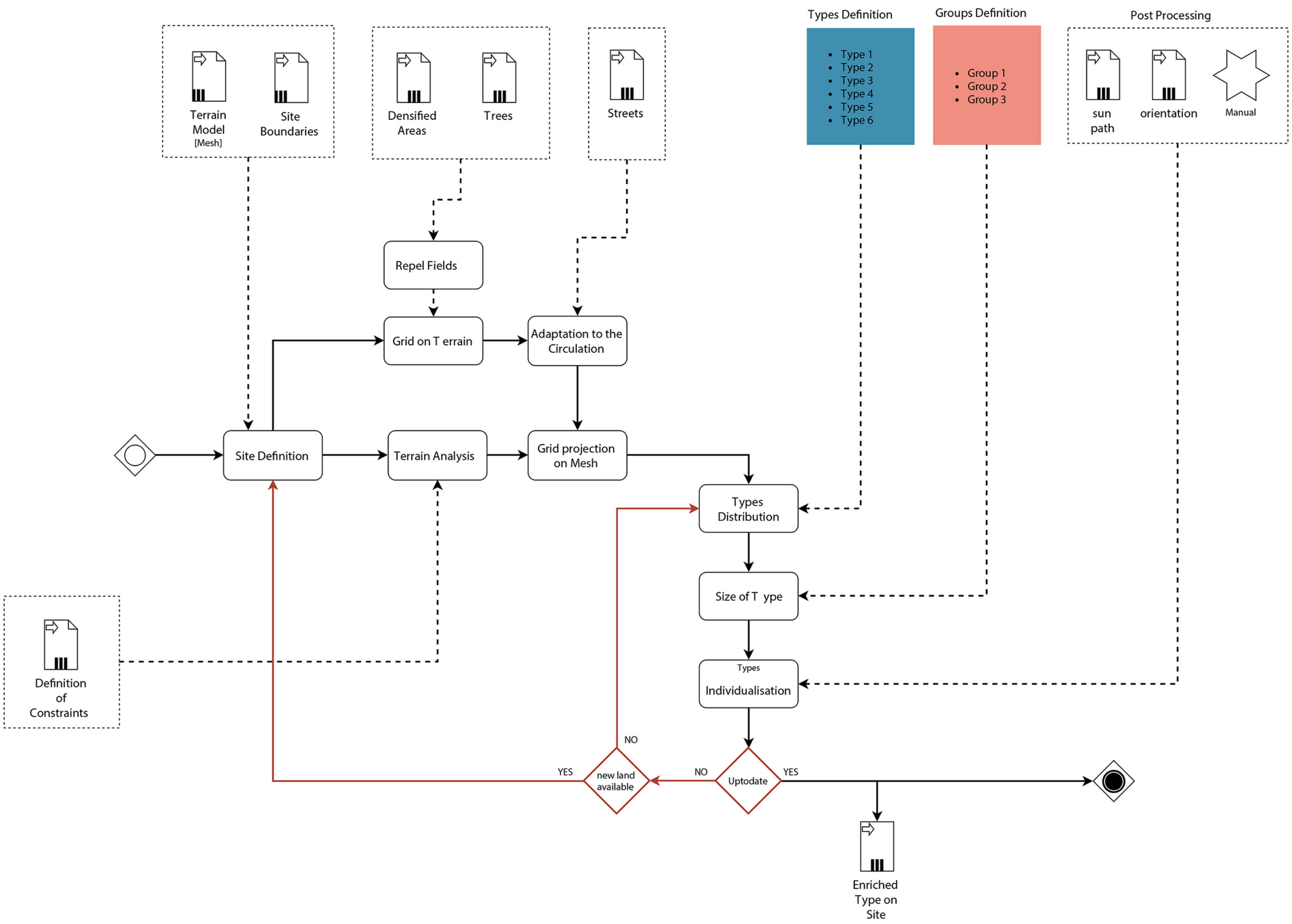
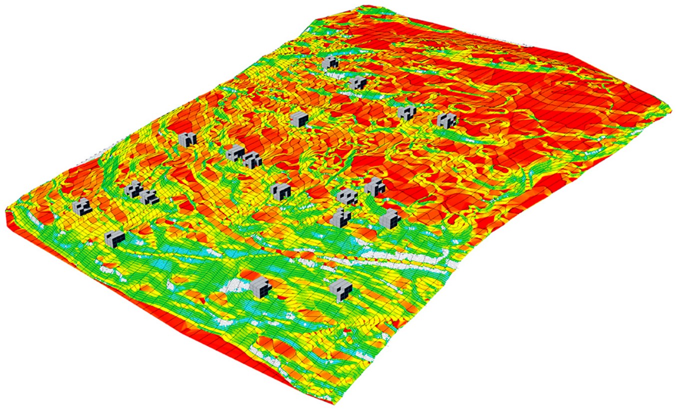


FIGURE 6 A newrevised illustration is provided. Caption: Top: Table of terrain specific architectures. Bottom: sample section through the site with allocated terrain specific architectures. Embedded Architectures Studio: Tina Selami and Fabian Pitschneider, 2019.





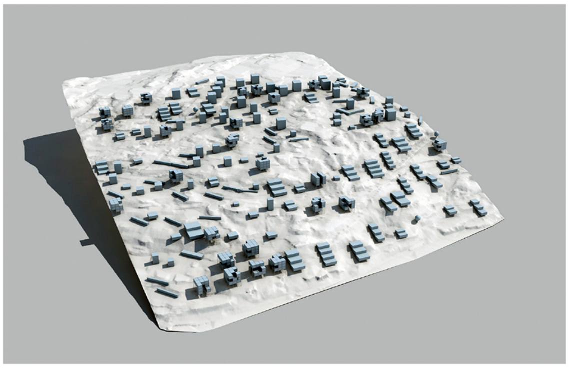


FIGURE 7 Top: computational workflow for developing terrain-specific circulation and dwelling type distribution. Bottom left: distribution of dwelling type 4 relative to the specified terrain features. Bottom right: one possible configuration of all dwelling types relative to their specified terrain features. Embedded Architectures Studio: Tina Selami and Fabian Pitscheider, 2019.

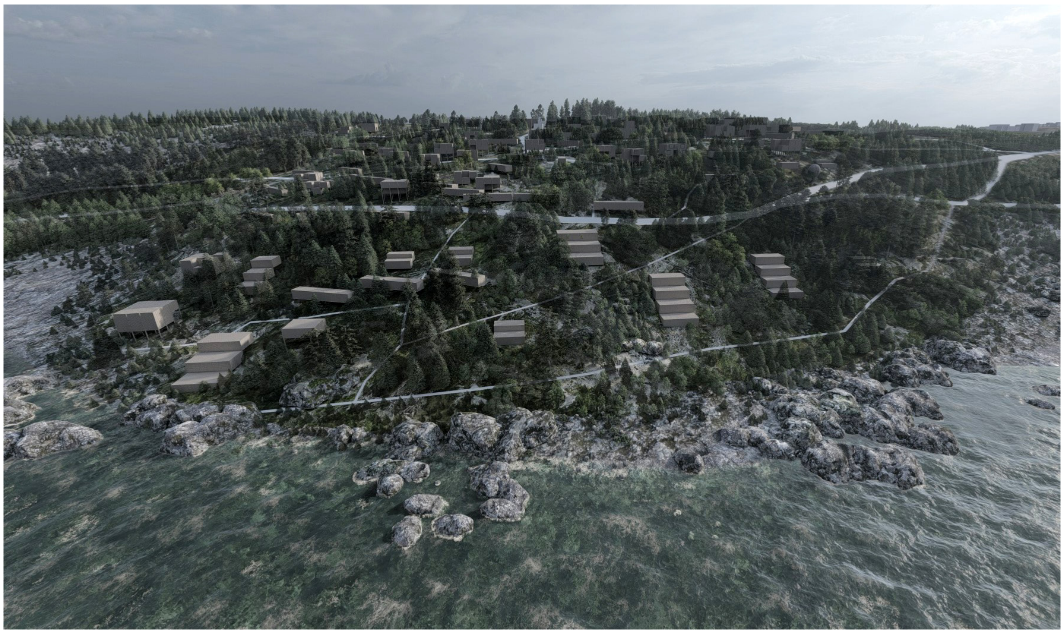


FIGURE 8 Top: rendered view of one possible configuration of all dwelling types relative to their specified terrain features. Embedded Architectures Studio: Tina Selami and Fabian Pitscheider, 2019.

In follow-up design studios we have since increasingly utilized GIS data as input for the design process, including a broader range of terrain analysis, as well as a series of GIS-based simulation tools. With the increasing amount of spatio-temporal data available for the design process, the need arose to integrate and correlate this data. As in the workflow we configured for the Lamole research project, we opted for a voxel model in combination with a CAD model. This workflow brings together computational methods and tools that are normally used in either planning or design, resulting in a structured and seamless data-integrated multi-directional workflow.

Convergence of data-driven workflows

The purpose-configured computational workflows for the above-discussed lines of research converge towards an integrated solution for the purpose of trans-scalar, data-driven analysis and design, as well as design decision support (Fig. 10). The synthesized workflow includes multi-modal data acquisition to derive multiple and heterogeneous datasets to support multi-domain modelling and design. While individual datasets are specific to spatial and temporal scales, emphasis is placed on acquiring and instrumentalizing datasets on multiple spatial and temporal scales to facilitate a trans-scalar approach. The different spatio-temporal datasets are integrated and correlated in an information model and, based on specific inquiries, selectively incorporated in a voxel model where insights into their correlation can be gained.

Various methodological questions arise from this including, for instance, the handling of Big Data via deep learning, or the role that Artificial Intelligence can play in enabling design decision support. These are key aspects in the further development of our work and the related data-integrated workflows for planning and design. Another question is the extent to which the approach described here will require the presence of interdisciplinary teams in design practices and what kind of knowledge and skills will be required of the architects and planners. The answer to this question arguably depends to a great extent on the specific design inquiry and the related design problems. This will determine the required depth of expert knowledge in ensuring that an inquiry is adequately defined, that relevant data is acquired and integrated, that criteria for evaluating design outcomes are accurately identified and that design outcomes are appropriately validated. Instructive examples exist that successfully demonstrate how experts from other disciplines can be flexibly integrated into architectural design teams (Friedman, 2016).

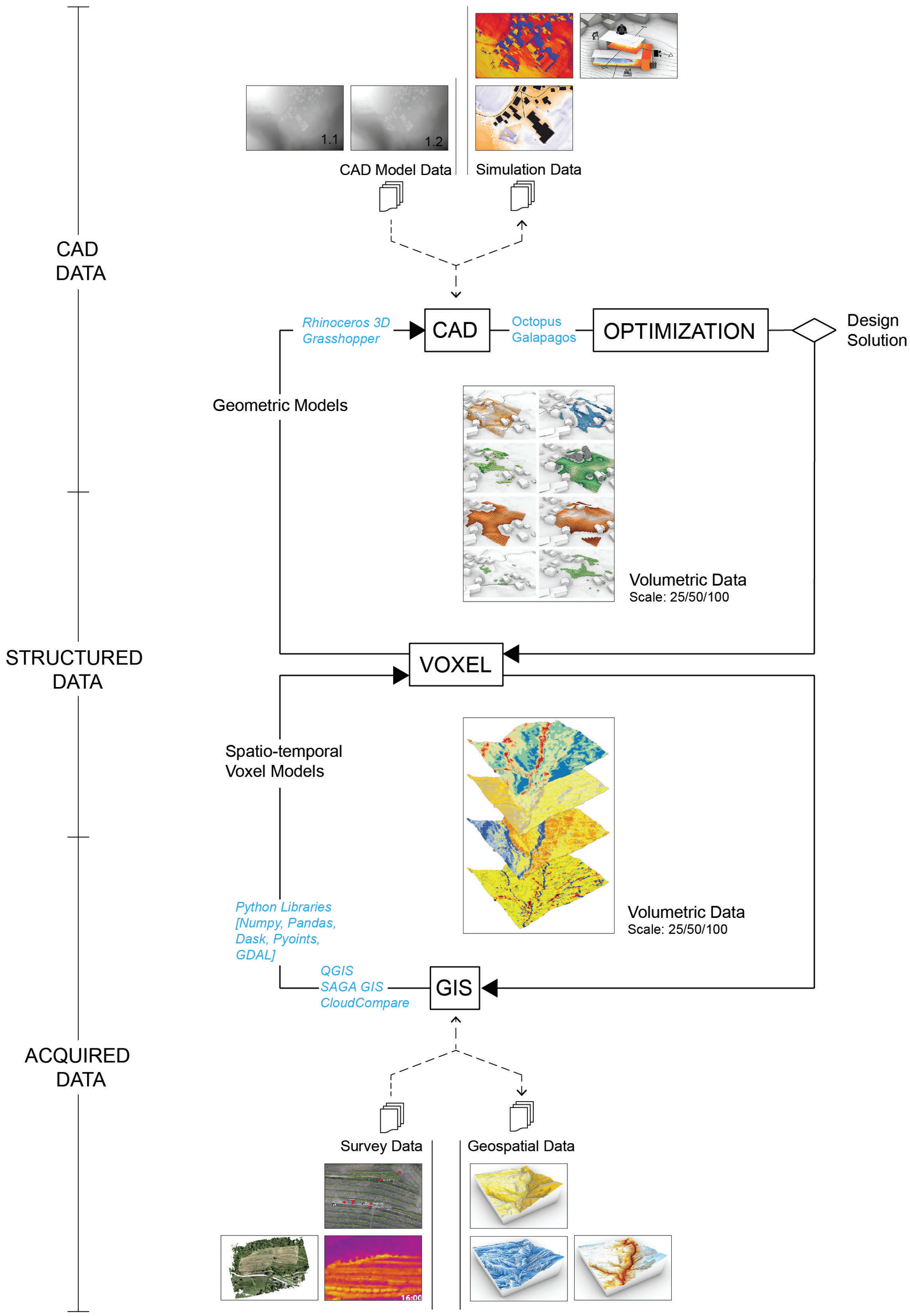


FIGURE 9 Data-integrated workflow that combines acquired data and GIS data in a voxel model linked with a CAD model that incorporates various simulation and optimization processes.

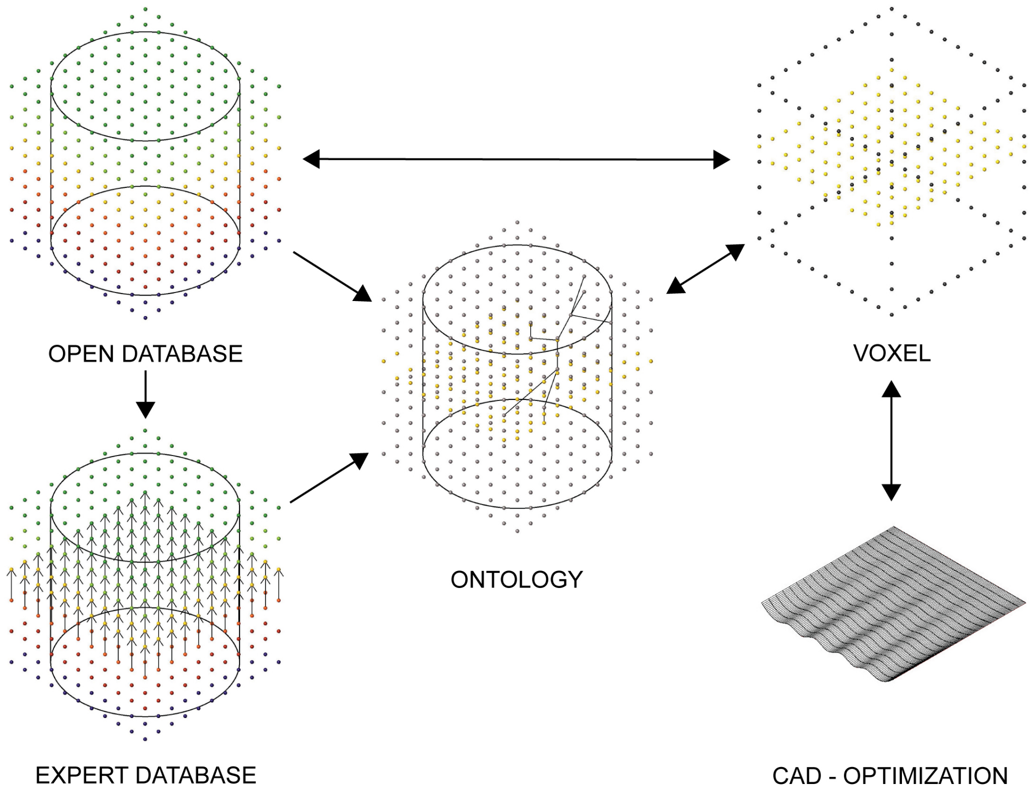


FIGURE 10 This diagram shows the key components of the design decision support system and how they are linked for data processing. Target sets from open spatial data integrated, managed and extracted from, e.g. GIS tools, feed into a relational expert database, built to expand and inform the ontology, and into the (volumetric data) voxel model, which the ontology can query and provide instructions for its generation and manipulation. Voxel instances are translated into CAD model geometry for input from further analysis and optimization.

In this context it is also necessary to decide what to teach to architecture and planning students today, so that they are able to handle present and emerging challenges. Furthermore, this relates to the knowledge fields that future architects should be able to access and communicate with, as well as the capacity to adopt new concepts, approaches, methods and tools, to configure adequate workflows and to select and integrate relevant data in the design process. To that extent the specific workflows described above should not be understood as universally applicable but, rather, as examples of custom-configured problem-specific attempts to address defined inquiries and design problems. For this reason it is of importance to obtain knowledge and skills for configuring multi-domain and trans-scalar data-driven design processes. Decision support plays a more universal role in such processes and the underlying information models can be defined and extended to fit a given purpose. How this can best be done is the question that we are currently working on in the context of architecture and environment integration.

Conclusions

The rapidly increasing complexity of compound sustainability problems requires interdisciplinary approaches that address multiple knowledge domains, multiple dynamics and multiple spatial, temporal and functional scales. There is currently a gap in adequate data-driven and data-integrated workflows, methods and tools for planners and architects for tackling these complex issues in an integrated and coordinated way. To fill this gap we are developing an interdisciplinary computational framework and related custom-configured and problem-specific workflows for multi-domain and trans-scalar modelling that integrate planning and design scales from the territorial scale to the building scale. This effort unfolds along two trajectories: (1) *understanding environments* for the purpose of discovering, recovering and adapting land knowledge to different conditions and contexts, and (2) *designing environments* with a focus on developing an approach and computational workflow for data-integrated planning and design. These two lines of research converge in a combined data-integrated computational workflow for an intensified integration of architectures and environments.

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